
Planetary Science Vision 2050 Workshop
February 27–28 and March 1, 2017
NASA Headquarters, Washington DC

Program

Planetary Science Vision 2050 Workshop

February 27–28 and March 1, 2017 • Washington, DC

Organizer

Lunar and Planetary Institute

Conveners

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NASA Planetary Science Division

Doris Daou
NASA Planetary Science Division

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Abstracts for this workshop are available via the workshop website at

www.hou.usra.edu/meetings/V2050/

Abstracts can be cited as

Author A. B. and Author C. D. (2017) Title of abstract. In *Planetary Science Vision 2050 Workshop,* Abstract #XXXX. LPI Contribution No. 1989, Lunar and Planetary Institute, Houston.

Guide to Sessions

Monday, February 27, 2017

8:30 a.m.	Auditorium	Welcome
9:00 a.m.	Auditorium	Life
11:15 a.m.	Auditorium	Life: Panel Discussion
1:30 p.m.	Auditorium	Origins
3:45 p.m.	Auditorium	Origins: Panel Discussion
5:30 p.m.	Residence Inn	Life: Poster Session
5:30 p.m.	Residence Inn	Origins: Poster Session
5:30 p.m.	Residence Inn	Workings: Poster Session

Tuesday, February 28, 2017

8:30 a.m.	Auditorium	Workings
10:45 a.m.	Auditorium	Workings: Panel Discussion
1:00 p.m.	Auditorium	Defense and Resources
3:15 p.m.	Auditorium	Defense and Resources: Panel Discussion
5:00 p.m.	Residence Inn	Defense and Resources: Poster Session
5:00 p.m.	Residence Inn	Policy, Pathways, Techniques, and Capabilities: Poster Session

Wednesday, March 1, 2017

8:30 a.m.	Auditorium	Policy, Pathways, Techniques, and Capabilities
10:45 a.m.	Auditorium	Policy, Pathways, Techniques, and Capabilities: Panel Discussion
1:00 p.m.	Auditorium	Future Technologies: Panel Discussion
2:30 p.m.	Auditorium	Overarching Issues

Print Only

Abstracts assigned to print only within each workshop theme can be found in the online program at http://www.hou.usra.edu/meetings/V2050/pdf/program.pdf

Program

Monday, February 27, 2017
WELCOME
8:30 a.m. Auditorium

Chair: **Steve Mackwell**

8:30 a.m. Green J. L. *
Welcome and Introduction of Thomas Zurbuchen

8:35 a.m. Zurbuchen T. *
Welcome and Opening Remarks

Monday, February 27, 2017
LIFE
9:00 a.m. Auditorium

In this theme, we will be looking forward over the next 35 years of exploration seeking locations where life could have existed or could exist today, and improving our understanding of the origin and evolution of life on Earth to guide our search for life elsewhere.

Chairs: **Norm Wainwright**
Carrie Anderson

9:00 a.m. Domagal-Goldman S. D. * Roberge A. Arney G. N. Mandell A. M. Kopparapu R. K. LUVOIR Sci. Tech. Definition Team
The Next Generation of Observations of Planets Beyond Our Solar System **[#8189]**
This presentation will give an overview of the (exo)planetary science capabilities of the Large UV-Optical-Infrared (LUVOIR) Surveyor, a mission concept being studied by NASA in preparation for the 2020 Astrophysics Decadal Survey.

9:15 a.m. Johnson J. * Beaty D. W. Bussey B. Christensen P. Hamilton V. Hubbard S. Meyer M. Ori G. Pratt L. Zurek R. Diniega S. Hays L.
The Long-Range Future of the Scientific Exploration of Mars **[#8073]**
Over the next three decades, if we assume that MSR has been completed, results may yield a Branch point in our long-range planning that revolves around the question: Do the samples contain either permissive or definitive evidence of martian life?

9:30 a.m. Hand K. P. * Murray A. E. Garvin J. Horst S. Brinkerhoff W. Edgett K. Hoehler T. Russell M. Rhoden A. Yingst A. German C. Schmidt B. Paranicas C. Smith D. Willis P. Hayes A. Ehlmann B. Lunine J. Templeton A. Nealson K. Cable M. Craft K. Pappalardo B. Phillips C.
Exploration Pathways for Europa After Initial In Situ Analyses for Biosignatures **[#8240]**
The 2016 Europa Lander Science Definition Team has recently completed its report on the science goals, objectives, and investigations to be conducted by a robotic lander on Europa's surface. We will present this mission in the context of 2050.

9:45 a.m. Hendrix A. R. * Hurford T. A. ROW Team
Roadmaps to Ocean Worlds **[#8171]**
We summarize the work and results of the Roadmaps to Ocean Worlds team, established by OPAG to develop community-based science goals, concepts for mission scenarios, and needed technologies to investigate ocean worlds and search for extant life.

10:00 a.m. Hammel H. B. * Mountain M. Grunsfeld J. M.
Search for Life in the Solar System and Beyond: A Unifying Vision for NASA Science Through 2050 **[#8039]**
The search for life beyond Earth defines the frontier for our generation. The search will require a multi-dimensional space where scientists, technologists, engineers, entrepreneurs, and educators can jointly collaborate, explore, and innovate.

10:15 a.m. Boston P. J. *
From Rube Goldberg to Tricorders: Astrobiology Technology Needs **[#8234]**
Astrobiology technology requires investments in a suite of selected areas to advance our goals to access and definitively detect life.

10:30 a.m. Lorenz R. D. Turtle E. P. * Barnes J. W.
Aerial Mobility: The Key to Exploring Titan's Rich Chemical Diversity **[#8217]**
Titan provides abundant complex carbon-rich chemistry on an ice-dominated ocean world but the most compelling astrobiological sites need mobile *in situ* exploration, for which Titan's atmosphere makes it uniquely suited for a heavier-than-air vehicle.

10:33 a.m. Quinn R. C. * Ricco A. J. Davila A. Koehne J. E. McKay C. P. Dateo C. E. Fonda M. L.
Scientific and Technological Approaches to Searching for Extant Life in the Solar System **[#8106]**
NASA ARC is currently developing a multi-dimensional approach to enable the definitive detection of extant extraterrestrial life in future NASA missions.

10:36 a.m. Owen T. * Bolton S. J.
A Plan for Searching for Life at Mars and Europa **[#8107]**
Mars remains the most likely habitat for extra-terrestrial life in our solar system. We propose to investigate places on Mars where there is water and return samples.

10:39 a.m. Bains W. Schulze-Makuch D. *
Rare Earth or Cosmic Zoo: Testing the Frequency of Complex Life in the Universe **[#8011]**
We propose how to test between two major hypotheses about the frequency of life in the universe (Rare Earth and Cosmic Zoo) using future remote sensing capabilities targeted at exoplanets and site visits of planetary bodies in our solar system.

10:42 a.m. Alkalai L. A. * Arora N. A. Turyshev S. T. Shao M. S.
Friedman L. F. Solar Gravity Lens Team
Mission to the Solar Gravity Lens Focus: Natural High-Ground for Imaging Earth- Like Exoplanets **[#8203]**
We propose an astrophysics probe to the Solar Gravity Lens (SGL) to effectively build an astronomical telescope capable of direct megapixel high-resolution imaging and spectroscopy of a potentially habitable exoplanet.

10:45 a.m. Pavlov A. A. * Pavlov A. K.
Missions to Special Regions of Mars to Find Currently Active Martian Biosphere **[#8216]**
To find life on Mars we need to look for life on Mars not just the traces of life from billions of years ago. We propose to design a mission to the special regions of Mars and look for the active martian biosphere.

10:48 a.m. Del Genio A. D. * Domagal-Goldman S. D. Kiang N. Y. Kopparapu R. K.
Schmidt G. A. Sohl L. E.
The Future of Planetary Climate Modeling and Weather Prediction **[#8124]**
We discuss the evolution of 3-D climate and weather prediction models that will be used increasingly to simulate and understand conditions on other solar system planets, to understand their past habitability, and to help identify potentially habitable exoplanets.

10:51 a.m. Elrod M. K. * Conway P. G.
Moving from Earth Science Technologies to Planetary and Exoplanet Visions **[#8125]**
Creating technology that transitions from Earth science to planetary missions to exoplanetary observations.

10:54 a.m. Rymer A. M. * Phillips C. B. Diniega S. Vance S. D. Craft K. L. Gudipati M. S. Roberts J. H. Blacksberg J. Cochrane C. J. Cable M. L. Hayne P. O. Ray T. L. Daubar I. J. Klima R. L. Ernst C. M. Edgington S. G.
Pioneering Outer Planet Ocean Exploration at Europa and Beyond **[#8192]**
Exploration of Europa pioneering a new age of planetary ocean exploration and search for life missions.

10:57 a.m. Cleaves H. J. * Giri C.
Universal Mass Spectrometry-Based Life Detection **[#8081]**
The search for ET life will be an important 21st century solar system exploration goal. Mass spectrometry offers a comprehensive, rapid way of "chemotyping" environmental samples. Preparation of a reference catalogue of abiotic and biological samples is described.

11:00 a.m. BREAK

Monday, February 27, 2017
LIFE: PANEL DISCUSSION
11:15 a.m. Auditorium

In this theme, we will be looking forward over the next 35 years of exploration seeking locations where life could have existed or could exist today, and improving our understanding of the origin and evolution of life on Earth to guide our search for life elsewhere.

Moderator: **David Beaty**

Panel Members: **Jason Dworkin**
John Rummel
Britney Schmidt
Lindsay Hays (synthesizer)

Monday, February 27, 2017
ORIGINS
1:30 p.m.   Auditorium

In this theme, we will be looking forward over the next 35 years to discuss our understanding of the origins and evolution of planetary systems, planets, moons, and the necessary starting conditions for life to exist on these worlds.

Chairs: **Larry Nittler**
Francis McCubbin

1:30 p.m. Stern S. A. * McKinnon W. B. Moore J. M. Buie M. W. Zangari A. Spencer J. R. Parker A. H. McNutt R. L.
Exploration Missions to the Kuiper Belt and Oort Cloud **[#8024]**
The Kuiper Belt and Oort Cloud offer deep insights into the origin of our solar system and the workings of small planets. The exploration of these regions beckons for new missions exploring new worlds and returning to explore Pluto in more detail.

1:45 p.m. Chabot N. L. * McNutt R. L. Blewett D. T. Denevi B. W. Ernst C. M. Mazarico E. Jozwiak L. M.
Future Mercury Exploration: Unique Science Opportunities from Our Solar System's Innermost Planet **[#8046]**
Mercury is one of only five inner solar system terrestrial bodies, each of which is unique. What properties and processes made these bodies so diverse? Future planetary exploration must include Mercury to make advances on this fundamental question.

2:00 p.m. Hofstadter M. * Simon A. Atreya S. Banfield D. Fortney J. Hayes A. Hedman M. Hospodarsky G. Mandt K. Masters A. Showalter M. Soderlund K. Turrini D. Turtle E. P. Elliott J. Reh K.
A Vision for Ice Giant Exploration **[#8115]**
This paper presents conclusions from the just-completed Pre-Decadal Ice Giant Mission study (commissioned by NASA), and discusses how those results feed into a vision for where planetary science can be in 2050 and the technologies to get us there.

2:15 p.m. McFadden L. A. Thomas C. A. Englander J. A. * Ruesch O. Hosseini S. Goossens S. J. Mazarico E. M. Schmerr N.
BAOBAB (Big and Outrageously Bold Asteroid Belt) Project **[#8121]**
Thirty-three years from now there should be more detailed characterization of the Main Asteroid Belt to determine the composition and distribution of disrupted protoplanets versus rubble pile asteroids from solar nebula condensation.

2:30 p.m. Rivkin A. S. * Denevi B. W. Klima R. L. Ernst C. M. Chabot N. L. Barnouin O. S. Cohen B. A.
Asteroid Studies: A 35-Year Forecast **[#8017]**
We are in an active time for asteroid studies, which fall at the intersection of science, planetary defense, human exploration, and *in situ* resource utilization. We look forward and extrapolate what the future may hold for asteroid science.

2:45 p.m. Treiman A. H. *
Sampling the Solar System: The Next Level of Understanding **[#8037]**
In its long-term plans, NASA should formally encourage many sample returns from all types of solar system objects. This program should build from successful architectures outward to larger samples and to more difficult logistics and curation needs.

3:00 p.m. Stroud R. M. *
A Ground Truth-Based Approach to Future Solar System Origins Research **[#8148]**
To expand our understanding of how the solar system, and thus humanity itself, came into being, we must push forward the state-of-the-art in planetary materials analysis capabilities over the next three decades.

3:15 p.m. Mandt K. E. * Atreya S. A. Luspay-Kuti A. Mousis O. Simon A. Hofstadter M. D.
Isotope Geochemistry for Comparative Planetology of Exoplanets **[#8045]**
Isotope geochemistry has played a critical role in understanding the origins of solar system bodies. Application of these techniques to exoplanets would be revolutionary and would allow comparative planetology with origins of exoplanet systems.

3:30 p.m. BREAK

Monday, February 27, 2017
ORIGINS: PANEL DISCUSSION
3:45 p.m. Auditorium

In this theme, we will be looking forward over the next 35 years to discuss our understanding of the origins and evolution of planetary systems, planets, moons, and the necessary starting conditions for life to exist on these worlds.

Moderator: **Larry Nittler**

Panel Members: **Francis McCubbin (synthesizer)**
Aki Roberge
Scott Bolton
Bill Bottke

Monday, February 27, 2017
LIFE: POSTER SESSION
5:30 p.m. Residence Inn

Dworkin J. P. Glavin D. P. Lupisella M. Williams D. R. Kminek G. Rummel J. D.
The Moon as a Laboratory for Biological Contamination Research **[#8064]**
The study of historical artifacts on the Moon can serve as a way to examine biological, chemical, and materials properties after decades of space exposure.

Rummel J. D.
"Be Careful What You Wish For:" The Scientific, Practical, and Cultural Implications of Discovering Life in Our Solar System **[#8163]**
This abstract describes some of the consequences of a successful search for life in our solar system, and notes some of the pitfalls possible in finding life on Mars and on Europa. It is meant to encourage thinking about this very real possibility.

Blake D. F. Sarrazin P. Thompson K.
The Importance of Particle Induced X-Ray Emission (PIXE) Analysis and Imaging to the Search for Life on the Ocean Worlds **[#8138]**
Detection of the biogenic elements on Ocean Worlds is important in establishing evidence of life and its context. PIXE analysis using 244-Cm is essential for this measurement. The development of a 244-Cm source is strategically important to NASA.

Sherwood B. Lunine J. Sotin C. Cwik T. Naderi F.
Follow the (Outer Solar System) Water: Program Options to Explore Ocean Worlds **[#8034]**
The envisioned Ocean Worlds Exploration Program cannot match the success of the Mars Exploration Program since 2001. Programmatic and technical constraints, policy gaps, and options with high leverage over program viability and velocity are analyzed.

Wainwright N. R. Steele A. Monaco L. Fries M.
Analogies Among Current and Future Life Detection Missions and the Pharmaceutical/ Biomedical Industries **[#8175]**
Life detection goals and technologies are remarkably similar between several types of NASA missions and the pharmaceutical and biotechnology industries. Needs for sensitivity, specificity, speed have driven techniques and equipment to common ends.

Tani J. Ruvkun G. Zuber M. T. Carr C. E.
On Neuromorphic Architectures for Efficient, Robust, and Adaptable Autonomy in Life Detection and Other Deep Space Missions **[#8080]**
Neuromorphic architectures enable cross-cutting capabilities relevant to the search for life beyond Earth, and to all future deep space missions: event based sensing, ultra efficient data processing, fault tolerance, robustness, and adaptability.

Niles P. B. Beaty D. Hays L. Bass D. Bell M. S. Bleacher J. Cabrol N. A. Conrad P. Eppler D. Hamilton V. Head J. Kahre M. Levy J. Lyons T. Rafkin S. Rice J. Rice M.
Scientific Investigations Associated with the Human Exploration of Mars in the Next 35 Years **[#8167]**
We present a summary of the findings of the Human Science Objectives Science Analysis Group (HSO-SAG) chartered by MEPAG in 2015 to address science objectives and landing site criteria for future human missions to Mars which could provide incredible scientific discovery.

Matthies L. H. Abid M. M. Backes P. G. Del Castillo L. Wilcox B. H. Jones M. A. Beauchamp P. M. Cutts J. A.
Technologies for Missions to Ocean Worlds **[#8165]**
We summarize roadmaps for technology advances needed to enable Ocean Worlds exploration, including pin-point landing, sub-surface ice sampling, cryogenic ice sample return, planetary protection, and low temperature electronics and mechanisms.

Schmidt B. E.
Don’t Invent the Wheel: Seeking Life in the Subsurface of Multiple Icy Ocean Worlds by 2050 **[#8242]**
Flyby. Orbit. Land. Drill. Swim. Find Life.

Castillo-Rogez J. C.   Raymond C. A.   Russell C. T.   Rivkin A. S.   Neveu M.
Roadmap for the Exploration of Dwarf Planet Ceres **[#8077]**
Ceres, the largest asteroid and only dwarf planet found in the inner solar system, offers a playground for testing hypotheses pertaining to the early solar system evolution as well as the habitability potential of large volatile-rich bodies.

Monday, February 27, 2017
ORIGINS: POSTER SESSION
5:30 p.m. Residence Inn

Quick L. C. Adams E. Barr A. C.
Prospects for Detecting Cryovolcanic Activity in Exoplanetary Systems **[#8036]**
We consider prospects for the detection of explosive cryovolcanism on cold, water-rich exoplanets by next-generation space telescopes.

Milam S. N. Hammel H. B.
Planetary Science with Next Generation Large Astrophysics Missions **[#8210]**
Next generation airborne and space-based telescopes will work in concert with future *in situ* missions and large ground-based facilities to address key questions of molecular inheritance throughout star and planet formation to our solar system.

Brenker F. E. Vincze L. Prior D. J.
Laboratory Studies of Extraterrestrial Ices — Sample Return from Icy Bodies **[#8122]**
A comprehensive analytical study of ices in laboratories on Earth is fundamental for the understanding of the formation and evolution of our solar system. We predict that ice sample return will be one of the most important and exciting challenges.

Danielson L. R. Draper D. Righter K. McCubbin F. Boyce J.
Exploring the Largest Mass Fraction of the Solar System: The Case for Planetary Interiors **[#8120]**
Planetary interiors hold the key to planetary origins via accretionary and early differentiation processes. Our vision is to establish a 5000 ton press open user facility that will serve the planetary science and the greater scientific community.

Rymer A. M. Turtle E. P. Hofstadter M. D. Simon A. A. Hospodarsky G. B.
'It Takes a Village.' Collaborative Outer Planet Missions **[#8199]**
How an Ice Giant mission could represent numerous research targets. The case for cross disciplinary collaboration and how to enable it.

Bottke W. F. Nesvorny D. Marchi S. Levison H. Canup R.
Exploring Planet Migration and Early Solar System Bombardment **[#8137]**
Understanding planet migration and early bombardment are key Decadal Survey goals because they define the nature of many solar system worlds. Both can be constrained by dating ancient terrains, basins, and craters found on the Moon and Mars.

Oleson S. R. Landis G. A.
Triton Hopper: Exploring Neptune's Captured Kuiper Belt Object **[#8145]**
Neptune's moon Triton is a fascinating object, a dynamic moon with an atmosphere and geysers. This work will describe the mission options to get to Triton and design of an ISRU propellant supplied hopper to explore large parts of Triton.

McCubbin F. M. Allton J. H. Barnes J. J. Boyce J. W. Burton A. S. Draper D. S. Evans C. A. Fries M. D. Jones J. H. Keller L. P. Lawrence S. J. Messenger S. R. Ming D. W. Morris R. V. Nakamura-Messenger K. Niles P. B. Righter K. Simon J. I. Snead C. J. Steele A. Treiman A. H. Vander Kaaden K. E. Zeigler R. A. Zolensky M. Stansbery E. K.
Priority Science Targets for Future Sample Return Missions Within the Solar System Out to the Year 2050 **[#8224]**
This abstract highlights some of the priority science targets for future sample return missions over the next 35 years and some of the sample handling and storage challenges that would arise if such samples were to be collected and returned to Earth.

Zeigler R. A.   Allton J. H.   Evans C. A.   Fries M. D.   McCubbin F. M.   Nakamura-Messenger K.   Righter K.   Zolensky M.   Stansbery E. K.
Advanced Curation Activities at NASA: Preparing for the Next Waves of Astromaterials Sample Return **[#8196]**
We discuss the current curatorial efforts for NASA's astromaterials collections, as well as efforts that are underway (or need to be undertaken) to prepare for the challenging curation conditions required by future sample return missions.

Asmar S. W.   Armstrong J. W.   Atkinson D. H.   Bell D. J.   Bird M. K.   Dehant V.   Iess L.   Lazio T. J. W.   Linscott I. R.   Mannucci A. J.   Mazarico E.   Park R. S.   Patzold M.   Preston R. A.   Simpson R. A.
The Future of Planetary Atmospheric, Surface, and Interior Science Using Radio and Laser Links **[#8181]**
Radio science experiments have been conducted on almost every planetary mission in the past five decades and led to numerous discoveries. More science breakthroughs are expected that fit Planetary Vision 2050 themes with described technical advances.

Mandell A. M.   Pulkkinen A. A.   Domagal-Goldman S.
The GSFC Exoplanet Modeling and Analysis Center **[#8094]**
The GSFC Exoplanet Modeling and Analysis Center is meant to provide an accessible platform for the planetary atmosphere modeling and analysis community to host their software for modeling and interpreting current and future NASA exoplanet data.

Pauken M. T.   Hall J. L.   Matthies L.   Malaska M.   Cutts J. A.   Tokumaru P.   Goldman B.   De Jong M.
Science at a Variety of Scientific Regions at Titan Using Aerial Platforms **[#8177]**
Titan has an abundant supply of organic species and could harbor exotic forms of life. Aerial platforms are ideal for performing reconnaissance and *in situ* analysis. We describe a range of vehicles in development for exploring Titan.

Bolton S. J.   Owen T.   Waite J. H.
Origins and Life, the Next Steps Beyond the Initial Survey of Our Solar System **[#8105]**
A plan and outline for the next decades of solar system exploration to address key questions regarding the origin of the planets and life. Comparative study of the composition of the planets and small bodies will be advocated.

de Val-Borro M.   Milam S. N.   Cordiner M. A.   Charnley S. B.
Prospects for the Study of Comets with Surface Sample Return Spacecraft **[#8245]**
Comets are small bodies composed of molecular ices and dust that spent most of their lifetime far from the Sun.

Monday, February 27, 2017
WORKINGS: POSTER SESSION
5:30 p.m. Residence Inn

Masiero J. R. Bauer J. M. Grav T. Mainzer A. K.
When Worlds Collide: Witnessing Planetary-Scale Impacts in the Coming Decades **[#8020]**
Asteroid impacts offer a unique opportunity to study the collisional processes that shape planetary systems. In the coming decades, expanded surveys may give us the chance to predict an impact with enough advance warning to observe it *in situ*.

Carter L. M. Kruse S. Bleacher J. E. Ghent R. R. Schmerr N. Petro N. E. Baker D. M. H.
Exploring Below the Surface at Human Scales: Adding a Third Dimension to Our Knowledge of Planets **[#8078]**
In the next 30 years, advances in instrument technology, automation, and data downlink could provide the opportunity to fill in the gaps in our knowledge of the subsurface, and create subsurface maps that integrate seamlessly with our surface images.

Hurley D. M. LEAG Executive Committee
Lunar Volatiles as a Resource for Science and Exploration **[#8096]**
Water and other volatiles on the Moon have compelling use for science and exploration. The timeline for exploration, science, and ISRU is presented.

Hendrix A. R. Vilas F. Retherford K. D. McClintock W. E. Nikzad S. Hansen C. J. Schneider N. M. Holsclaw G. M.
UV Imaging Spectroscopy: The 2050 Vision **[#8130]**
We present highlights of the utility and potential of UV imaging spectroscopy for planetary science, addressing the themes of Workings, Life, and Threats and Resources.

Petro N. E. Richardson J. Bleacher J. E. Hollibaugh-Baker D. Farrell W. Williams D. Schwadron N. Siegler M. Schmerr N. Carter L. Cohen B.
Long Duration Surface Experiments on Airless Bodies: The Need for Extended In Situ Measurements and Lessons from ALSEP **[#8055]**
Any future surface exploration (human or robotic) should be accompanied by the deployment of long-lived surface experiments. These experiments need to be treated as special facilities, and should be protected from financial and logistical threats.

Guzewich S. D. Bleacher J. E. Smith M. D. Khayat A. Conrad P.
Astronaut-Deployable Geophysical and Environmental Monitoring Stations **[#8092]**
Geophysical and environmental monitoring stations could be deployed by astronauts exploring Mars, the Moon, or asteroids, and create a broad network that would collect high-value scientific information while also enhancing astronaut safety.

Thangavelautham J. Asphaug E. Schwartz S.
On-Orbit Planetary Science Laboratories for Simulating Surface Conditions of Planets and Small Bodies **[#8059]**
Our work has identified the use of on-orbit centrifuge science laboratories as a key enabler towards low-cost, fast-track physical simulation of off-world environments for future planetary science missions.

Hayne P. O. Siegler M. A. Paige D. A. Reck T.
Planetary Heat Flow Mapping from Orbit **[#8133]**
Heat flow is fundamental to understanding planetary interior evolution. We imagine an innovative orbital approach, which could provide global heat flow mapping of planets and satellites with dramatically reduced cost and complexity.

Nixon C. A.   Achterberg R. K.   Buch A.   Clark R. N.   Coll P.   Flasar F. M.   Hayes A. G.   Iess L.   Lorenz R. D.   Lopes R.   Mastroguiseppe M.   Raulin F.   Smith T.   Solomidou A.   Sotin C.   Strobel D. F.   Turtle E. P.   Vuitton V.   West R. A.   Yelle R.
Riddles of the Sphinx: Titan Science Questions at the End of Cassini-Huygens **[#8156]**
The paper will describe the outstanding high-level questions for Titan science that are remaining at the end of the Cassini-Huygens mission, compiled by a cross-section of scientists from multiple instrument teams.

Neal C. R.   Currie D.   Grimm R.   Kedar S.   Nagihara S.   Siegler M.   Weber R.   Zacny K.
Enabling Technologies for a Future Lunar and Planetary Geophysical Network **[#8143]**
A long-lived, multi-station, global lunar geophysical network will yield information about primary terrestrial differentiation, as well as potential hazards to long term human surface exploration. The technology can be applied to other planets.

Thomas C. A.   McFadden L. A.
The Future of Asteroid Characterization **[#8228]**
Characterization of asteroids is important for understanding the past and current evolution of our solar system. We will discover a large number of objects and our ability to study them will be greatly improved. We need to define future priorities.

Tuesday, February 28, 2017
WORKINGS
8:30 a.m. Auditorium

Provide the 2050 prospect of key topics related to the workings of stellar systems at a time thousands of exoplanets have been detected and first terrestrial exoplanets have been imaged.

Chairs: **Christophe Sotin**
Carrie Anderson

8:30 a.m. Zuber M. T. * Smith D. E. Mazarico E. Lunine J. I. Neumann G. A. Lemoine F. G. Genova A. Goossens S. J. Sun X.
From Copernicus to Newton to Einstein: Toward a Dynamical Understanding of the Solar System **[#8074]**
Fusion of hydrogen to helium in sun combined with solar wind are major contributors to slow decrease of the sun's mass over time. This decrease should cause solar system to expand at rate that is conceivably measurable using laser ranging techniques.

8:45 a.m. Simon A. A. *
Science and Exploration in the Outer Solar System in 2050 **[#8007]**
Our knowledge of the outer solar system has changed vastly in 35 years and will continue to do so, but complete understanding of the giant planet systems is critical to informing exoplanet, solar system formation, and atmospheric dynamic studies.

9:00 a.m. Horst S. M. *
Titan's Atmosphere and Climate: Unanswered Questions **[#8204]**
By 2050 / We must unravel Titan's / Complex chemistry.

9:15 a.m. Cutts J. A. * Grimm R. E. Gilmore M.
Venus Exploration to 2050 **[#8015]**
Venus should be an Earth-like planet due to its similar size and position in the solar system, but it has developed very differently. The Venus Exploration Assessment Group (VEXAG) has formulated long-range plans to explore our puzzling sister planet.

9:30 a.m. Head J. W. * Pieters C. Scott D. Johnson B. Potter R. Hoffman J. Foing B. Zelenyi L. Mitrofanov I. Marov M. Basilevsky A. Ivanov M. Jaumann R. Xiao L. Haruyama J. Ohtake M. Senthil Kumar P. Aharonson O.
Exploration of Planetary Crusts: A Human/Robotic Exploration Design Reference Campaign to the Lunar Orientale Basin **[#8170]**
By 2050 we need to be working on fundamental scientific problems in an integrated fashion to provide insights into early planetary processes by exploring and characterizing the crust of the Moon.

9:45 a.m. Ehlmann B. L. * Johnson S. S. Horgan B. Niles P. B. Amador E. S. Archer P. D. Byrne S. Edwards C. S. Fraeman A. A. Glavin D. P. Glotch T. D. Hardgrove C. Hayne P. O. Kite E. S. Lanza N. L. Lapotre M. G. A. Michalski J. Rice M. Rogers A. D.
Mars Exploration Science in 2050 **[#8236]**
We describe an approach to Mars exploration in 2050 and the decades leading in that couples fundamental science on the workings of planets and the search for life with collection of information on resources and hazards essential for human exploration.

10:00 a.m. Neal C. R. * Lawrence S. J.
A Multi-Decadal Sample Return Campaign will Advance Lunar and Solar System Science and Exploration by 2050 **[#8142]**
Given the global datasets now available for the Moon, a targeted sample return (robotic and human) campaign is the next logical step in advancing lunar and solar system science.

10:03 a.m. Cohen B. A. * Arevalo R. Bottke W. F. Conrad P. G. Farley K. A. Fasset C. I. Jolliff B. L. Lawrence S. J. Mahaffy P. R. Malespin C. Swindle T. D. Wadhwa M.
Geochronology as a Framework for Planetary History Through 2050 **[#8047]**
In the next 40 years, we advocate constructing a common framework of geologic time across our solar system, linking major geologic events during planetary formation, evolution, and surface environments to solar system history.

10:06 a.m. Bauer J. M. * Sonnett S. Kramer E. A. Mainzer A. K. Masiero J. R. Grav T.
Surveys of Sizes and Basic Compositions of Outer Solar System Populations from Infrared Space-Based Platforms **[#8067]**
Statistically meaningful samples of hundreds of thousands of asteroid diameters have been measured. Several future infrared missions have the potential to sample more distant populations. We will discuss some of these and their potential surveys.

10:09 a.m. Crary F. * Bagenal F. Clark G. Delamere P. A. Ebert R. Rymer A. M. Vought M. 26 Other Planetary Magnetospheres Scientists
Exploring Outer Planet Magnetospheres with Small Focused Missions **[#8099]**
The exploration of planetary magnetospheres can be accomplished using small, focused missions. As stand-alone missions or as secondary payloads, this will provide an efficient, flexible framework for magnetospheric science in the outer solar system.

10:12 a.m. Harris W. M. * Schmidt B. E. Villanueva G. L.
Solar System Exploration with the Large Ultraviolet Optical and Infrared Surveyor (LUVOIR) **[#8247]**
This abstract talks about the exoplanet habitability and biosignatures science that would be enabled by LUVOIR.

10:15 a.m. DISCUSSION

10:30 a.m. BREAK

Tuesday, February 28, 2017
WORKINGS: PANEL DISCUSSION
10:45 a.m. Auditorium

Provide the 2050 prospect of key topics related to the workings of stellar systems at a time thousands of exoplanets have been detected and first terrestrial exoplanets have been imaged.

Moderator: **Larry Paxton**

Panel Members: **Louise Prockter**
Jim Garvin
Carol Raymond
Hannah Wakeford (synthesizer)

Tuesday, February 28, 2017
DEFENSE AND RESOURCES
1:00 p.m. Auditorium

In this theme, we will be looking forward over the next 35 years at progress in understanding, characterizing, and mitigating risk to Earth from Near Earth Objects, and in characterization, exploitation, and utilization of resources on planetary bodies.

Chairs: **Lisa Gaddis**
Julie Stopar

1:00 p.m. Mainzer A. * Bauer J. Grav T. Masiero J. Nugent C. Reddy V.
The Future of Planetary Defense **[#8225]**
By 2050, advanced near-Earth object (NEO) surveys will have identified many potential hazardous objects. Focus will shift to improving orbit knowledge, searching for smaller NEOs, discovering long period comets, and planning mitigations as needed.

1:15 p.m. Gertsch L. S. * Morris K. A.
Advancing the Science of ISRU **[#8202]**
The sustainable exploration of space requires *in situ* resource utilization (ISRU). Successful ISRU depends on a solid science foundation; consequently, planetary science must include basic and applied science investigations to support ISRU.

1:30 p.m. Lawrence S. J. * Neal C. R. LEAG Executive Committee
The Open Gateway: Lunar Exploration in 2050 **[#8028]**
The Lunar Exploration Roadmap (LER) is the definitive plan to enable science advances for the entire solar system. We describe our vision for the Moon in 2050 following LER implementation and the needed strategies and technologies to make it happen.

1:45 p.m. Swindle T. D. * Chabot N. Barbee B. Bauer J. Bierhaus B. Britt D. Castillo-Rogez J. Chodas P. Feaga L. Hartzell C. Mercer C. Stickle A.
Small Bodies Exploration in the Next 35 Years **[#8041]**
Small bodies (asteroids, comets, KBOs, centaurs, martian moons, meteorites, etc.) are important for science, planetary defense, and human exploration. Possibilities for the next 35 years are considered.

2:00 p.m. McAdam A. C. * Glavin D. P. Bleacher J. E. Arzoumanian Z. Young K. E. Gendreau K. ten Kate I. L. Malespin C. A. Franz H. B. Mahaffy P. R.
Characterization of Water in Surface and Near-Surface Materials for Studies of Planetary History and Resource Prospecting **[#8043]**
We discuss the importance of understanding volatile inventories, especially water inventories, in planetary materials, and approaches and technologies to carry out these studies.

2:15 p.m. Bishop J. L. *
Harnessing Water and Resources from Clay Minerals on Mars and Planetary Bodies **[#8131]**
Clay minerals provide a source of water, metals, and cations that can be harvested to provide resources for human exploration on Mars, asteroids, etc. Planning how to access these resources from clays could be a vital component of human exploration.

2:30 p.m. Metzger P. T. *
Economic Planetary Science in the 21st Century **[#8126]**
Economic planetary science is a young discipline set to expand rapidly with potential to become a primary driver of science in this century and a vital contributor to the health of our planet.

2:45 p.m. Bleacher J. E. * Conrad P. G. Domagal-Goldman S. D. Evans C. A. Glavin G. P. Glotch T. D. Graff T. G. Guzewich S. D. Lewis R. Lupisella M. L. McAdam A. Niles P. B. Petro N. E. Rogers A. D. Skinner J. Stern J. C. van Susante P. Trainer M. G. Young K. E. Bell M. S. Hoffman S. J. Needham D. H. Hays L. E. Hurowitz J. A.
Long Term Environmental Monitoring: Necessary Strategy and Integrated Technologies to Ensure Successful Science, Resource Utilization, and Planetary Protection During Human Exploration **[#8087]**
Long term environmental monitoring of any planetary surface on which humans plan to operate should be a requirement of responsible human exploration.

3:00 p.m. BREAK

Tuesday, February 28, 2017
DEFENSE AND RESOURCES: PANEL DISCUSSION
3:15 p.m. Auditorium

In this theme, we will be looking forward over the next 35 years at progress in understanding, characterizing, and mitigating risk to Earth from Near Earth Objects, and in characterization, exploitation, and utilization of resources on planetary bodies.

Moderator: **Amy Mainzer**

Panel Members: **Carolyn Ernst**
Kris Zacny
Lisa Gaddis
Julie Stopar (synthesizer)

Tuesday, February 28, 2017
DEFENSE AND RESOURCES: POSTER SESSION
5:00 p.m. Residence Inn

Rolley R. J. Saikia S. J.
Strategies for Prospecting and Extracting Water on Mars for Long-Term Human Exploration **[#8149]**
We aim to develop a specific set of criteria to classify water reserves on Mars, and to design water prospecting and extraction systems for various human landing sites using a requirements-driven framework.

Mantovani J. G. Sibille L. Kulcinski G. L. Santarius J. F.
Free-Flyers for Exploration and Resource Mapping for ISRU and Planetary Science **[#8238]**
This presentation discusses prospecting for resources on a planetary surface using a free-flyer platform to assist in achieving a sustainable human presence in space beyond low Earth orbit and in exploring the evolution of the solar system.

Glass B. Bergman D. Davis R. Hoftun C. Lee P. Johansen B.
Reaching Water: Planetary Deep Drilling **[#8098]**
Deeper drilling to 100m depths is easy on Earth, but an extreme challenge on other solar system bodies. Deeper planetary subsurface access into ocean worlds or to the Mars cryosphere is possible with new drilling concepts.

Dissly R. W. Scheeres D. J.
Toward the Complete Characterization and Mitigation of the Earth Impact Risk by 2050 **[#8128]**
An approach is outlined to mitigate the risk of asteroid impacts by 2050, covering both the needed infrastructure for detection of all NEOs down to 20m, and filling the gaps in our understanding of the geophysical parameters needed for mitigation.

Taylor P. A. Benner L. A. M. Rivera-Valentin E. G. Virkki A. Busch M. W. Nolan M. C.
Ground-Based Radar Observations: Enabling the Future of Small-Body Science, Planetary Defense, and Solar System Exploration **[#8233]**
Radar is arguably the most powerful technique for post-discovery tracking and characterization of the near-Earth asteroid population. As such, it shapes our understanding of small bodies, guides planetary defense, and informs mission planning.

Keszthelyi L. Trilling D. Hagerty J. Moskovitz N. Milazzo M.
Solar System Resource Assessment in 2050 **[#8132]**
Given this potential to enable human activity in deep space, we expect that Congress will have directed the USGS by 2050 to provide resource assessments of the NEOs, likely landing sites on Mars, and perhaps the Moon.

Wyrick D. Y. Buczkowski D. L. Durda D. D.
Characterizing Asteroid Internal Structure Through Tectonic Analyses **[#8139]**
Critical data gaps remain in characterizing the mechanical strength and internal structure of asteroids. Understanding asteroid internal coherency is required to develop effective mitigation, diversion, or destruction strategies against impact threat.

Nesvold E. R. Erasmus N. Greenberg A. van Heerden E. Galache J. L. Dahlstrom E. Marchis F.
The Deflector Selector: A Machine Learning Framework for Prioritizing Deflection Technology Development **[#8050]**
We present a machine learning model that can predict which asteroid deflection technology would be most effective, given the likely population of impactors. Our model can help policy and funding agencies prioritize technology development.

Lewicki C. Bradford K. J. Frank E. A. Beasley M.
Prospecting and Mining Space Resources: Planetary Resources' Outlook and the Planetary Science Impact **[#8119]**
Planetary Resources is leading the way in bringing private finance to planetary science with the aim of prospecting and mining Near-Earth Asteroids.

Tuesday, February 28, 2017
POLICY, PATHWAYS, TECHNIQUES, AND CAPABILITIES: POSTER SESSION
5:00 p.m. Residence Inn

Elvis M.
A Framework for Organizing a Long-Term Planetary Science Program **[#8014]**
Rapid cost growth has cut the number of planetary missions to rates that are too small to sustain a vigorous program. Planning needs well-chosen principles to change this state of affairs, and commercial space offers a long-term solution.

Bagenal F. Horanyi M.
Student Involvement in Space Exploration: The Next Generation **[#8237]**
Involvement of students in space missions exposes them to the technical realities of space exploration – delivers deep learning experience and feeds the professional pipeline. Give students the opportunity to explore every corner of the solar system.

Shibata E. Lu Y. Pradeepkumar A. Cutts J. A. Saikia S. J.
A Venus Atmosphere Sample Return Mission Concept: Feasibility and Technology Requirements **[#8164]**
Although Venus is similar in size to Earth, their atmospheres are completely different. This study will look at past Venus sample return missions, and revisit them with modern technology, as well as propose an additional sample return strategy.

Westlake J. H. Brandt P. C. McNutt R. L. Mitchell D. G. Rymer A. M.
How Planetary Magnetospheres Have and Can Continue to Drive Solar System Exploration **[#8072]**
We will discuss the evolution of planetary magnetospheric research and our vision for the future including targets within the solar system and how magnetospheric research can advance our knowledge of exoplanetary systems.

Persson E.
Manned Missions, Geoengineering, and Planetary Protection – How Safe is Safe Enough? **[#8062]**
Before we start geoengineering or even send humans to other worlds, we need to make sure not to destroy any existing life, but how can we determine the probability that there is no existing life unless we find life there and how sure do we need to be?

Diniega S. Beaty D. W. Bass D. Hays L. Whetsel C. Whitley R. Zurek R.
Getting Humans to Mars, a Possible Future **[#8071]**
We envision that it is 2050 and humans are exploring the martian surface *in situ*. This presentation explores the scientific and engineering datasets and missions that could lead to this state.

Zacny K. Paulsen G.
Status and Future of Planetary Sampling Technologies **[#8023]**
We present a review of drilling and sampling technologies in the 1 cm, 10 cm, 1 m, 10 m, 100 m, and 1 km range.

McSween H. Y. McKeegan K. D.
Planetary Science in the Next Decades: The Astromaterials Perspective **[#8021]**
Sample return missions will become increasingly important in the coming decades. A wish list of such missions and complementary laboratory analysis programs can potentially address all of NASA's planetary science goals.

Showalter M. R. Tiscareno M. S. French R. S.
Archival Data and Computational Power in Planetary Astronomy: Lessons Learned 1979–2016 and a Vision for 2020–2050 **[#8108]**
Computing technology has advanced tremendously over recent decades. Projecting those trends forward, we explore ways that new technologies will change our approaches to planetary data analysis, using both archival data and that from future missions.

Radebaugh J.   Thomson B. J.   Archinal B.   Hagerty J.   Gaddis L.   Lawrence S. J.   Sutton S.
MAPSIT Steering Committee
Obtaining and Using Planetary Spatial Data into the Future: The Role of the Mapping and Planetary Spatial Infrastructure Team (MAPSIT) **[#8084]**
Planetary spatial data continue to increase in volume and complexity. These data are the hard-earned fruits of planetary exploration, and MAPSIT's mission is to ensure their availability for any conceivable investigation, now or in the future.

Hardgrove C.   Ehlmann B. L.
Achieving Visionary Planetary Science Goals with Deep Space CubeSats **[#8183]**
Throughout the 2020's–2050's, CubeSats will help enrich the scientific return from large planetary science missions by providing high-risk, high-reward complementary data to the primary spacecraft mission.

Wyatt E. J.   Castillo-Rogez J. C.   Chien S. A.   Clare L. P.   Fraeman A. A.   Herzig S. J.
Nesnas I. A.   Lazio J.
Novel Planetary Science Enabled by Networked Constellations **[#8091]**
This abstract summarizes the state of thinking in constellation architectures as a means to address the 2050 Vision themes and pave the way for human exploration of the Moon, Mars, and asteroids.

Retherford K. D.
Remote Sensing Science and Instrument Development Paradigms Will Radically Change as Deep Space Optical Communications Infrastructure is Standardized **[#8113]**
Deep Space Optical Communications (DSOC) systems are already inducing a sea change on our approach to designing mission concepts. A revolution in instrument concepts and mission operations will ensue as we move to observatory probe type missions.

Race M. S.   Thronson H. A.   Siegel B.   Spry J. A.
Addressing Potential Challenges and Opportunities in the Years Before PSV 2050: Anticipating Revolutions Still to Come in Science, Technology, and Society **[#8159]**
This proposed panel presentation will summarize several recent US and international workshops that have identified and prioritized important R&TD gaps related to future science exploration activities and human missions of relevance to PSV 2050.

Johnson L.   Krause L. H.   Wiegmann B.   Bilen S.   Gilchrist B.
Propulsion and Power Using Electrodynamics **[#8069]**
Electrodynamic tethers provide propulsion and power by interacting with planetary magnetospheres, enabling propulsive-intense maneuvers and high-power without fuel or radioisotope power. Electric sails can propel spacecraft throughout the solar system.

Young K. E.   Bleacher J. E.   Rogers A. D.   McAdam A.   Evans C. A.   Graff T. G.   Garry W. B.   Whelley P. L.
Scheidt S.   Carter L.   Coan D.   Reagan M.   Glotch T.   Lewis R.
Developing Science Operations Concepts for the Future of Planetary Surface Exploration **[#8197]**
Human exploration of other planetary bodies is crucial in answering critical science questions about our solar system. As we seek to put humans on other surfaces by 2050, we must understand the science operations concepts needed for planetary EVA.

Plescia J. B.
Capabilities to Enable Future Planetary Science **[#8185]**
The list of outstanding scientific questions is perhaps longer today than it was in 1958, although the questions are more detailed and complex.

Brandt P. C.   McNutt R.   Hallinan G.   Shao M.   Mewaldt R.   Brown M.   Alkalai L.   Arora N.   McGuire J.   Turyshev S.   Biswas A.   Liewer P.   Murphy N.   Desai M.   McComas D.   Opher M.   Stone E.   Zank G.   Friedman L.
The Interstellar Probe Mission: Humanity's First Explicit Step in Reaching Another Star **[#8173]**
An Interstellar Probe Mission concept to the Interstellar Medium is discussed that would represent humanity's first explicit step scientifically, technologically, and programmatically to reach another star.

Rathbun J. A.   Cohen B. A.   Turtle E. P.   Vertesi J. A.   Rivkin A. S.   Hörst S. M.   Tiscareno M. S.   Marchis F.   Milazzo M.   Diniega S.   Lakdawalla E.   Zellner N.
The Planetary Science Workforce: Goals Through 2050 **[#8079]**
The planetary science workforce is not nearly as diverse as the society from which its membership is drawn and from which the majority of our funding comes. We discuss the current state and recommendations for improvement.

Wednesday, March 1, 2017
POLICY, PATHWAYS, TECHNIQUES, AND CAPABILITIES
8:30 a.m. Auditorium

In this theme, we will be looking forward over the next 35 years at progress in a range of areas that span the other themes or step beyond them, including policy issues, technology, techniques, and workforce issues.

Chairs: **Dana Hurley**
Craig Hardgrove

8:30 a.m. Ghosh A. *
Planetary Science Exploration Through 2050: Strategic Gaps in Commercial and International Partnerships **[#8235]**
Planetary science will see greater participation from the commercial sector and international space agencies. It is critical to understand how these entities can partner with NASA through 2050 and help realize NASA's goals in planetary science.

8:45 a.m. Castillo-Rogez J. C. * Feldman S. M. Baker J. D. Vane G.
Small Instruments for Planetary Science Applications — Status and Way Forward **[#8160]**
This abstract covers technology gaps for small instruments. It is relevant to all the themes of the Planetary Visions 2050 Workshop in support of science applications that might leverage or be best addressed by small spacecraft.

9:00 a.m. Jakosky B. M.
Mars Exploration 2050: Human and Robotic Exploration Intertwined **[#8016]**
Mars exploration over the next thirty years will have increased collaboration between human and robotic missions. Combined, we can explore fundamental science questions. We have the technology to start mission definition and development today.

9:15 a.m. Lewis R. * Niles P. Fries M. McCubbin F. Archer D. Bleacher J. Boyce J. Cohen B. Evans C. Graff T. Gruener J. Lawrence S. Lupisella M. Ming D. Needham D. Young K.
Sample Return Enabled by a Crewed Presence in Cislunar or Cismartian Space: Farther Reach, Better Science **[#8211]**
Human presence in/on lunar and Mars space/surfaces provides a unique opportunity to utilize robust spacecraft infrastructure as well as the capabilities of humans to fundamentally improve sample return well beyond current capabilities.

9:30 a.m. Milazzo M. P. * Kestay L. Dundas C.
The Challenge for 2050: Cohesive Analysis of More than One Hundred Years of Planetary Data **[#8070]**
The year 2050 will mark 106 years since humans opened the door to space and to the solar system. The amount of valuable planetary science data collected over those years will require new ideas and new tools to enable cohesive analysis of these data.

9:45 a.m. Green J. L. * Hollingsworth J. Brain D. Airapetian V. Pulkkinen A. Dong C. Bamford R.
A Future Mars Environment for Science and Exploration **[#8250]**
Investigation of a greatly enhanced atmosphere of higher pressure and temperature of Mars can be accomplished using existing simulation tools. Simulation results will be reviewed and a projection of how long it may take for Mars to become an exciting new planet to study and to live on.

10:00 a.m. Freeman A. *
Small is Beautiful — Technology Trends in the Satellite Industry and Their Implications for Planetary Science Missions **[#8085]**
It's an exciting time in the space business – new technologies being developed under the 'NewSpace' umbrella have some profound implications for planetary science missions over the next three decades.

10:15 a.m. Kring D. A. *
Exploring the Solar System with an Integrated Human and Robotic Deep Space Program **[#8025]**
Deep space human exploration capabilities offer enormous opportunities for studying the solar system and will change how planetary science functions.

10:30 a.m. BREAK

Wednesday, March 1, 2017
POLICY, PATHWAYS, TECHNIQUES, AND CAPABILITIES: PANEL DISCUSSION
10:45 a.m. Auditorium

In this panel, we are looking to discuss the integration of the commercial enterprises into planetary exploration over the coming decades.

Moderator: **Greg Schmidt**

Panel Members:
Alan Stern
Leslie Gertsch
Jennifer Heldmann
Craig Hardgrove (synthesizer)

Wednesday, March 1, 2017
FUTURE TECHNOLOGIES: PANEL DISCUSSION
1:00 p.m. Auditorium

This panel will discuss the range of technologies needed to advance the various planetary science themes over the coming decades, and the timescales over which technology development needs to be implemented.

Moderator:	**Tony Freeman**
Panel Members:	**Brook Lakew** **Jay Falker** **Deborah Amato (synthesizer)** **Zibby Turtle**

Wednesday, March 1, 2017
OVERARCHING ISSUES
2:30 p.m. Auditorium

Perspectives on the future of planetary exploration from Europe, and issues with deep space communication, launch vehicles, and workforce in the coming decades. Synopses of the Planetary Vision 2050 themes.

Chair: **Steve Mackwell**

2:30 p.m. Blanc M. * Harri A.-M. Rodrigo R. Krupp N. Zarnecki J. Szego K.
Horizon 2061 Working Group Planetary Exploration Horizon 2061 Team
Planetary Exploration, Horizon 2061: A Joint ISSI-Europlanet Community Foresight Exercise **[#8044]**
This communication will be the first presentation of the outputs of a community forum organized in September 2016 in Bern by ISSI and Europlanet. It will present a foresight of the key questions that should drive planetary space missions up to the 2061 horizon.

2:45 p.m. Deutsch L. J. Lazio T. J. W. * Townes S. A.
Enabling Rich and Robust Data Sets Across the Solar System via Deep Space Communications **[#8049]**
The 2050 Vision is likely to include richer data sets. Instruments will be more capable and small spacecraft will open new possibilities. We sketch a roadmap for ensuring that the community obtains the data from instruments and missions in 2050.

3:00 p.m. Creech S. D. Baker J. D. Jackman A. * Vane G.
Space Launch System Payload Transportation Beyond LEO **[#8060]**
This presentation describes space launch system ground and flight accommodations, interfaces, resources, and performance planned to be available to potential science users. It also invites dialog with users on their unique accommodation requirements.

3:15 p.m. Kaminski A. P. Bowman C. D. Buquo L. E. Conrad P. G. Davis R. M. Domagal-Goldman S. Pirtle Z. T. Skytland N. G. Tahu G. J. Thaller M. L. Viotti M. A.
Our Solar System 2050: Advancing the Science, Technology, and Societal Relevance of Planetary Exploration Through Public Participation **[#8213]**
We show how citizen science, crowdsourcing, prize competitions, and other modalities can expand public participation and prove valuable for enhancing the science, technology, and societal relevance of planetary exploration over the next few decades.

3:30 p.m. BREAK

3:45 p.m. *Life Theme Synopsis*

3:55 p.m. *Origins Theme Synopsis*

4:05 p.m. *Workings Theme Synopsis*

4:15 p.m. *Defense and Resources Synopsis*

4:25 p.m. *Policy, Pathways, Techniques, and Capabilities Theme*

4:35 p.m. *Future Technologies Synopsis*

OBSERVATIONS OF PLANETARY ATMOSPHERIC WINDS AND GASES WITH LIDAR

J.B. Abshire (james.b.abshire@nasa.gov)[1], S. D. Guzewich[1], M.D. Smith[1], H. Riris[1], G. R. Allan[2]
[1]NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD, 20771, USA., [2]Sigma Space Corporation, Greenbelt, MD 20771, USA.

Introduction: Winds are the key variable to understand atmospheric transport and answer fundamental questions about planetary atmospheric circulation. On Mars, winds link the three primary cycles of the martian climate: CO_2, H_2O, and dust. The Mars Exploration Analysis Group's Next Orbiter Science Analysis Group (NEX-SAG) has recently identified atmospheric wind measurements as one of 5 top compelling science objectives for a future Mars orbiter [1]. To date, only isolated lander observations of martian winds exist while cloud-tracked winds remain the only data source for Venus and Titan. However, the direct lack of wind observations in planetary atmospheres and imprecise and indirect inferences from temperature observations leave many basic questions about atmospheric circulation unanswered. In addition to addressing high priority science questions, direct orbital wind observations would help validate 3D general circulation models (GCMs) while also providing key input to atmospheric reanalyses.

Additionally, the observation and systematic mapping of trace gas concentrations in planetary atmospheres serves as another diagnostic of atmospheric circulation while also adding insight on chemical processes within the atmosphere and surface-atmosphere exchange.

Lidar Measurement Approach: Orbiting lidar instrument concepts [2] are being designed to observe the atmosphere from a nominally circular polar orbit around Mars. The Mars LIdar for global wind profiles (MARLI) lidar measurement concept is shown in Figure 1. The instrument would be pointed ~30° off-nadir in a cross-track viewing direction. The MARLI lidar will continuously measure dust aerosol backscatter profiles, cross polarized backscatter profiles (for water ice aerosols), the component of the Doppler shift from wind profiles along the instrument's line-of-sight, and the range to the planet's surface. The present MARLI approach uses a Nd:YAG laser and makes measurements at 1064 nm [3] and its measurement types are shown in Figure 2. Vector-resolved winds may also be measured by either using a dual-telescope approach, or by using a single lidar on a movable pointing platform.

Lasers and lidar measurement techniques are also available to measure atmospheric trace gases. Differential absorption techniques use tunable lasers to measure multiple atmospheric gases (e.g., the primary atmospheric gas and the desired trace gas). The lasers are tunable and allow sampling multiple wavelengths within and around the chosen absorption line of the target gas. By precisely retrieving the absorption line shape, and knowing the background atmospheric pressure, a column-integrated trace gas abundance can be retrieved [4]. Range-resolved retrieval approaches may also be used to measure the height resolved profiles of gases, such as water vapor, that have higher abundances.

Lidar Description: The laser backscatter from the Mars atmosphere is weak and is distributed in range and thus a highly sensitive lidar approach is necessary. The present MARLI approach measures the atmospheric characteristics along a single line-of-sight. The MARLI lidar uses a compact efficient ND:YAG laser with flight heritage, a low-mass receiver telescope and photon counting sensitive detectors. For denser atmospheres such as Venus or Titan, reduced lidar power and/or a smaller receiver telescope can be used to retrieve atmospheric gases and winds above the densest and cloudiest regions of the atmosphere (e.g., above approximately 60 km altitude on Venus).

The baseline design of MARLI utilizes a pulsed single-frequency diode-pumped Nd:YAG laser. Its output pulses are wavelength stabilized near 1064 nm. The laser emits ~50 nsec wide pulses at a 1 kHz pulse rate. Nominally, the receiver uses a ~70 cm diameter telescope and splits the returned signal into 3 paths. One path is a cross-polarized channel to allow dust/ice discrimination. The other two paths are used to illuminate an etalon then are refocused onto detectors. This part of the receiver is configured as a double-edge Doppler (optical frequency-shift) discriminator.

Our approach leverages new lidar components developed for NASA, including tunable single frequency lasers and photon-sensitive HgCdTe detectors. Our targeted MARLI instrument size is a ~80 cm cube, comparable to a medium-sized instrument such as the Mars Orbiter Laser Altimeter (MOLA). Nominal payload parameters are < 40 kg, < 90 W, and ~50 Kbits/sec. This approach leverages on measuring terrestrial winds and lidar technology supported by the NASA ESTO Instrument Incubator program.

References: [1] MEPAG: Chaired by B. Campbell and R. Zurek (2015), *Report from the Next Orbiter Science Analysis Group,* http://mepag.nasa.gov/reports.cfm

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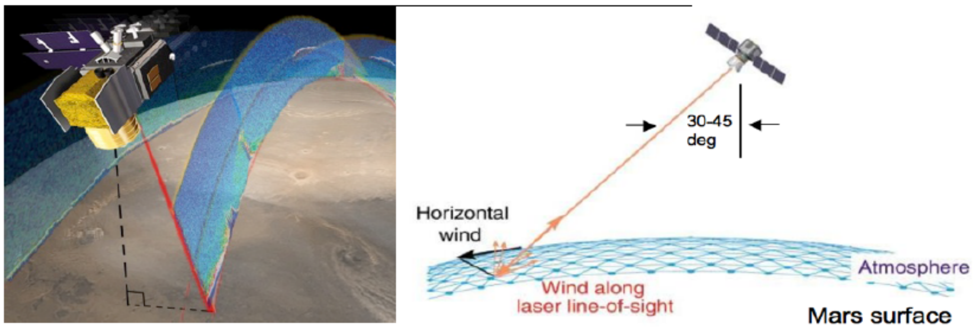

Figure 1. (Left) MARLI measurement approach, which continuously measures the aerosol backscatter profile, the cross-polarized (ice) backscatter profile, the Doppler (wind) profiles, the CO_2 column absorption (surface pressure), and the range to the scattering surface from orbit. (Right) Measurement orientation. Nominally, the lidar is pointed cross-track at ~30° off-nadir to measure the Doppler shift of the wind in the cross-track direction.

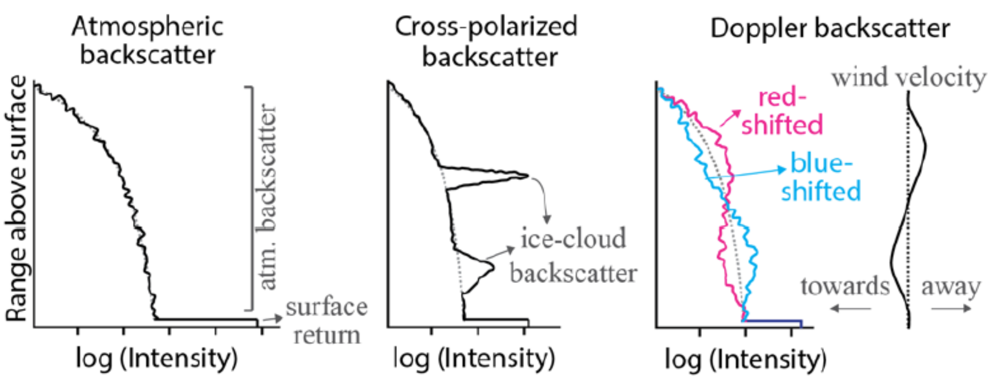

Figure 2. Illustrations of the measurement and retrieval of winds and aerosols. (Left) Range (height) resolved aerosol backscatter profiles. The strong echo pulses reflected from the surface are used for the CO_2 column density measurements. (Middle) Profiles of cross-polarized backscatter, caused by clouds with ice-crystals. (Right) Height-resolved Doppler (wind) backscatter profiles as seen by the two detectors after passing through the double-edged filter. The horizontal wind profile (Far Right) is computed from the scaled ratio (difference/sum) from the detectors after the double-edge filter.

Real-time In Situ Landing Site Assessment

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Landing spacecraft on other objects in the solar system provides a unique opportunity to make direct *in situ* science measurements, but extraterrestrial environments create unique challenges for the design and testing of the system. For many science destinations of interest it is either not possible or not practical to map landing sites of interest prior to landing. This is especially true for moons of the outer planets as reconnaissance requires long-range planning and mapping orbits that may not be practical (*e.g.*, the high-radiation environment that would be experienced by a spacecraft in orbit around Europa). In some cases, exploration can both draw upon technologies from past missions and also make more direct use of Earth-based technology developments to produce exciting mission opportunities while reducing risk. Two main areas to consider are the propulsion/lift systems employed during descent and sensing systems for landing technologies.

Many targets of interest have low surface gravities which allow unique opportunities for identifying safe landing sites by extending the landing timeline with reduced use of resources. This additional time can be used to execute landing-site assessment. With the development of new, improved technologies and more complex mission architectures, methods for ensuring safe landing sites have advanced significantly over the years. Initial landing concepts can be viewed as *a priori* identification of safe landing sites with large landing areas and limited knowledge of the terrain. This approach was used for the Surveyor lunar landers and for Mars landers, which had landing-ellipse errors on the order 10 km and 100 km respectively. For such missions, planners must target a large safe landing area and accept risk of landing on a large hazard. More recent mission concepts make use of terrain relative navigation (TRN) to more precisely target a landing site using higher resolution maps of the region. This type of approach can be used to identify a smaller safe landing site such as is planned for Mars 2020 and the Europa Lander project. In this approach, the vehicle uses an on-board map to fly to the known safe landing site. A third approach is to add onboard capability to perform safe landing site identification. With this strategy, the exact obstacles may not be known *a priori* so an onboard sensor is used to scan the terrain below the lander for a safe landing site. This type of technology was demonstrated as part of NASA's ALHAT program using a gimbaled flash lidar, and image-based hazard detection has been flown on the Chinese Chang'e lunar lander.

A typical landing sequence would include a number of basic phases. First, coarse targeting would be executed, based on science objectives and available survey information, to a region containing relatively flat areas. Second, the vehicle would perform a controlled descent to translate over terrain while descending to the surface and using onboard sensors to identify a safe landing site. These sensors can include TRN flash lidar, and scanning lidar. Lidar sensors are very accurate, and the data they produce can be processed quickly to assess the suitability of a landing site on an on-the-fly basis. Mission risk can be further reduced by including a hover phase (*e.g.*, MSL sky crane) during terminal descent to allow very fine landing-site details to be observed and to optimize the final landing site selection. This suite of sensors constitutes a very powerful means for performing high-precision landing site assessment that far exceeds the capability of orbital assets and can be flown at a fraction of the cost of traditional survey platforms. Implementation of real-time *in situ* landing-site assessment will significantly broaden the number of accessible science targets. These technologies are economical and are ready to implement today.

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Detecting The Beacons of Life With Exo-Life Beacon Space Telescope (ELBST). Vladimir S. Airapetian[1], William C. Danchi[1], Peter C. Chen[1], Douglas M. Rabin[1], Kenneth G. Carpenter[1], Martin G. Mlynczak[2], [1]NASA/GSFC, 8800 Greenbelt Road, Greenblelt, MD (vladimir.airapetian@nasa.gov), [2]NASA/LARC, Hampton, VA.

Introduction: The current explosion in detection and characterization of thousands of extrasolar planets with the *Kepler* mission, *HST* and ground-based telescopes opens a new era in searching for Earth analogs suitable for life. The best way to find signatures of life on terrestrial-type planets is to detect and identify chemical compounds associated with life. Currently, signatures of life are associated with detection of the most common molecules in the Earth's troposphere, including O_2, O_3, H_2O, and CH_4 [1]. The presence of molecular oxygen, a strong marker of the presence of oxygen producing forms of life, together with CH_4, the marker of biological decay, would suggest that the atmosphere is far from the thermodynamic equilibrium driven by biological activity. However, direct detection of the strongest signal from molecular oxygen in the O_2 optical band (around 760 nm) through transmission spectra requires many weeks of observations with extremely large ground-based telescopes. In our paper, we propose a new observational strategy for detecting the signatures of "beacons" of life defined as high signal and low spectral resolution thermal emission from molecules that trace or are associated with the formation of life [2].

Signals from Beacons of Life.

In our recent study of the habitability of early Earth, we proposed that a nitrogen-rich atmosphere of an Earth-like planet is one of the fundamental prerequisites for life, because fixation of molecular nitrogen in the lower atmosphere is crucial but ineffective process to produce a) nitrous oxide, a very potent greenhouse gas required to keep the planet warm; and b) nitrogen cyanide, HCN, the precursors for prebiotic chemistry and life\ [3]. Thus, in a nitrogen, oxygen and water vapor rich rich atmosphere, we can expect the formation of nitric oxide, NO, hydroxyl, OH and O_2 molecules as they are observed from the thermospheric emission of our Earth. TIMED/ SABER observations performed over the last 15 years show that OH emission at 1.6 and 2 microns can reach the power of 0.2 TW, NO emission at 5.3 microns peaks at 3 TW during large geomagnetic storms, while O_2 emission at 1.27 microns can be as hig as 200 TW. and 2 microns can reach the power of 0.2 TW [2, 4]. The major requirement of production of NO and OH molecules is the dissociation of N_2 and H_2O.

We find that during larger geomagnetic storms that produce shock-driven solar energetic particle events, NO production can be increased by a factor of 100, so that expected emission from NO at 5.3 microns will be enhanced up to 300 TW. This suggests that if we observe an Earth-like exoplanet with N_2 and O_2 rich atmosphere at distances of 10-50 pc, the expected emission fluxes from this planet in a direct imaging mode are on the order of 10^{-21} -10^{-20} erg/cm^2/s.

Detecting Beacons of Life with *ELBST*

These molecules all have strong spectral features in the thermal infrared region, in the band from 1 to 10 microns. They can potentially be detected by two methods. The first is through transit spectroscopy by using instruments on *JWST* in the near-term starting in 2018, for example, with MIRI, NIRCAM, and NIRSPEC. In the longer term, into the 2030s, direct imaging techniques can be used. For the short wavelength region up to 2 microns, direct imaging and low resolution spectroscopy with R ~ 150 could be done with the *LUVOIR* telescope, which a mission concept currently under study by NASA [5]. This mission concept will be presented to the 2020 Decadal Survey as a potential large mission for a new start close to the time WFIRST is launched, in the mid-2020s.

In the very long term, a "Vision Mission" has be discussed in the recently published document, "Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades." [6] An ExoEarth Mapper mission concept is presented, and notionally consists of up to 20 6-m class telescopes combined as an interferometer, with up to 600 km, baselines at wavelengths from 0.3 to 1 micron. This concept would allow for the possibility of generating maps of the surfaces of exoplanets around nearby solar-type stars at distances of up to 10 parsecs from the solar system.

What is missing, however, are the important mid-infrared bands at wavelengths longer than 1 micron. In the past decade, from approximately 2002 to 2010, two NASA teams studied two mission concepts for this spectral region. One was a flagship mission concept, called the "Terrestrial Planet Finder Interferometer," or *TPF-I*, the other was meant to be a MIDEX cost-capped concept called the "Fourier-Kelvin Stellar Interferometer," or *FKSI* [7]. This concept was extensively studied but never proposed because both grass-roots and parametric cost estimates had the total cost for *FKSI* significantly above the MIDEX cap, of the order of $500 M as a lifecycle cost. The *TPF-I* concept was costed at significantly above that of *JWST*.

The FKSI concept was based on technology derived from JWST, and it was a structurally connected interferometer with a modest 12.5 baseline, with two 0.5-m telescopes, operating with a science band from 3 to 8 microns, with potential to operate as long as 10 microns or more [8]. An additional study was done, for a version operating at a center wavelength of 10 microns, with telescopes ranging from 1-2-m in diameter with a 20-m baseline. This version of FKSI, called FKSI-2, was capable of detecting Earth-sized planets in the habitable zone of nearby stars, if such planets are common[9].

Much of the history of the past work was presented in the chapter on "Infrared Direct Imaging," in the Exoplanet Community Report [10], published in late 2009, just prior to the 2010 Decadal Survey.

After this report, considerable progress has been made in terms of the technologies needed for such missions, and many signicant milestones have been passed, including reaching the contrast level necessary for directly imaging and characterizing exoplanes in the mid-infrared [10].

Building on the previous work with FKSI and TPF-I, it is worthwhile to consider developing a "Probe-Class" mission concept, based on the FKSI concept, which we call the "Exo-Life Beacon Space Telescope" or *ELBST*. Given the rising costs for Flagship missions, Probe-class missions with life cycle costs of approximately $1 B, are an attractive option assuming NASA has a cost-constrained budget in the coming years.

An *ELBST* mission could utilize emerging technologies such as ultra-lightweight optics being developed that use carbon-nanotubes, fibers, and polymers, to craft supersmooth precision surfaces [11].

A near-term Probe-class science and technology driven mission concept like *ELBST* could address not only exoplanet science, but it will allow very high angular resolution observations of planets and moons and other solar system bodies including the larger asteroids, and extragalactic astrophysics, particularly the nuclei of active galaxies.

A comprehensize technology assessment and plan is needed, not only for the near term, but also to provide a pathway to the ExoEarth Mapper mission that could be realized beyond the 2030s into the 2050s.

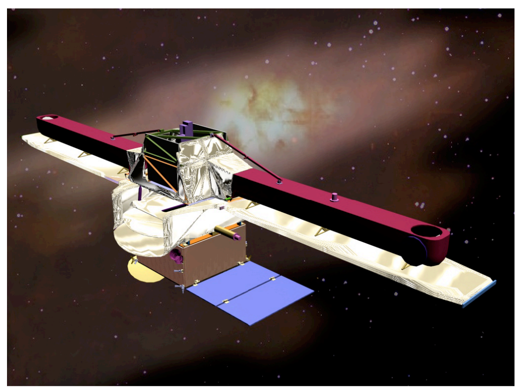

Figure 1. Artist's conception of the FKSI observatory [10].

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MISSION TO THE SOLAR GRAVITY LENS FOCUS: NATURAL HIGHGROUND FOR IMAGING EARTH-LIKE EXOPLANETS

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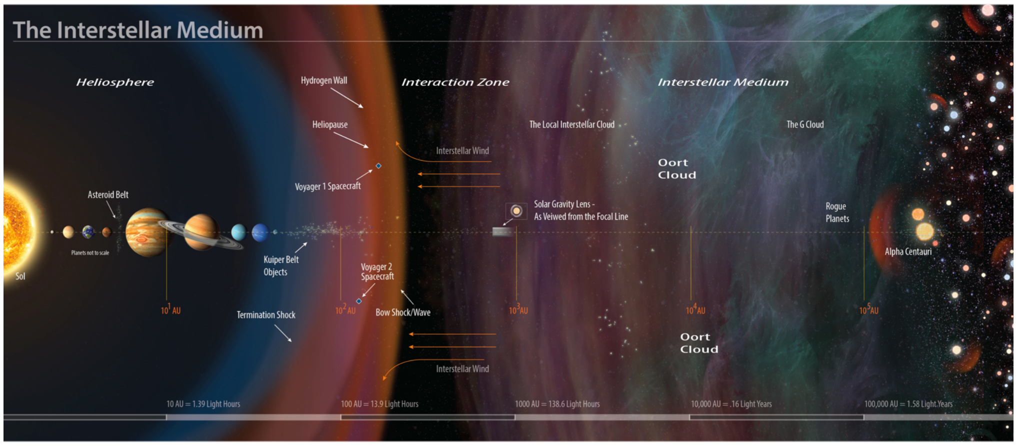

Figure 1: A SGL Probe Mission is a first step in the goal to search and study potential habitable exoplanets. This figure was developed as a product of two Keck Institute for Space Studies (KISS) workshops on the topic of the "*Science and Enabling Technologies for the Exploration of the Interstellar Medium*" led by E. Stone, L. Alkalai and L. Friedman.

Introduction: Recent data from Voyager 1, Kepler and New Horizons spacecraft have resulted in breath-taking discoveries that have excited the public and invigorated the space science community. Voyager 1, the first spacecraft to arrive at the Heliopause, discovered that the interstellar medium is far more complicated and turbulent than expected; the Kepler telescope discovered that exoplanets are not only ubiquitous but also diverse in our galaxy and that Earth-like exoplanets are not unusual; and New Horizons has revealed an unexpected Pluto with remarkable features suggesting a varied range of Kuiper Belt Objects (KBO). These results inspire intellectual curiosity, new scientific questions, and bold mission concepts reaching far into the deep interstellar medium and one day to exoplanets.

Science Rationale: Recent reports from the Kepler telescope provide a wealth of targets of opportunity for additional remote sensing using ground-based telescopes and current and future space-borne assets. However, all of these assets currently in existence or under consideration for deployment in the near future, are limited by the telescope aperture size or the interferometric baseline distance. The natural high-ground for multi-pixel imaging of exoplanets resides along the line (region) called the Solar Gravitational Lens (SGL) Focus (or foci) that takes advantage of the fact that the Sun's large gravitational field focuses light from faint, distant sources into the SGL region.

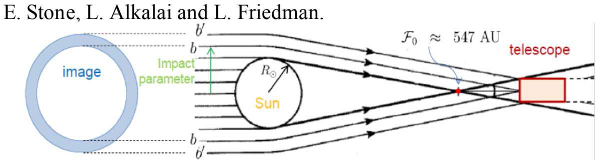

Fig. 2. Imaging of an exo-Earth with solar gravitational Lens. The exo-Earth occupies (1km×1km) area at the image plane. Using a 1m telescope as a 1 pixel detector provides a (1000×1000) pixel image!

According to Einstein's general relativity, gravity induces refractive properties of space-time causing a massive object to act as a lens by bending light. As a result, the gravitationally deflected rays of light passing from around of the lensing mass converge at a set of focal points, as shown in Fig. 2, where the focal length is defined by the mass of the Sun. Of all the solar system bodies, only the Sun is massive enough that the focal length resides within range of a realistic mission from Earth. The focus of the SGL is a semi-infinite line that begins at ~550AU from Earth (Figure 2).

While all currently envisioned NASA exoplanetary imaging concepts aim at getting just a small number of pixels (in most cases just one) to study an exoplanet, a mission to deploy a small telescope at the SGL opens up a revolutionary possibility for direct (1000×1000) pixel imaging and spectroscopy of an Earth-like planet up to 30 parsecs (pc) away, with resolution of ~10 km on its surface, enough to see its surface features and signs of habitability. Such a possibility is truly unique and merits a detailed study in the context of a realistic mission.

We present a daring and breakthrough mission concept to the SGL Focus (SGLF, ~550 AU) to deploy an optical telescope capable of direct imaging of an Earth-like exoplanet at unprecedented resolution.

Possible Mission Instrumentation: The SLGF mission instrument would be a ~1m telescope with a large focal plane, 0.4° field of view (FOV) with point-spread function (PSF) Nyquist-sampled and metrology systems that would calibrate instrumental errors in the focal plane and optics at the μas level. The instrument will require a miniature diffraction-limited high-resolution spectrograph, taking full advantage of the SGL amplification and differential motions (exo-Earth rotation).

The telescope will use a coronagraph to block the light from our Sun. At 1 μm, the gain of the SGL is ~110dB (27.5 mag), so an exoplanet, which is 32.4 mag object, will become a ~4.9 mag object. When averaged over a 1m telescope (the gain is $\sim 2\times10^9$), it would be 9.2 mag, which is sufficiently bright (even on the solar background). A conventional coronagraph would block just the light from the Sun, but here we want the coronagraph to transmit light only at the Einstein ring where the planet light would be. Instrument design should be matured in a detailed study. Trades between a single big telescope versus multiple smaller telescopes should also be evaluated.

Mission Concept Design: As of 2016, Voyager 1 has traveled a distance of ~137 AU from the Sun in 39 years since its launch, and is travelling at ~17.26 km/s relative to the Sun. It recently entered the Interstellar Medium (ISM) and is humanity's first (functioning) interstellar spacecraft. To reach the SGL the spacecraft needs to travel a distance of ~550 AU. A spacecraft travelling at the speed of Voyager 1 will take >150 years to reach the SGLF. To make the SGLF mission viable, an order of magnitude reduction in trip time is needed.

We have set the following mission goals, to be achieved using near-term technology coupled with innovative mission design concepts:

1. Reach the local ISM (100-120 AU) in < 8-10 years, compared to Voyager's 120 AU in 40 years.
2. Reach the SGLF in <50 yrs. from launch for exoplanet imaging using an optical telescope.
3. Perform Heliophysics, Astrophysics, ISM, KBO fly-by investigations on the way to SGLF.

As pointed out in the KISS ref. design study, multiple mission design options exist to realize such a mission and can be broadly classified into two types: 1) mission requiring a powered Jupiter flyby, 2) mission requiring a perihelion maneuver deep in Sun's gravity well (3-4 solar radii). Recent work has shown that it is possible to achieve solar-system exit speeds in excess of 15 AU/Yr. More optimized mission concepts may result in even higher escape speeds. Given the high launch energies, the SGLF mission is uniquely enabled by using the NASA's upcoming heavy lift launch vehicle, SLS.

The KISS design reference mission (DRM 1.0) along with recent papers on this topic has shown that a pathfinder precursor mission can be deployed as early as 2025 that would demonstrate all the basic elements of the mission architecture including a perihelion (Oberth) maneuver using advanced thermal protection system, and other relevant capabilities. A subsequent mission with scaled capabilities can then achieve the goal of placing an optical observatory to the SGLF for the detailed imaging of Earth-like exoplanets.

Spacecraft Technologies: The spacecraft for this mission would benefit from the ongoing small-spacecraft (CubeSat) revolution and will require a highly integrated, fault tolerant flight system design capable of lasting in excess of 50 years from launch. Given, the high launch energy and large mission ΔV requirements, emphasis has to be placed on reducing mass and power on the spacecraft. Spacecraft power would rely and benefit from latest advancements in radioisotope power system (RPS) technology. There are already efforts at JPL to advance the lifetime of existing RPS technology. The challenge of communication from SGL with reasonable data rates and power requirements can be addressed by using a hybrid radio and Deep Space Optical Commutations system.

The proposed mission concept builds upon the technology under development for the Solar Probe Plus (SPP) mission that will launch in 2018, to survive the thermal environment at perihelion. A more detailed look at optimizing the heatshield design and spacecraft thermal protection system is required. Finally, the spacecraft should have sufficient autonomy/re-configurability so that it detects, reacts and recovers from a multitude of off-nominal conditions with advanced autonomous capabilities.

Programmatic Considerations: Given the multidisciplinary nature of a mission deep into the ISM and the SGL, programmatic creativity is essential for mission success. Stakeholders for the SGLF mission include: ExoPlanets, Astrophysics, and Planetary Science. Heliophysics will also be interested to add small instrument package on the mission.

SGLF Probe Notional Timeline	
<2020	Solidify Baseline mission, technical feasibility and instrument prototype
Early 2020s	Acquisition of SLS launch slot.
2020s	Launch
2030s	Enter local ISM, do ISM and KBO science
>2060s	Reach the SGL, start exoplanet imaging
>2080s	Go beyond into the unknown

AN ARCHITECTURE TO GUIDE PLANETARY EXPLORATION FOR THE NEXT THREE DECADES: UNDERSTANDING SOLAR SYSTEM EVOLUTION THROUGH TIME. F. S. Anderson[1], [1]Southwest Research Institute, 1050 Walnut, Suite 300, Boulder, CO 80302 (anderson@boulder.swri.edu).

Introduction: To address the opportunities of an expanding planetary science program over the next three decades, today's scientists need to develop a plan that builds on the foundation of the current decadal survey and identifying a unifying architecture that spans all solar system bodies. We expect planetary exploration will continue to evolve from an emphasis on fly-by encounters and remote sensing, to in situ robotic exploration, to robotic sample return, and to, eventually, in situ science investigations and sample selection performed by human explorers on select worlds. Each step is going to require increasingly sophisticated technical advances, as well as strategic planning and coordination to insure both feasibility and a realistic cost framework. This needs to be achieved by explicitly emphasizing fundamental scientific exploration in geology, geophysics, glaciology, tectonics, climatology, and solar system evolution, while maintaining current priorities such as astrobiology and exploration of the outer planets. We propose a specific overarching architecture of "Understanding Solar System evolution through time", which will drive planetary science across all planetary bodies.

This theme directly addresses origins, and is inclusive of understanding solar system workings, the search for life, and understanding of resources. It builds on our current top scientific goals, such as astrobiology for Mars and the outer solar system, while allowing us to maintain and further develop scientific investment in less dramatic, but equally fundamental science, such as the evolution of igneous rocks on Mars, or the interior structure and activity of icy bodies in the outer solar system. This architecture achieves its inclusive nature by explicitly recognizing the encompassing nature of time in all solar system science investigations.

1. Trends In Planetary Science Goals: The proposed architecture enables scientific exploration across disciplines and solar system bodies, and provides a unifying direction for future development. Over the next decade, we anticipate that current science investigations will head broadly in three directions:

1. Expanding from single local assessments to multiple, spatially extensive lander/rover-based global measurements, for example, for addressing the detailed bombardment history of planetary bodies;
2. Advancing current measurements by far more detailed local assessments, for example, for Mars, by delving more deeply (both literally and figuratively) into sedimentological and geochemical evidence to assess habitability; and,
3. Continuing the current efforts to find habitable environments and potential life throughout the solar system, as well as expanding our knowledge of insufficiently explored bodies, such as Venus, asteroids, and the outer solar system.

"Understanding Solar System evolution through time", is in essence a statement of seeking to understand the *history* of every process in the solar system, and provides a single unifying architecture that allows us to inclusively argue for the broad array of continuing and new science targets and goals we can achieve in the next three decades.

2. History As A Science Goal: At the top-level, the three most important goals for the next three decades in planetary science are likely to be a) continuing to search for and understand extraterrestrial life, b) continuing the exploration of insufficiently explored bodies like Mercury, asteroids, and the outer planets, and c) improving our understanding of solar system history. Of these, a) and b) are relatively obvious, however, c) may need some explanation.

Specifically, the chronology of the inner solar system is based on models relating the crater densities of planetary surfaces, calibrated by radiometric dates of well-provenanced lunar samples. However, work comparing the numerous lunar chronology models in the literature illustrates differences between the models of up to one billion years, peaking around 3 Ga. For the Moon and Mars, the period between ~2.8 to 3.3 Ga includes the cessation of abundant volcanism, and, for Mars, the apparent termination of volatile production as well as formation of hydrated minerals. Under the new chronology functions, these processes could have lasted for a billion additional years, undermining models for thermal evolution of the Moon, and resulting in a longer era of abundant volatiles and hence potential habitability for Mars. In fact, we have the most confidence in the period from 3.5-4 Ga, or stated differently, only 20% of the history of the solar system. Hence all rocky planets, as well as dynamical models of solar system evolution, would benefit from new dates from multiple terranes on multiple planets.

3. Potential of New Technologies and Trends: These investigations will build on rapidly advancing technologies reducing launch costs, standardizing sample handling (including grasping, grinding, coring, sectioning, and storing), and increasing sophistication of geochemical and geophysical measurement approaches.

However, it must be recognized that even as some costs go down, the costs associated with addressing ever more sophisticated science questions may well go up. We anticipate that the next decades will see paradigm shifts; for example, because missions are created to address science hypotheses, in the future science instruments may be more than 10% of the mission costs, depending on the hypothesis. Launch services and spacecraft providers can expect to make up for this shift through more launches to more targets, albeit with greater standardization, such as communications and command and data handling systems (e.g., inclusion of Electra radios on multiple missions).

Earlier instrument development has enabled some imaging, geochemistry and mineralogy systems to be flown (and evolved) on multiple missions (e.g. variants of LIBS, or laser range-finding instruments). In the next three decades, this trend will continue, with evolved instrument *suites* becoming more commonplace, and used repeatedly in more spatially separated environments. Furthermore, new early-TRL instruments for detecting potential biomarkers and providing in-situ dating measurements will move from one-off measurements to systems that are flown more frequently, enabling greater spatial exploration (§1.1). As instruments become more robust, faster, with simpler or standardized sample handling, their cost will be driven down.. This will collaterally allow their use to explore a single environment in much greater detail, with samples acquired at higher lateral resolution and from greater depths (§1.2). Finally, the use of well-developed instrument approaches (such as currently little-used but crucially important seismometry), will become more commonplace.

These systems will build on the earlier discoveries of sample return and laboratory analysis, which will better enable us to provide the most appropriate detailed context measurements. These future systems will be attuned to multiple measures of habitability, biosignatures (for example, PAH's and DNA), or dating (e.g. U-Th-Pb-Pb, K-Ar, Nd-Sm, Rb-Sr, and elemental and mineralogical context, all obtained simultaneously). These improvements will strengthen confidence in measurement interpretations and enable their use for stand-alone use and triage.

4. Human Spaceflight: We anticipate that human and robotic spaceflight efforts will continue to become more interrelated, specifically driven by two counterbalancing forces:

a) politicians can most easily sell, and the public broadly understands, NASA as a human spaceflight organization, driven by the geopolitical needs of national prestige and maintaining a presence in near earth orbit and the Moon to avoid the weaponization of space;
b) there is a need for better justification to risk human life and expend the additional funds required to support humans in the space environment.

These issues are readily addressed by enabling astronauts to do real planetary science on appropriate bodies (asteroids, Mars, Phobos, Deimos, and the Moon), by *becoming* the scientists, and answering real science questions *in real-time*. Fortunately, in the architecture described herein, the instruments required to enable *iterative, repeated exploration of a locale*, not just to pick up samples and go home, will be available in the 2030 to 2050 timeframe (§2). For example, an astronaut on the surface of Mars could collect a sample from a promising outcrop, and assess its age and potential biosignatures. She could then move on to an older outcrop, and identify potential biosignatures associated with that era. After assessing how this fits in with the history of aqueous mineralogy, she might look in new areas of the same age for additional biomarkers.

5. Needed Investments: In order to support this architecture, investments in simplifying launch and spacecraft technologies are needed, as well as continuing investment in cutting edge instrumentation. However, these investments should be made with an eye towards joint integration and standardization before missions are identified, allowing for integrated instrument development to TRL 6 early in the process. This should include sample handling standardization. Finally, funds should be specifically allocated for integrating astronauts and instrument scientists, as a matter of course, into the testing, deployment, operation, and interpretation of existing and new science measurements.

6. The Importance of Time: All of planetary science can be cast in terms of when in history a given process was important, and how that process evolved with time. However, as we saw in §2, time itself is a science goal. Fortunately, time can be the architectural backbone under which all other exploration takes place, and also be a goal that we already know planetary science can deliver. Future missions, both robotic and human, will go to many disparate places searching for life, and attempting to understand the processes that acted on a locale. All of these can be placed in the broader context of origins, evolution, history, and hence time. Ultimately, an architecture based on understanding an encompassing scientific goal for which NASA can guarantee delivery, while enabling us to engage in science and exploration of *all* types, is crucial to preparing for the decades from 2020 to 2050.

FUTURE PLANETARY SCIENCE OPPORTUNITIES AUGMENTED BY EXPLORATION TELEPRESENCE. R.C. Anderson[1], K. Hodges[2], J. Burdick[3], and D. Lester[4], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 Robert.C.Anderson@jpl.nasa.gov, [2]Arizona State University, P.O. Box 876004, Tempe, AZ 85287-6004 kvhodges@asu.edu, [3]California Institute of Technology, Pasadena, CA 91109 jwb@robotics.caltech.edu, [4]Exinetics, Austin TX 78757 dfl@astro.as.utexas.edu .

***Introduction**:* Since the conclusion of the Apollo program, mankind has conducted scientific studies on multiple planetary surfaces using teleoperated robots. Operations of these mobile assets require strategies to mitigate the effects of two issues related to long distances from Earth to the research targets: 1) long communication delays (high latency); and 2) the limited rate of two-way information flow (low bandwidth). Despite the proven successes of doing science using surface assets such as *Opportunity* and *Curiosity*, it is as yet unclear what penalties might be associated with the use of current teleoperation modes for planetary field research. These as compared to alternative strategies that involve placing scientists more proximal to research targets so as to drastically reduce latencies and minimize the effects of bandwidth limitations. To what extent will low latency telerobotics improve the efficiency and effectiveness of science? What planetary processes that are high-value research targets can/cannot be effectively studied using telerobotics at high latencies? Is there special value to placing scientists in a position to teleoperate robots with communication latencies less than a few hundred milliseconds, such that the scientists could effectively conduct "real-time" research as if they were physically there on a planetary surface?

Recent Study: In our recently completed Keck Institute of Space Studies workshop* on Low Latency Telerobotics (LLT), a consensus emerged. This was that despite the fact that planetary field science has deployed an increasingly sophisticated array of robotic assets over the past four decades on a variety of planetary surfaces, the planetary science community still largely regards the research accomplishments of scientists on site as the standard against which the success of robotic field science must be measured. As a consequence, there are reasons to believe that new strategies may accelerate the pace of robotic field science and yield even greater scientific returns approaching those possible with scientists on site. These include the use of fully autonomous robotic agents, variably supervised robotic agents, and robotic agents teleoperated by scientists sufficiently proximal to the study site so as to achieve telepresence. Of these, given the current state of autonomous robotics, science by telepresence (SBT) offers many attractive, near-term opportunities to improve robotic planetary field science.

SBT more readily enables opportunistic science, encouraging the kind of real-time adaptive approaches that characterize the highest-quality field research on Earth. SBT also would lead to a dramatic improvement in the efficiency with which a set of research tasks could be completed. This efficiency, in turn, likely increases the realistic geographic scope of research activities and an increase in science return on other planetary surfaces.

Workshop participants noted additional factors that might favor SBT instead of on-site field research by in-situ astronaut scientists. For example, one of the most interesting scientific enterprises on Mars – the search for signs of biological activity – will be conducted in regions where there is strong incentive to keep human bodies out until those searches are complete (planetary protection). In addition, participants agreed that low-latency telerobotic control of surface assets from orbit would likely be much less expensive than putting humans on the surface, and would increase crew safety.

SBT may be particularly advantageous for three kinds of planetary field science. First, it may be the only way to do the highest-quality field science in environments which are so extreme that presently

*Conducted October 2016: reference http://www.kiss.caltech.edu/new_website/workshops/telepresence/telepresence.html#.

available technology will not offer suitable protection for on-site astronauts. Second, it may be necessary to do research on transient events (e.g., cryovolcanic eruptions, recurring slope lineae - RSL, or atmospheric phenomena such as dust devils), the timescales of which preclude effective study by high-latency telerobotics. Finally, SBT may permit more effective teleoperation of multiple, geographically distributed robotic assets on a planetary surface, enabling rapid, large-scale reconnaissance which could guide more detailed future research.

Despite the promise of new robotic strategies for planetary exploration science, there are many questions that need to be answered before these modes of research can reach their full potential. Many roboticists at the workshop felt confident that there will be dramatic advances in artificial intelligence, autonomy, and haptics between now and the anticipated timeframe for human travel to regions in the vicinity of high-value exploration targets like Mars. The harnessing of these advances to produce the next generation of robotic assets (or partners) for planetary field science will require concerted efforts in robotics research with sufficient support from NASA and other funding sources. Similarly, all participants recognized that we really have very little experience in doing planetary field science with LLT, even with a large degree of supervised autonomy. As a consequence, there is an urgent need to create an effective funding stream for research on best practices of science operations under low-latency conditions. In addition, well-designed experiments are needed to compare and contrast the efficiency and effectiveness of high- and low-latency research modalities as we contemplate the role of strategies such as SBT into mission planning.

E SAIL FOR FAST INTERPLANETARY TRAVEL. M. Aru[1], P. Janhunen[2], [1]University of Tartu, Estonia, [2]Finnish Meteorological Institute, Finland

Introduction: Propulsion is a significant factor for our access to the Solar System and the time consumption of the missions. We propose to use the electric solar wind sail (E-sail), which can provide remarkable low thrust propulsion without needing propellant [1, 2].

The E-sail is a propellantless propulsion concept that uses centrifugally stretched, charged tethers to extract momentum from the solar wind to produce thrust. Over periods of months, this small but continuous thrust can accelerate the spacecraft to great speeds of approximately 20 to 30 au/year. For example, distances of 100 au could be reached in <10 years, which is groundbreaking [1].

The principles of operation: A full-scale E-sail includes up to 100 thin, many kilometers long tethers, which are held at a high positive potential by an onboard electron gun. A high-voltage charge on the tethers deflects the solar wind protons that flow radially away from the sun which results in a reaction force on the tethers. The thrust vector, which points roughly radially away from the sun, can be turned within a ~30° cone by inclining the sail [3]. The sail's thrust is proportional to the product of the solar wind dynamic pressure and the effective sail area. The range of the tethers' electric field can be about a million times larger than the tether itself, which more than compensates for the very weak dynamic pressure of the solar wind [4].

An E-sail's operating principle differs from the solar sail, which is based on momentum transfer from solar photons [5]. The thrust produced by an E-sail decreases as 1/r (where r is the solar distance) and it provides acceleration to distances up to 30 au. In comparison, a solar sail's thrust declines at a rate of $1/r^2$ and is capable of accelerating a spacecraft to only ~5 au [6].

Applications: The E-sail's acceleration is up to 2 mm/s^2 in maximum, but over time great speeds would be achieved. Missions to Saturn and Jupiter can be accomplished in 1-2 years. Neptune and Uranus can be reached in 3-5 years. Furthermore, an E-sail mission to the Heliopause would take 10 to 15 years, while Voyager spacecrafts travelled there for 36 years.

Since the sail can produce continuous thrust, non-Keplerian orbits and stable off-Lagrange positions could be maintained [7]. Other applications include inner planets and sample return missions, asteroid deflection, multi-asteroid touring, and flyby or orbiter missions to outer planets [4, 8, 9, 10, 11]. Thus, new areas of scientific research and new types of missions could be imagined and created, improving our understanding of the Solar System.

Manned presence on Mars. A spacecraft equipped with a large E-sail, that provides 1 N of thrust at 1 au from Sun, can travel from Earth to the asteroid belt in a year. One such spacecraft can bring back three tonnes of water in three years, and repeat the journey multiple times within its estimated lifetime of at least ten years [9, 12]. The water can be converted to synthetic cryogenic rocket fuel in orbital fuelling stations where manned vehicles travelling between Earth and Mars can be fuelled. This dramatically reduces the overall mission fuel ratio at launch, and opens up possibilities for affordable continuous manned presence on Mars [13].

Multi-asteroid touring. Asteroids are of significant interest since they not only contain valuable resources and pose a danger of impacting the Earth, but also provide insights into the origin of the Solar System. A proposal to compose a survey of hundreds of asteroids by a fleet of nanosatellites was submitted to the European Space Agency's "Call for new ideas" call in September, 2016. Each CubeSat carries a single tether as a downscaled E-sail and is equipped with a lightweight optical and near infrared imaging system. Image data allows us to measure the asteroid's albedo and size during a flyby, while spectral data allows us to detect surface minerals of the studied asteroids. Furthermore, information about surface geology, geophysics, and thermal properties can be obtained. Knowing geophysical properties of asteroids such as mass, interior structure and composition is needed for selecting suitable targets and technologies for asteroid mining, and assessment of the asteroid impact threat. Furthermore, a statistical view to size and compositional distributions for asteroid families is important for constraining the Solar System's evolution models. Asteroid families are vital for studying the composition and structure of the planetesimals from which Earth and other planets once formed [14].

The size of the fleet is scalable. Each spacecraft makes a flyby of 6-7 asteroids, typically, and the fleet of 50 will study a groundbreaking number of 300+ near-Earth objects and mainbelt asteroids. They could be launched by India's Polar Satellite Launch Vehicle (PSLV), for example.

Opportunities for planetary science. The E-sail can be used for flyby missions towards inner and outer planets of the Solar System. Examples include remote sensing of planets from non-Keplerian orbits, gas giant planet atmosphere probe, and deep space planetary or planetary moon flyby [15].

A sample return mission is possible as well, as it has been analyzed for an asteroid. The mission can be divided into three phases. In the first phase, the E-sail based spacecraft travels from the Earth's heliocentric orbit to the target's orbit, and maintains a determined orbit relative to it after the rendezvous. In the second phase, a lander can be used to reach the object's surface and collect material samples. At the end of that phase, the lander performs a docking maneuver with the spacecraft. The third phase involves the return, and ends with an Earth's rendezvous [12].

E sail pro ects 1 :

ESAIL EU FP7 project (2010-2013): An international project during which laboratory prototypes of the electric sail's key components were built.

ESTCube-1 (2013-2015): The first satellite to test the working principles of E-sail in low Earth orbit. An attempt was made to deploy a 10 m long tether from the one-unit CubeSat by centrifugal force. However, the deployment was unsuccessful.

NASA HERTS (Heliopause Electrostatic Rapid Transit System): A project for the development of E-sail at NASA's Marshall Space Flight Center. In April 2016, tests for examining the rate of proton and electron collisions with a positively charged wire began at the High Intensity Solar Environment Test system.

Aalto-1 (2017): A Finnish mission of a three-unit CubeSat, which will test a 100 m long E-sail tether for deorbiting the satellite in Earth's magnetosphere. This is planned for the end of the satellite's operational lifespan to avoid the creation of space debris.

ESA Asteroid Touring by Electric Sail Technology study, 2015-2017.

ESTCube-2 (planned for 2018): An Estonian mission of a three-unit CubeSat, which will test a 300 m long E-sail tether in a similar way to Aalto-1.

ESTCube-3: An Estonian mission of a three-unit CubeSat with a goal to orbit the Moon, which the solar wind reaches unlike the Earth's magnetosphere.

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Waypoints for Opportunistic SmallSat/CubeSat Missions to Comets & Asteroids.

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Introduction: Waypoints to indefinitely park a deep space SmallSat or CubeSat is a novel solution for opportunistic missions to explore new comets and circumvents mission risk due to launch system delays. Comet apparitions into the inner solar system (<0.4 AU from Earth) are accessible to CubeSat class missions that can return unique data not obtainable from ground-based telescopes. Primitive bodies such as comets are key to understanding Solar System formation.

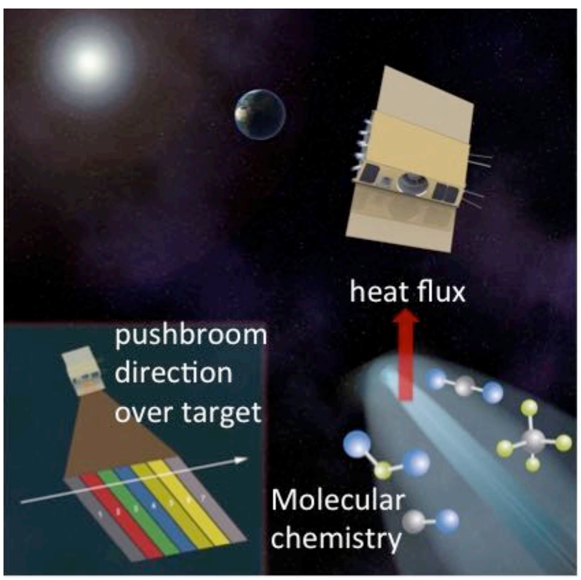

Fig. 1. PrOVE will accomplish important science investigations and measurements of the nucleus and coma of comets. Solar insolation causes volatile outgassing, lofting dust from the nucleus. A close flyby will obtain unique and unprecedented mapping of inner coma molecular species and nucleus temperatures with high spatial resolution in seven filter bands.

For example, our mission concept Primitive Object Volatile Explorer (PrOVE, [1]) utilizes a 6U CubeSat mission, to perform a close flyby of a Jupiter-family or new comet near perihelion with maximum volatile activity (Fig. 1). We judiciously designed a CubeSat science payload to return unique data not obtainable from ground-based telescopes and to complement data from orbiting observatories. The PrOVE mission will (1) investigate chemical heterogeneity of a comet nucleus by quantifying abundances of volatile species and how these change with solar insolation, (2) map the spatial distribution of volatiles and determine any variations, and (3) determine the frequency and distribution of outbursts.

Such measurements uniquely probe the origin of the nucleus, and the formation and evolution of our Solar System. Cost profiles of CubeSat infrastructure permits Class-D missions not otherwise practical with conventional missions such as waiting for opportunistic targets. The low-risk and highly versatile multispectral Comet CAMera (ComCAM) on PrOVE targets the most important cometary volatiles: H_2O, CO_2, CO, and organics; CO_2 is observable only from space due to telluric extinction. These molecules are best probed by their non-thermal fluorescence signatures (Fig. 2) in the 2–5 μm Mid-Wave InfraRed (MWIR) spectral region, which PrOVE will use to map all four species simultaneously.

Thermal emission dominates spectral wavelengths

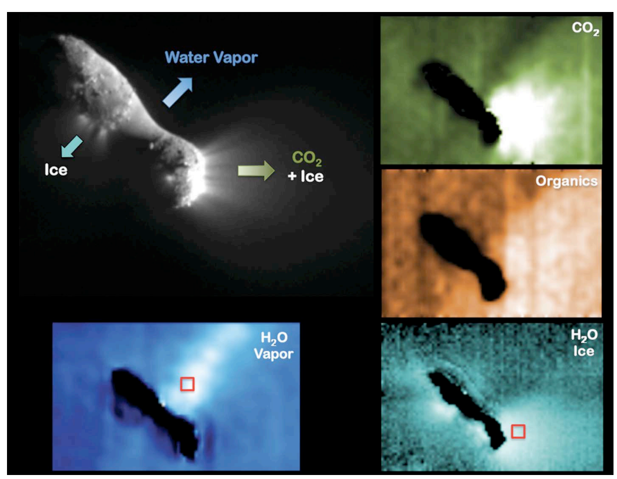

Fig. 2. PrOVE will establish the abundance and distribution of volatile species in the volatile rich inner coma, building on the *Deep Impact* investigation of 103P/Hartley 2 that showed CO_2 sublimation driving comet activity (A'Hearn *et al.*, Science 332(6) 2011). Red boxes show a 275 m scale – which also matches ComCAM's effective resolution at a 200 km range.

>5 µm in the inner coma, which enables PrOVE to map the inner coma temperature distribution by measuring 7-10 and 8-14 µm Long-Wave InfraRed (LWIR) emission. The flyby will discriminate measured quantities at high spatial resolution of ~0.3 km, comparable to 0.005" angular resolution for a ground-based observatory for a comet ~10^7 km from Earth.

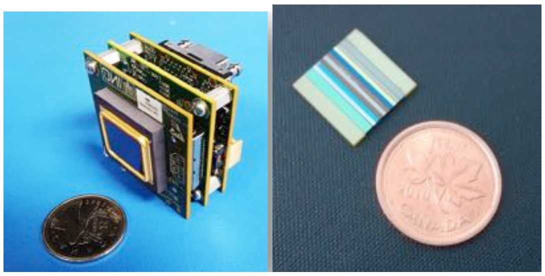

Fig. 3. (*left*) ComCAM will be built around the INO µXCAM OEM sensor. (*right*) Example of Multi-Zone filters manufactured by Iridian. These filters will be integrated onto the sensor focal plane. The optical assemblies are not shown.

A microbolometer based multispectral camera will be used to accomplish ComCAM science goals. ComCAM will span MWIR and LWIR spectral regions with integrated filters and 80 mm aperture imaging optics (Fig. 3). ComCAM, propulsion, and infrastructure will fit neatly into a 6U spacecraft bus (Fig. 4).

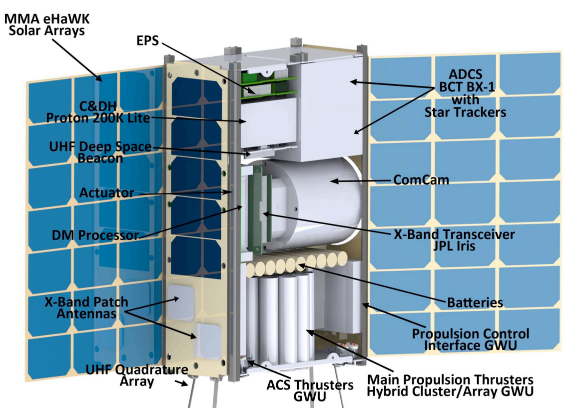

Fig. 4. PrOVE deep space 6U Cubesat bus subsystem layout with ComCAM.

A number of propulsion system are now available for deep space CubeSat missions. For example, the a multi-channel Micro-Cathode Arc Thruster (µCAT) micropropulsion subsystem which is an outgrowth of GWU Micropropulsion and Nanotechnology Laboratory (MpNL) research in scalable small spacecraft electric propulsion. The µCAT is an electric propulsion device, based on the well-researched ablative vacuum arc process, enhanced by an external magnetic field that uses its own thruster cathode as propellant. The cathode terminal can be any conductive material. The applied magnetic field extends operation lifetime while reliance on a thruster element for propellant reduces system mass for micropropulsion compatible with 1-50 kg class satellites, including all CubeSat forms.

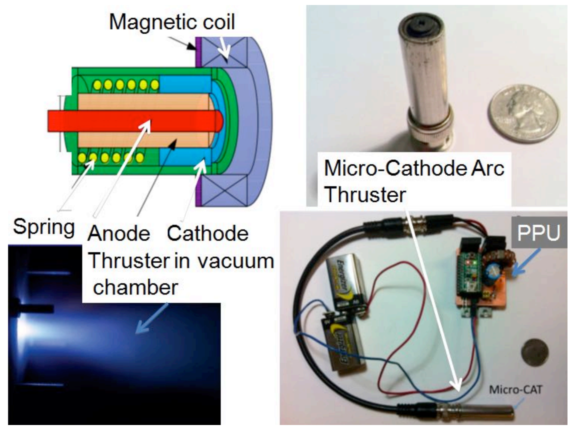

Fig. 5: µCAT schematic and components.

Waypoints – Mission Architectures for 2050: A potential impediment to a mission to a comet approaching perihelion are uncertainties due to launch delays. We believe a solution that eliminates the impact of launch delays is ideal for spacecraft missions to study transient celestial events such as short period comets near perihelion, but especially of new comets and asteroids reaching the inner solar system for the first apparition; hence, the concept of *waypoints*. Our recent studies of trajectories to comets such as Wirtanen. However, mission goals can be compromised by extended launch delay.

Pathways to Waypoints: Missions such as PrOVE can be launched aboard a NASA, DoD, or NOAA LEO, MEO, or GTO EELV rideshare mission and use the launch vehicle's excess capacity to reach escape, or near escape, velocities and then use a series of lunar and/or earth flybys to increase apogee to permit a comet flyby (private communication and analysis, D. Folta and P. Spidaliere). While rideshare manifesting on a specific planetary mission is a good opportunity, we believe seeking and exploiting excess capacity on more frequent mission (likely with significantly greater excess capacity) launches provides a viable and mission enabling prospects provided waypoints can be identified as an intermediate mission phase for the target. Waypoints can also be used to store spacecraft for mass deployment as a constellation to a single target or individualistically to different targets.

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THE FUTURE OF PLANETARY ATMOSPHERIC, SURFACE, AND INTERIOR SCIENCE USING RADIO AND LASER LINKS.

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Introduction: Studies of planetary systems using spacecraft radio links constitute the field of Radio Science (RS). RS experiments have been conducted on almost every planetary mission in the past five decades and have led to numerous discoveries. With substantial technical advancements in recent years, the following significant accomplishments fit NASA's *Planetary Vision 2050* themes:

***ORIGINS*:**

- Elucidated the thermal history of the Moon from the GRAIL high precision gravitational field,
- Unveiled the interiors of Titan, Enceladus, Mercury, Phobos, Vesta, Ceres, and cometary nuclei from gravity fields, contributing to understanding their origins (Fig. 1),
- Sounded Titan, Saturn, and Pluto's atmospheres,
- Explored the surface properties of Pluto and 67P/Churyumov-Gerasimenko, and
- Refined models for the atmospheres, surfaces, and interior structure of Mars and Venus.
- *In progress*: Juno and Cassini RS experiments are measuring the gravitational fields of Jupiter and Saturn to reveal their interior structures.

***LIFE*:**

- Provided key evidence for identifying subsurface oceans on icy moons, helping expand our understanding of potentially habitable bodies.

***WORKINGS*:**

- Investigated the solar corona and the interaction of the solar wind with planetary atmospheres, and
- Profiled the structure of Saturn's rings, which interact with moonlets.

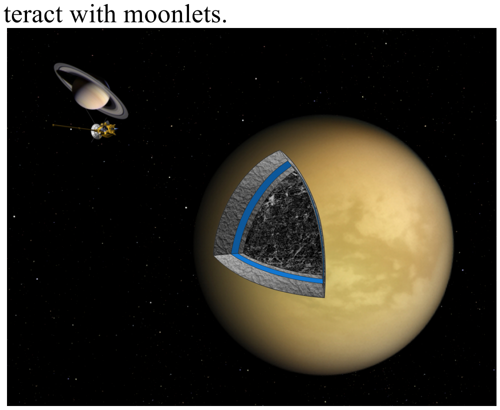

Fig. 1: Representation of Cassini Titan observations for deducing interior structure [1].

Outlook to 2050: InSight will soon characterize the Martian core and Akatsuki will study Venus' atmosphere via RS techniques. Experiments at Mercury, Jupiter, and other environments are in the development or planning phases. Over the next 30 years, advances in radio and laser technologies, such as ones shown below, could enable many scientific breakthroughs. With an order of magnitude improvement achieved in range-rate and similar improvement achievable in range accuracy, many discoveries akin to the unanticipated detection of buried empty lunar lava tubes with GRAIL's high resolution gravity data, for example, are possible at other planets. Selected future exploration Concepts include:

Characterizing Ice Thickness: RS experiments could provide stringent constraints on the thickness of ice and the characteristics of any sub-surface ocean at icy moons. NASA and ESA missions to Europa and Ganymede have such potential, and JUICE will utilize advanced radio instrumentation to explore the Jovian environment. Missions to other icy moons or small bodies could also exploit RS techniques.

Networks for Atmospheric Dynamics: Spacecraft-to-DSN radio occultations have unveiled structural details that have led to better understanding of atmospheric processes. Significant increases in temporal and spatial global coverage are possible using crosslinks among a network of small spacecraft orbiting a planet (Fig. 2), akin to radio occultation with constellations at Earth. Network science will also contribute to safe operations of future human and robotic Mars missions.

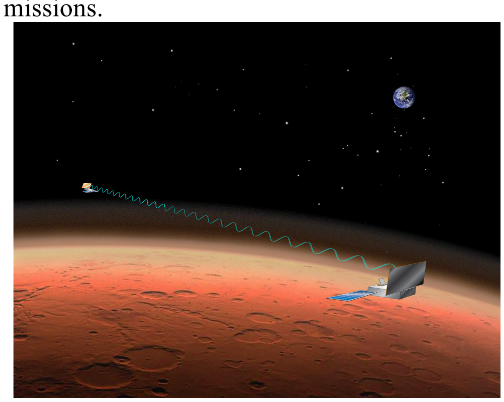

Fig 2: Artist conception of CubeSats Mars network for atmospheric occultations [2].

Networks for Interior Dynamics: Precision gravity experiments via spacecraft-to-spacecraft links can be applied to planetary targets for high-impact geophysical exploration of the interiors and monitoring of mass transport. Airless bodies such as Mercury are best suited for dual-spacecraft GRAIL-like production of high resolution gravitational fields, while GRACE-like resolved monitoring of time-variable gravity would considerably improve our understanding of the Martian climate.

Rotational State & Tidal Deformations via Same Antenna Interferometry: Tracking two or more planetary landers from the same ground antenna enables high precision measurements as many common mode noise sources are suppressed. In turn, determination of the planetary rotational state and tidal deformations can be measured (Fig. 3).

Atmospheric Dynamics via Doppler Wind Experiments: Radio links from descending probes to proximity spacecraft or directly to ground stations provide information on dynamics relevant to atmospheric workings as well as planning the landing of future rovers. Dual-link Doppler measurements, one link between the probe and a spacecraft, and a second link between the probe and a ground station, allow derivation of two-dimensional wind vectors. Absorption on the probe's radio link can be used to infer concentrations of ammonia or sulfuric acid.

Solar System Dynamics via Precision Ranging: ESA's BepiColombo Mercury mission will utilize coherent simultaneous Ka- and X-band Doppler links as well as the first ever precision ranging (under 20 cm) at Ka-band. Advanced ranging instrumentation onboard the spacecraft and at the DSN will be utilized to investigate Solar System dynamics as well as tests of General Relativity.

Surface Properties from Scattering Studies: Bistatic radar in the uplink configuration provides higher SNR, as demonstrated by the New Horizons and LRO Mini-RF observations. Global spacecraft networks make surveying new planetary targets feasible and yield information on surface properties at spatial scales important to the safety of landers and rovers.

Enhanced Atmospheric & Interior Science via Optical Links: With the advent of optical communications, laser links can augment radio links for atmospheric propagation science and provide precision *optimetrics* to improve gravitational experiments and knowledge of Solar System ephemerides.

Enhanced Planetary Gravity via Atomic Clocks: Space borne atomic clocks would revolutionize spacecraft tracking methods. Future one-way uplinks could achieve accuracies comparable to traditional two-way coherent links. This could enable nearly continuous tracking using smaller ground antennas, opening a window for enhanced gravitational field measurements and improved models of planetary structures.

Solar System Dynamics Data Quality with Suppressed Antenna Mechanical Noise: With the most sensitive Doppler fractional frequency stability data to date of ≈$3X10^{-15}$ (at 1000 s), the leading noise was the unmodeled motion of the ground antenna's phase center. This intrinsic mechanical noise can be suppressed when two-way and (3-way) receive-only Doppler data from a smaller and stiffer antenna are suitably combined, further enhancing radio-metric observations for Solar System dynamics experiments.

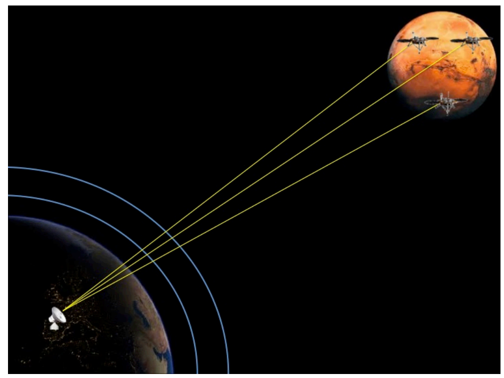

Fig. 3: Artist conception of interferometry technique for planetary rotational/tidal deformations [3].

Selected Science-Enabling Technologies:

- Advanced precision ranging for Solar System dynamics and tests of General Relativity,
- Next generation ultra-stable oscillators,
- Chip-based atomic clocks,
- Antenna mechanical noise reduction for precision Doppler gravity measurements,
- High power Ka-band transmitters for precision Doppler gravity measurements,
- Optical link science,
- Uplink RS as a DSN service,
- RS spacecraft-to-spacecraft link instrumentation,
- Next generation Mars Cube One (MarCO) for RS
- Space-based assets and CubeSat networks, and
- Array communication architectures.

Acknowledgement: This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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STRATEGIES FOR DETECTING RADIOLYSIS-POWERED ECOSYSTEMS BEYOND EARTH.

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Introduction: The discovery of *Desulforudis audaxviator* in a South African gold mine was a major milestone in our understanding of life [1]. The sulfate reducing bacterium was powered exclusively by radiolysis, induced by radiation from U, Th and K present in radioactive rocks. Ionizing radiation dissociate molecules in its surroundings which is used by the bacterium for its metabolism. This was the first discovery of a single-species ecosystem completely cut off from rest of the biosphere existing independently on radiolysis [1].

Beyond Earth, another source of ionizing radiation is Galactic Cosmic Rays (GCRs) which upon interacting with the planetary objects can induce radiolysis in its subsurface environment. Monte Carlo simulations suggest that for planets such as Mars and Europa which negligible atmospheres, the subsurface energy deposition by GCRs [2] is comparable to the energy utilized by *D. audaxviator* for its metabolism [2, 3].

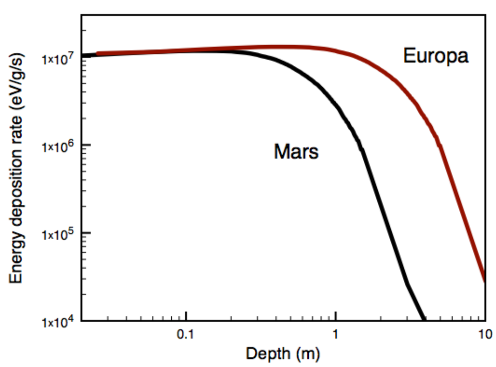

Figure 1: Energy deposition profile for Mars and Europa produced by interaction with Galactic Cosmic Rays.

Simulation Results: Figure 1 shows the energy availability in the subsurface environment of Mars and Europa. *D. audaxviator* powers is metabolism from a radiation dose rate of ~ 10^6 eV/g/s [1, 3] whereas simulations on Mars and Europa show a dose rate from ~10^7 eV/g/s going down to 0 with depth [2]. In presence of suitable nutrients along with this constant source of energy, pockets of "habitability" could exist on such planets where ecosystems are powered exclusively by radiolysis.

Discussion: Extremophiles have always surprised us with their ability to survive in the most extreme situations imaginable. The existence of an ionizing radiation-powered organism, *D. audaxviator*, has opened up new possibilities for life to exist beyond Earth. I will discuss the possibility of such ecosystems within our Solar system, their potential signatures and propose detection strategies for future planetary science missions.

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DATA TECHNOLOGIES FOR PLANETARY SCIENCE OF THE NEXT DECADES. K.-M. Aye[1], A. Muench[2]; [1]Laboratory for Atmosphere and Space Physics, University of Colorado Boulder, 1234 Innovation Drive, Boulder, CO 80303 (michael.aye@lasp.colorado.edu), [2]American Astronomical Society

Introduction: With increasing capabilities of remote sensing technologies and improvements in data downlink rates using optical communication, the amount of data available for planetary science will drastically increase, once the required investments in new and more ground stations required for optical communication have been performed.

But already today planetary scientists have in principle access to data from many different planetary missions. We say 'in principle' because in reality there are many hurdles for inter-mission inter-instrumental data analyses to overcome. It starts with identifying the existing data, continues with reading in data formats of vastly different kinds, created within decades of exploration, then combining data taken at different resolutions in time and space.

This also creates a problem for scientific reproducibility. Publishers do not yet have facitilites to store one-click data archives for all data used for a research paper. This problem will only get worse when the amount of available data increases and the frequency of inter-instrumental data analyses increases. Our future vision tries to address several of these obstacles by identifying technologies that exist today, but require to be connected with each other to maximize their benefit to the scientific community.

Data identification and retrieval: The Planetary Data System (PDS) and its European pendent Planetary Science Archive (PSA) are currently the most future-proof data storage locations for planetary science data. But data retrieveal from different missions is still hard. In the best case, some meta-data have been combined into databases across all instruments of a mission or even across missions. However, using web-based data search engines is highly time-consuming, automatic search and retrieve interfaces to existing analysis environments like IDL, Matlab and Python are mostly non-existing. Additionally, advanced users that want to combine data from different nodes of the PDS will have to suffer from non-uniform interfaces, requiring relearning each time, and a subsequent combination of data outputs with different structure and formats.

However, we believe the technologies to improve this situation exist today, and are beginning to spread soon. The PDS "Ring-Moon Systems Node" has recently implemented a meta-database that covers a much higher number of science-constraining parameters than other PDS nodes offer. Additionally, this node also offers an easy to exploit application programmer interface (API) for searching and downloading data by creating URL strings. An example of how this can be implemented in Python can be seen at [1]. Using technologies like these, users of all analysis environments that support systematic string creation could create interfaces to planetary science data with the convienience of the analysis environment they are most familiar with. We envision that these kind of easily accessible meta-data interfaces will create vast time savings in future data analyses that encompass multiple instruments on multiple missions.

Situational awareness (SPICE). For more efficient identification of data of interest, we envision the use of existing technologies like webGL, directly at browse-time of the PDS and PSA, to be shown a mission and instrument relevant 3D situational overview for any chosen moment in time, similar to what is shown in Figure 1. When a user is browsing data from a mission with orbital travel as complicated as Cassini for example, it would be immensely helpful to have an immediate graphical overview of the current orbital configuration for any time of interest. We only identify lack of funding as a reason to not have these technologies in place today and are hopeful that this instantaneous connection of SPICE data displays to planetary databases will be made at some point in the next decade [2].

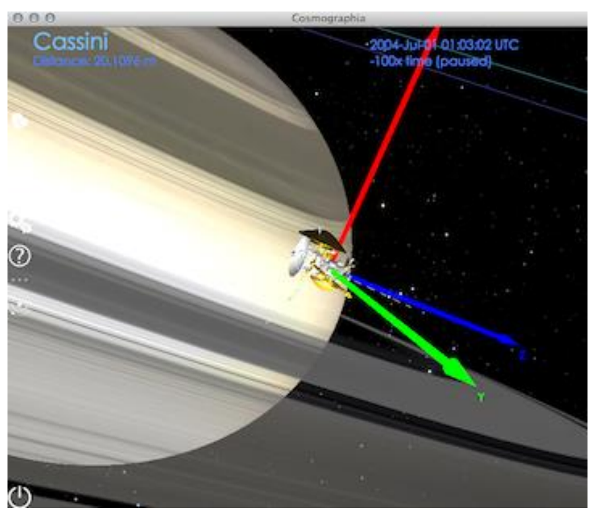

Figure 1 NAIF SPICE preview using Cosmographia Source: NASA NAIF ebsite

Data analyses in parallel: The amount and size of available data will increase sufficiently that using parallel computing technologies will be absolutely unavoidable. We have technologies available today, but not yet wide-spread, that make it much easier to work in the parallel computing paradigm than only 5 years ago. Programming and working in parallel requires a quite different mindset from the linear programming techniques that the average planetary scientist applies. But already today, some of these technologies either are using automatic parallelization (Intel numerical libraries), or offering interfaces to parallelization that reduce the learning curve to a minimum.

We envision that the Jupyter notebook technology, funded multiple times by the Sloan foundation, is a key element to provide these technologies. Jupyter notebooks had been developed using Python as the computing kernel, but has since grown to be a computing kernel independent webbrowser based computing system, that supports a multitude of computing languages. Python-based parallel computing libraries enable the average data user to manage dozens to hundreds of cores of large parallel computing clusters, simply by clicking interfaces in their web-browser, but also directly interfaced with their Python functions.

We believe that minor investments in educating planetary scientists in parallel computing and IT departments in deploying these existing technologies will vastly improve the access to more computing power, as is required by the upcoming data challenges of the next decades.

Reproducability: We envision much deeper connections between planetary science data, research analysis, and peer reviewed articles. Scholarly publishing, as part of its shifting focus to born digital research results, will begin to incorporate the tools of research directly into the publications of the future.

Tools such as Jupyter notebooks and virtualization containers allow for the packaging and distribution of complete research projects. Notebooks wrap analysis scripts and pipelines in a descriptive narrative that parallel directly the LaTeX formatted papers written today. The difference is that by incorporating these tools into the published article, Journals will bring computational power to the now static text. Virtualization containers such as docker enable the capture of entire workflows for replication and reuse. Future capabilities of planetary science archives will provide deep persistent links between published articles and well documented datasets, while peer reviewed articles will expose these links to ensure reproducibility of results and reuse of data. Connecting these software and data to articles via citation and persistent linking is most important to the broader scholarly commons where a richer set of research objects, e.g., software, are recognized and attributed to individuals and groups.

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STUDENT INVOLEMENT IN SPACE EXPLORATION: THE NEXT GENERATION. F. Bagenal and M. Horanyi, Laboratory for Atmospheric & Space Physics, University of Colorado, Boulder CO (bagenal@colorado.edu)

Involvement of students in space missions exposes students to the technical realities of space exploration – delivers deep learning experience and feeds the professional pipeline.

Student involvement at space missions: In the earlier days of space exploration student involvement in experimental work was limited to rocket and balloon payloads. LASP has a strong history of involving students in orbital missions and throughout all mission phases: design, build, test, operation, data analysis and science. Under the Directorship of Charles Barth, LASP built and operated two successful student-based missions in Earth orbit, SNOE and AIM which studied the Earth's upper atmosphere. This tradition has continued with student-based cubesats CSSWE (which measures energetic particles in the Earth's radiation belt) and MinXSS (which measures x-rays from the Sun). Students are also involved with single instruments on larger spacecraft, the most notable being the Student Dust Counter (PI M. Horanyi) on the New Horizons mission that flew past Pluto on 14 July 2015. In addition to specifically student-based missions and instruments, LASP involves students in many aspects of regular space missions, particularly operations and science.

Venetia Burney Student Dust Counter: SDC is part of the Education and Public Outreach (EPO) effort of the New Horizons mission and is the first science instrument on a planetary mission to be designed, built, tested and operated by students. The SDC project has an unusual history. A similar professional dust instrument was part of a competing proposal to New Horizons in a parallel Phase A study. After the selection of New Horizons, motivated by the potential scientific contribution of a dust instrument, the idea emerged to redirect some of the funds from traditional EPO activities so that a group of students could try their hands at building space hardware. The advanced state of the rest of the New Horizons payload and the risk of involving unexperienced students made this request difficult. With the strong support of the mission PI, the NASA EPO board agreed to try the "SDC experiment."

To minimize the risk SDC might pose to the mission, all quality assurance inspections and the final flight assembly was done by NASA-certified personnel, and student activities were supervised by professionals. However, the student team, consisting of up to 20 engineering and physics undergraduate and graduate students, was responsible for the work done in all phases of this project, including presentations at all NASA milestone reviews. SDC was built and tested to the same NASA engineering standards as every other flight instrument. After launch of the New Horizons spacecraft on 19 January 2006, the SDC instrument was named after Venetia Burney, the young woman who named Pluto in 1930.

SDC provides the first set of dedicated dust measurements in the solar system beyond 18 AU, and will continue its observations while traversing into the Kuiper Belt (KB). Its data already provided unique and valuable science results, including an estimate of the total dust production rate in the KB. To date five publications on SDC data have been published in refereed scientific journals, and the results have been used in several other studies on the effects of dust influx to bodies in the outer solar system.

A total of 26 students have been involved in SDC with new students taking over responsibility for data processing and analysis through the extended mission. Due to the long duration of New Horizons, multiple generations of students continue to be involved, handing over their skills to the groups that follow. These SDC-trained students have moved on to a wide variety of professions. All undergraduates who applied to graduate school on graduation from CU were accepted to their first choice school (e.g., Stanford, New Hampshire). Several of them were hired at LASP as professional space scientists or engineers. Many continued in the space business at places such as NASA, SWRI, Orbital ATK, Ball, and Blue Canyon. All speak enthusiastically about their experience of being involved in SDC.

While NASA offered several opportunities since SDC to propose a student instrument for various missions, to date only the OSIRIS-Rex mission includes another student instrument.

REXIS on OSIRIS-REX: After a competitive selection process REXIS was selected as a Student Collaboration Experiment as part of OSIRIS-REx. The Regolith X-ray Imaging Spectrometer (REXIS) will provide an X-ray spectroscopy map of Bennu, complementing core OSIRIS-REx mission science. REXIS is a collaborative development by four groups within Massachusetts Institute of Technology (MIT) and Harvard University, with the potential to involve more than 100 students throughout the process. At MIT, faculty leadership is provided by Professor David Miller, Professor Richard Binzel, Professor Rebecca Masterson and Professor Sara Seager. At Harvard, faculty leadership is provided by Professor Josh Grindlay.

Students operate missions: The LASP Mission Operations & Data Systems (MO&DS) group staffs several

Mission Operations Centers and Science Operations Centers for the day-to-day operations of NASA spacecraft and instrument missions. LASP is one of very few university-based mission operations centers. One of the most exciting and unusual aspects of mission operations at LASP is the opportunity for CU undergraduate students to become certied mission operators. The student operators, who must pass a summer-long course held at LASP, work under the supervision of professional staff and perform mission operations for NASA satellites – from LASP-built student cubestat missions to national facilities such as Kepler. Each day, more than 100 gigabytes of data come through LASP servers to support ongoing space missions, as well as the scientific data that scientists from all over the world rely on.

There real-world experience in mission operations is a valuable balance to the academic training of their University coursework and these students are keenly recruited into a range of professions.

The workforce pipeline in planetary science: While we have mostly used examples at the University of Colorado's Laboratory for Atmospheric & Space Physics, there are similar examples at other universities across the US. But the reality is that the requirements associated with NASA missions of increasing technical sophistication, growing management, and escalating security mean that fewer universities are able to maintain student involvement in space missions. Yet the value – both educationally and creatively – of engaging young people in planetary exploration is glaringly obvious to anyone who witnessed the students presenting SDC to the New Horizons CDR panel or a student operator sitting down at the console for the next Kepler download.

The 2011 US Planetary Science Workforce Survey [1] estimates that there are about 1200 PhD planetary scientists working in the US. With many different types of university departments saying that they include planetary science it is hard to get an accurate number for the PhD production, but estimates are in the range of 75-100. About 90% come from just 10 universities. Experience suggests that only 20-30% continue as professional scientists. This indicates that planetary science is not over-producing PhDs – which is consistent with relatively small applicant pools for positions in planetary science and the relatively large number of non-US-born planetary scientists working in the US (including the two authors of this abstract). The number of planetary scientists graduating with experience in designing/building/testing/operating instruments is extremely small.

2050 vision for student involvement in planetary missions: To supply the creative workforce to implement NASA's Planetary Science Division's vision for solar system exploration in 2050 there needs to be a healthy pipeline of experienced scientists and engineers. An effect way to maintain such a trained workforce is through direct university involvement in space missions. The best training for students comes from hands-on involvement throughout all phases of missions via student-based missions and/or instruments on planetary missions. What types of missions or instruments are we proposing be student-based? Students have demonstrated they can build a successful instrument that has made space measurements for 11 years and out to 33 AU. Students have built and operated a cubesat that has outlived its original design life by a factor of 5. ***We see every reason to provide students the opportunity to explore every corner of the solar system.***

CU student Chelsey Bryant-Krug prepares for a calibration run of SDC in the dust accelerator in Heidelberg, Germany in 2004. Show is now a LASP professional engineer..

The flight-qualified electronics box of SDC

[1]http://lasp.colorado.edu/home/mop/resources/related-links/planetary-science- workforce-survey/

RARE EARTH OR COSMIC OO: TESTING THE FRE UENCY OF COMPLEX LIFE IN THE UNIVERSE. W: Bains[1] and D. Schulze-Makuch[2], [1]Department of Earth, Atmospheric and Planetary Science, MIT, 77 Mass. Ave., Cambridge, MA 02139, USA, bains@mit.edu, [2]Center of Astronomy and Astrophysics, Technical University Berlin, Hardenbergstr. 36, 10623 Berlin, Germany, schulze-makuch@tu-berlin.de, dirksm@wsu.edu.

Introduction: Is Earth an exceptional and unusual place for life in the cosmic neighborhood or is the universe teeming with complex, macroscopic life? In other words, do we live on a *Rare Earth* [1] or in a *Cosmic Zoo* [2,3]? The latter has been argued for because of recent insights gained from analysis of the key innovations during the evolution of complex life on Earth. Most key innovations have evolved many times with different origins and mechanisms but the same end function. Here, we propose on how to test between the two hypotheses during the next decades, tests which require plausible advancements in remote sensing capabities targeted at exoplanets and site visits of planetary bodies in our own solar system and beyond.

Recent Progress: The number of confirmed exoplanets now exceeds 3400, with an additional nearly 5000 exoplanet candidates awaiting confirmation [4]. Yet, we do not know how many planets of those will turn out to be Earth-like, meaning the existence of multiple environmental habitats and the presence of a sizable biosphere and complex ecosystems, without which Earth, as we experience it, would not exist [5]. Thus, the existence of a second Earth may be rare indeed. On the other hand life, even complex life, may not be constrained to "twins" of Earth if the biochemistry of life itself is different. As of now, the question cannot be decided whether an exoplanet is a host for life or even habitable (but possible uninhabited).It has been argued that the transitions toward complex life will be readily accomplished given enough time and habitable conditions on a planetary body [2].

Future Remote Sensing Capabilities: One of the inherent limitations of all the methods used today to study exoplanets is that we can only see the star and planet as a combined dot. Technologies currently in the early planning stage, such as Starshade [6] will overcome this, and provide the possibility to see star and planet as separate dots. Further development of technology could allow large-scale mapping of spectral features on the planet. Even though the planet would still appear as a single dot, that dot would change brightness and color as it rotated and orbited its star. If conditions are favorable, this information could be used to get a crude map of the distribution of color on its surface, perhaps including ice caps and major continents.

There are several chemical features of life that could be detected using advanced methods. One is the presence of a gas in the atmosphere that is likely to be produced by life, and not given off by volcanoes or other, non-living processes. Single gases are unlikely to be definitive markers of life; even oxygen can be generated by some astronomical and geological processes [7]. A combination of gases would have to be detected together, such as oxygen and methane together, which would only co-exist if continually produced.

Another often cited biosignature is the Vegetation Red Edge effect [8]. Life on Earth reflects light of wavelength 750 – 1000 nm very well, which results in a sharp 'edge' in the spectrum at about 750 nm. On Earth the Red Edge is quite characteristic, but on other worlds it may not be. Studies of how plants might use light on a world with an atmosphere made mostly of hydrogen concluded that plants there would show no Red Edge [9]. And plants under water have a much reduced Red Edge, as seen from above. If an exoplanet with a 'Red Edge' could be observed, then the conclusion might be that life was or is there, but seeing no Red Edge does not prove the opposite [3].

The challenges to detect any life are formidable, and will remain so for the foreseeable future. Detecting whether that life is complex, as opposed to an ecosystem solely of microbes, is an even harder challenge. However, if we can map an exoplanet, it would be in principle possible to determine the presence of complex life on that planet or moon if:

1) the planet can be mapped remotely in a way that differences on its surface can be analyzed.
2) land can be distinguished from seas. This may be accomplished by detecting the 'glint' of sunlight reflected off the seas, just as the Cassini orbiter detected the glint of sunlight off the polar lakes on Titan (Figure 1).
3) a distinctive spectral feature attributed to life on the land can be mapped, and it can be ensured that strangely coloured rocks, dust clouds or other features are not detected instead, by mistake.

Condition (1) is extraordinarily hard. Condition (2) is beyond any present planned capability, but is not impossible. Condition (3) we do not know how to do yet, but there are some ideas. For example, land plants have a substantial local effect on climate. Due to evapotranspiration and the release of aromatic chemicals into the air, plants increase rainfall over large forests, especially in the tropics. This changes the pattern of rainfall on Earth, alters the global cloud distribution, and cools the land. Trees can do this because they have a very large surface area, much larger than the ground they are growing on. In theory, this effect could be detected on another world as has been shown from modeling of "Desert world" planets and "Green planets" [10].

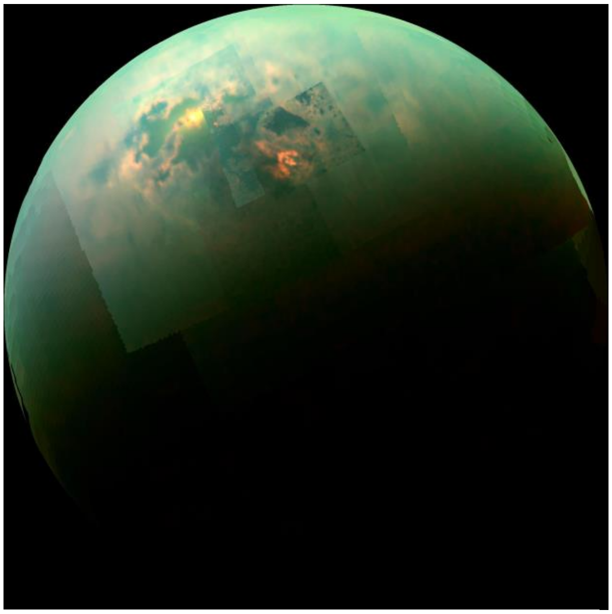

Figure 1 . Near-infrared, color mosaic from NASA's Cassini spacecraft showing the Sun glinting off Titan's north polar seas. The specular reflection is the bright area near the 11 o'clock position at upper left. Image from NASA.

Site Visit: A thorough astrobiological investigation requires becoming close and personal with your object of interest. There is only so much that can be achieved with remote sensing. Ultimately, confirmation that a planet hosts complex life, and indeed confirmation that it holds life at all, must come from close examination of the planet, including sampling its surface. And even that is challenging as the Viking life detection experiments showed.

The problem, of course, is that nearly all the potential targets are so far away. Proxima b in the Alpha Centauri system is the closest exoplanet being about 4.3 light years away from Earth. A few years ago such a journey to Proxima Centauri by a robotic probe would be all but out of question, but recent developments make this more of a possibility. Spacecraft technology has become so much more compact with microsatellites like Cubesats that are also low-budget. Also, gains have been made in innovative propulsion systems such as Starwisp [11], which in principle could reach 10% of the speed of light, getting to Proxima Centauri in 43 years [12]. The Breakthrough Starshot project has updated this concept and aims to reach 20 % of light velocity (https://breakthroughinitiatives.org). And the 100 year Starship Initiative funded and supported by NASA and the Department of Defense (USA) (http://100yss.org/), has the objective to make interstellar travel a reality within the next 100 years.

Fortunately, in addition to the above we can also investigate our own solar system to test the hypotheses. Our solar system contains many marginally habitable planets and moons. None of them is suited to terran life as the Earth is, but then life on Earth is adapted to its home planet, not to another world, so it is inevitable that other worlds will be less hospitable to our type of life. But if we could find life on another body in our own solar system, we can go there and analyze it. If such life existed, it would be a very strong argument that life on Earth was not an incredibly lucky event, but that life is common, even if those environments were too harsh, limited or transitory to allow complex life to develop. So before considering a mission to Proxima b, we should consider missions to some of the main contenders of being hosts for life in our own solar system: Mars, Titan, and Europa. The case of Europa provides an especially intriguing example, because it might be the only place in our solar system where we might have a chance to find some type of complex life (but certainly not as complex as life on Earth, [13]), especially if hydrothermal vents provide a correct analogy for the origin and colonization of life on other worlds [14].

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SURVEYS OF SIZES AND BASIC COMPOSITIONS OF OUTER SOLAR SYSTEM POPULATIONS FROM INFRARED SPACE-BASED PLATFORMS. J. M. Bauer[1,2], S. Sonnett[3], E. Kramer[1], A. K. Mainzer[1], J. R. Masiero[1], T. Grav[3], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA (James.M.Bauer@jpl.nasa.gov), [2]IPAC, California Institute of Technology, Pasadena, CA. [3]Planetary Science Institute, Tucson AZ.

Introduction: With the advent of the Infrared Astronomical Satellite (IRAS), statistically meaningful samples of asteroid sizes have been measured, and coupled with groundbased measurements, statistically large numbers of albedos [1-2]. For what was previously advanced by individual radar and occultation observations, IRAS measured thousands of sizes, and now NEOWISE [3-7] has provided hundreds of thousands of asteroid diameters which also yielded reflectance measurements. However, for outer solar system populations, namely long-period comets, Centaurs, Scattered Disk Objects (SDOs), and more generally Trans-Neptunian Objects (TNOs), the size distributions of these populations down to km sizes are only beginning to be constrained. Owing to the range of reflectances possible within these populations, from ~2% to ~90% [8, 9], thermal infrared measurements, in combination with reflected-light observations, have the best potential for revealing accurate sizes in these large numbers. Several future near, mid and far-infrared (IR) missions, well into their planning stages, have the potential to sample these more distant populations, and so trace primordial distributions of the quantity of material and volatiles in these bodies, relatively unaltered by insolation. We will discuss some of these platforms and the potential science cases associated with extending the reach of large-sample size surveys.

Comet Populations: Comets provide a special opportunity for the determination of size measurements of primordial populations from the outer solar system. These bodies are presumed to be less evolved as evidenced by the extant volatile reservoirs that drive their activity. However, as they may pass nearer to Earth they are more accessible to encounter missions and to space-based mid-IR (effective over the 3-25 micron wavelength range) measurements, whereby large numbers of nucleus diameters can be measured. Spitzer Space Telescope [10] and NEOWISE [11] have provided statistically meaningful constraints on the size distributions of Jupiter family comets (JFCs) and long period comets (LPCs), and NEOWISE's particularly regular cadence facilitates the debiasing of the sampled comets. Coma removal techniques in combination with debiasing have provided meaningful constraints on nucleus size distributions to within a factor of a few for the most distant Oort Cloud objects, the reservoir of LPCs [11]. In the near future, proposed and current missions undergoing fabrication may improve these constraints on size to within 25%.

Centaurs, SDOs, and TNOs: Farther out in the solar system, populations of objects that have undergone little or no de-volatilization present a means of separating the evolutional effects of near-solar approaches and the rate of change on bodies that such solar exposures induce. Near-IR survey missions, such as WFIRST and the proposed SphereX mission [12, 13], may provide information regarding volatile ice absorption features that indicate more primordial surface compositions, in large enough numbers to map distributions of these signatures across these outer-solar-system populations, while also assessing their reflected-light signals. These outer solar system populations are source regions of inner solar system populations. They serve as storehouses of volatiles, and may be the source of a significant fraction of the volatiles found in the terrestrial planet region, especially on Earth. Mapping spectral variations throughout these bodies can also constrain their formation and emplacement mechanisms, and so test models of early solar system evolution that involve, for example, giant planet migration. Broad-band far-IR surveys, such as the science studies outlined by the proposed Origins Space Telescope (OST) which span the wavelength ranges from several tens to several hundreds of microns, will afford the opportunity to explore the size distributions of SDO and TNO populations down to km sizes [14, 15] via radiometric methods. Such missions ultimately could map the outer solar system small bodies as NEOWISE did for the inner solar system, and move the number of size measurements from the hundreds, as provided by missions like Spitzer and Herschel [16], into the several thousands.

Target Selection for In-Situ Studies: Such missions, dedicated to surveying the outer solar system small bodies at wavelengths tailored to their detection and size characterization also facilitate future missions by providing multiple targets for in-situ study. A larger sample of TNOs and Centaurs with known sizes necessarily translates into a larger number of targets available for future in-situ studies, and the ability to exploit serendipitous opportunities, either with re-purposed spacecraft, as in the case of New Horizons, or with multiple lower-cost missions.

Special Case of an LPC "Constellation" Mission: One such example would be with the identification of targets for a multi-component cubesat or scout mission to image many LPC nuclei. At first it may seem surprising that no mission has yet imaged the nucleus of any LPC, with the possible exception of the Mars Reconnaissance Orbiter in the instance of the C/2013 A1 near-pass of Mars, and certainly none with sufficient detail to characterize the full shape or surface variegation. The range of JFC surfaces imaged by the missions to now six such comets show clear differences in topography, size, and activity, possibly attributable to the amount of time each of these comets have spent in the inner solar system [17]. This suggests the need for multiple comets to be sampled for any class of comets, but the LPCs are a particularly important class in that they are even less altered by the exposure to sunlight, and so provide a baseline of the evolutionary effects of insolation and a test for the origin of the variegated surfaces seen on JFCs.

The imaging of cometary nuclei is possible, as has been shown with the several JFC nuclei that have been imaged in detail, but the main problem lies in the delivery of the imaging instruments to particular targets. With Far-IR survey platforms dedicated to Centaur and TNO population mapping and size characterization, it would be possible to also identify LPCs at distances where missions can be planned and launched. LPCs detected at distances of 20-50 AU from the Sun allow for decade timescales for launch and cruise of the spacecraft to the target. This would facilitate the first line of LPC missions, simple modular and low-cost spacecraft which could fly by individual LPCs, one spacecraft per comet, and rapidly sample a number of comets within a decade, or even a few years, and possibly in preparation for more extended missions that may follow LPCs through their orbit, or even obtain samples from their surface. Such a multi-spacecraft "LPC constellation" mission, with modules launched simultaneously or in rapid succession, may be considerably less expensive and a more appealing first-line of investigation since it would avoid the necessity of matching the high Δv required for any more involved LPC in-situ study, while acquiring a statistically large number of imaged LPC nuclei in a relatively short interval of time.

Conclusion: An array of platforms of near-term and long-term missions being planned or built by both astrophysics and planetary divisions have the potential to sample and characterize the next region of solar system space. Mapping these most basic of properties, size and surface composition signatures, will likely deliver key information that will disentangle evolutionary effects from primordial composition in our solar system. In order to utilize these missions for this exploration, the possibilities for surveying more distant solar system bodies must be realized, and the necessary capabilities to facilitate these studies emplaced within platforms. This will require active participation in the development of these missions by the interested solar system communities. Alternatively, platforms would have to be dedicated and constructed separately. Such missions will both have considerable impact on our understanding of the formation and evolution of small bodies in the outer solar system, and will identify multiple targets for study, for example LPCs, for in-situ missions.

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TECHNOLOGY PLANNING FOR NASA's FUTURE PLANETARY SCIENCE MISSIONS Patricia M. Beauchamp[1], James A.Cutts[1], Leonard A. Dudzinski[2] and Carolyn Mercer[2], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, USA (pbeaucha@jpl.nasa.gov), [2]NASA Planetary Science Division, 300 E Street SW, Washington D.C. 20546-0001

Introduction: As we look far into the future and imagine what we might be doing in planetary science in 2050 and beyond, we must also understand how to plan for the technologies that will be required to fulfill our future scientific goals. The technology planning processes must be an iterative, dynamic one that can be updated, particularly when the knowledge base changes. At the request of the NASA Planetary Science Division we developed such a technology planning process that delineates the technological capabilities needed for near, mid-term and future missions as defined by the science and missions recommended by the Decadal Survey in *Visions and Voyages*[1] and updated by the planetary science community through the assessment groups as science knowledge has evolved. This allows the PSD to keep up with the changing face of planetary science and enables a nimble response to developing key technologies.

Goals: The primary goal of the technology planning process was to provide upcoming planetary science missions, as prioritized in *Visions and Voyages*, with the technologies required to successfully implement them (preferably, at lower cost and higher efficiency). It was also essential to identify the longer-term mission needs and the technology priorities to satisfy them.

Approach: It became clear that in order to achieve these goals the PSD had to diversify their technology development program and ready all technologies for upcoming future missions. Important in achieving this was to determine the status of the current portfolio and how PSD could improve portfolio diversification by determining what technologies are missing from the portfolio. Folded into that were considerations of how to maintain current capabilities and facilities for advancing and testing technologies. Finally, it was necessary to identify partners for PSD to augment the funding required to develop needed technologies.

Figure 1 illustrates the overall scheme employed in the technology planning process. Scientific goals are the major driver for developing technologies. Additional requirements come from technology needs identified during specific mission studies. Incorporated into the plan are existing 'push' technologies from the community planning and assessments documents prepared by technologists and the actual technology development work that is being conducted in a range of different programs internal and external to the PSD.

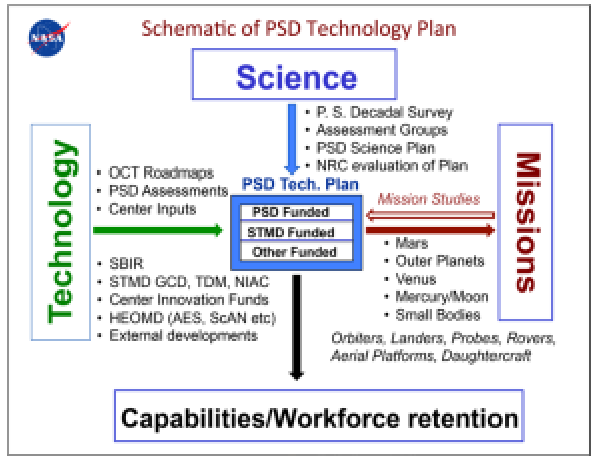

Figure 1: *PSD Technology Planning Elements*

To round out the information incorporated into our thinking, we conducted an assessment of disruptive technologies. These are technologies that would not necessarily show up in earlier documents or in a needs assessment and might not be a major part of existing technology programs but could radically change the way in which we conduct planetary exploration and potentially create totally new ways of exploring planets. The main focus in the current plan was miniaturization and, in particular, the impact of CubeSat technologies and applications to planetary exploration and the future needs of SmallSats (100–200 kg capable of planetary exploration, either as daughter-ships or launched with planetary missions as stand-alone spacecraft or landed elements).

Output: The primary output of this technology planning process is a technology gap analysis for all the mission types that are under consideration, which enables the PSD to develop a strategy for filling these gaps. Capability gaps are derived from analyzing the individual mission types and then looking for common capabilities needed across the missions and determining what was missing. An example of this is given in Table 1, where the color-coding indicates the maturity level given the current technology programs.

The technology gaps represent a menu of possibilities for PSD to examine as it formulates its technology program and advocates funding by other directorates. There are far more programs than there are resources to support them. Once the technologies have been identified, the PSD sets priorities for funding and/or co-funding and develops technology roadmaps delineating goals and objectives. In addition to the factors discussed earlier, answering the following questions aids in prioritizing:

1) Is this enabling or enhancing for a PSDS mission?
2) Is it applicable to multiple missions?
3) Will this technology save PSD resources in the short- or long-term?
4) What are the resource requirements?
5) What is the probability of success?
6) Can it be completed in time for the mission?

The ultimate goal is to infuse new technologies into scientific missions with minimal risk, so the critical final steps in any technology planning process involve managing the development of these prioritized technologies, assessing the readiness levels of the technology at all stages to monitor progress, and, importantly, planning for infusion into missions. All of these steps must be taken to ensure that the technology planning and development process is robust and that future missions reap the benefits of technological advances.

Conclusion: Significant and sustained technology investments throughout the next few decades are necessary to accomplish the existing planetary scientific objectives. This can only be achieved if a well-conceived, agreed-upon technology planning process exists and is practiced. The NASA PSD has embarked upon a technology planning process that will enable the development of novel scientific missions, whether they are competive or assigned missions. The process is flexible enough to accommodate improved scientific knowledge and the changes in direction that might result from those insights, as well as changes in direction that could arise from political shifts or technological breakthroughs. The process has now moved to a phase where detailed plans are being developed for those capabilities deemed to be of highest priority.

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	Technology Information	Near-Term Missions						Mid-Term Missions						Far Term-Missions				
	Capability/Functionality	Small Bodies	Outer Planets	Venus	Mars	Moon	Common-ality	Small Bodies	Outer Planets	Venus	Mars	Moon	Common-ality	Small Bodies	Outer Planets	Venus	Mars	Common-ality
System Technologies	**In Space Propulsion**						MOD						MOD					MOD
	Aerocapture/Aeroassist	NA		Aerobrake			LOW	NA					TBD	NA				MOD
	Entry including at Earth		↑	↑		Earth	HIGH		↑	↑			HIGH					MOD
	Descent and Deployment			Plains			MOD			Tessera			MOD					MOD
	Landing at target object				↑		LOW						MOD					MOD
	Aerial Platforms			Balloon	Rotorcraft		LOW		Balloon	Balloon			MOD			Balloon		LOW
	Landers - Short Duration						NA											LOW
	Landers - Long Duration						NA											LOW
	Mobile platform- surface near surface				↑		NA											
	Ascent Vehicle						NA						LOW					LOW
	Sample Return						NA						LOW					LOW
	Planetary Protection		↑				HIGH						MOD					MOD
Subsystem Technologies	Energy Storage- Batteries						HIGH						MOD					LOW
	Energy Generation - Solar																	MOD
	Energy Generation - Radioisotope Power											?	LOW					MOD
	Thermal Control - Passive						LOW						LOW					LOW
	Thermal Control - Active																	
	Rad Hard Electronics						LOW						LOW					
	Extreme temperature mechanisms						LOW						LOW					LOW
	Extreme temperature electronics						LOW						LOW					LOW
	Communications						HIGH	Optical	Optical	Optical	Optical		HIGH	Optical	Optical	RF-HT		HIGH
	Autonomous Operations						HIGH						HIGH					
	Guidance, Navigation and Control				↑		HIGH						HIGH					HIGH
Insutrument	Remote Sensing - Active		↑				MOD						LOW					HIGH
	Remote Sensing - Passive		↑				HIGH						HIGH					HIGH
	Probe - Aerial Platform						LOW						MOD					LOW
	In Situ - Space Physics																	
	In Situ Surface - Geophysical												LOW					LOW
	Sampling						LOW						LOW					HIGH
	In Situ Surface - Long Duration - Mobile						LOW						LOW					LOW

TRL Maturity Legend	
	Very High. Ready for flight. Same as TRL 6
↑	**High. Funding is in place to advance to Very High in one to four years**
	High. Limited development and testing still needed
	Moderate. Major R&D effort needed.
	Low. Major R&D effort needed with notable technical challenges

Table 1: *Maturity of technology capabilities for implementing planetary science missions (as of 2015). Typically, for Near-Term missions the maturity is high or very high and in many cases funding is in place to achieve the maturity needed for flight. For Mid-Term and Far-Term mission there are increasing umber of instances where the technology maturity is moderate or even low. The columm marked Commonality indicates the degree of similarity in the capabilities needed across the five categories of target object.*

LOOKING TO 2050: THE USGS INTEGRATED SOFTWARE FOR IMAGERS AND SPECTROMETERS (ISIS). T. L. Becker, K. L. Edmundson, S. Sides, T. M. Hare, J. R. Laura, U. S. Geological Survey, Astrogeology Science Center, Flagstaff AZ (tbecker@usgs.gov).

Introduction: Since 1971, the U. S. Geological Survey (USGS) Astrogeology Science Center (ASC) has developed scientific software to process NASA planetary image data [1]. At version 3, the system, currently called The Integrated Software for Imagers and Spectrometers (ISIS), has supported a diverse set of missions including flybys, orbiting spacecraft, landers, rovers and sample return missions funded by NASA, the European Space Agency (ESA), the Japanese Space Agency (JAXA), and the Indian Space Research Organization (ISRO). ISIS provides support for 63 sensor models (camera models). Data from these varied sensors represent spatial and spectral images of solid target bodies and rings throughout our Solar System from Mercury to Kuiper Belt dwarf planets.

Calibrated and controlled geospatial products are critical to support the integration and scientific comparison of data across missions, sensor types, and data scales, i.e., horizontal and vertical data. ISIS not only supports planetary research but the selection of safe landing sites and in-situ planning for robots and humans [2].

With a diverse workforce that includes Planetary Geologists, Computer Scientists, Photogrammetrists, Cartographers, Geodesists, Archive Specialists and Data Curators, the ASC recognizes the evolving needs of the planetary science community. The exploration of bodies within our Solar System depends upon these spatial computational capabilities today and will continue to do so in 2050. Predicting the future of hardware and software technology is difficult ten years-out and near impossible thirty-five years-out. Thus below, we offer a vision of how ISIS, in support of critical planetary spatial data infrastructure, may evolve as we approach the year 2050.

Open Technologies: We continue to develop and utilize open source software and are working toward providing functionality that will contribute to interoperability between tools used by the planetary science community. A long-term goal is to provide open standards and streamline data processes. To support this, it will be critical to integrate existing scientific and computational libraries and standard methodologies such that our community can concentrate on the idiosyncrasies within our planetary domain. Innovations developed within our community will then need to be incorporated back into those libraries to evolve the technology.

For example, more recent ISIS efforts include: 1) new and improved photogrammetric functionality and visualization environment [3]; 2) true 3D shape model formats and map projections in support of mapping irregularly shaped bodies [4]; 3) innovative techniques for efficient and accurate image matching; and 4) utilization of the Community Sensor Model [5]. The increased use of standards-driven software development cannot be understated; technology will undoubtedly progress rapidly over coming decades and standards-driven capabilities facilitate backwards compatibility, interoperability, and specialization within software libraries. Each of these initiatives are purposely built on existing ideas and technologies but are targeted for our planetary applications. To evolve with technological advancement, the solutions we derive will need to be documented and maintained in an open manner.

Innovative Needs Towards 2050: Photogrammetric control has been essential for accurate placement and exploitation of spatial data for almost 180 years and we see no indication that this will change over the next fifty years. The creation of controlled and geometrically precise image mosaics utilizing tens to thousands of individual images can be extremely challenging and time-consuming given the uncertainties of spacecraft pointing and sensor behavior. ASC can envision hardware and software capabilities progressing to a point that controlled mosaics can be created in real-time from data collected by drones (UAV), rovers, or humans. Further progress will enable the onboard, real-time creation of these products.

We anticipate the adoption of machine learning algorithms to support spatial data processing and classification. Challenges of scale disparity, extreme viewing conditions, and diverse cross instrument fusions will remain a challenge and the work being advanced within the terrestrial face and pattern recognition, remote sensing, and biological imaging sciences will be critical to adapt for planetary usage.

Fifty-plus years of planetary exploration has produced vast amounts of data and the exponential increase will continue unabated. We identify Big Data Software-as-a-Service (SaaS) infrastructures as continuing to play a significant role in supporting data discovery, analysis, and exploitation. Innovations in SaaS are strongly backed by the cyber infrastructure arm of the National Science Foundation (NSF, e.g.

Earth Cube initiative [6]). This is a movement toward portable code that ships along-side huge data sets in the cloud for distributed processing. ISIS must play a key role integrating into said distributed High Performance Computing (HPC) analysis environments.

Volume, Velocity, and Veracity characteristics of planetary Big Data are areas where significant technological headway is being made. We see this progress continuing and the ISIS software library is poised to focus on the trends in computing to meet these challenges.

Conclusion: As the past has shown, geometrically and radiometrically accurate spatial data products are required to explore and support the diverse sciences applied to planetary bodies. The future will continue to require these same products to supply the geospatial framework used to make decisions about landing sites, and resource availability. Scientists will need to compare past and future data sets using unified stable tools. For over 30 years, ASC has accomplished this for the existing 63 sensors in ISIS and is in a position to continue providing the necessary stability through the next 30 years while adapting to changes in hardware, software, sensor capabilities, and science requirements. This effort will require continuous maintenance along with major upgrades to take advantage of new technologies.

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The Incorporation of Multi-dimensional Spectroscopic Techniques in the Future of Planetary Science. C. J. Bennett[1], [1]Department of Physics, University of Central Florida, Orlando FL 32816 (e-mail: christopher.bennett@ucf.edu)

Introduction: A high-priority for NASA as outlined in the decadal Visions and Voyages survey is the development of versatile future instrumentation that is capable of meeting the needs of future proposed missions [1]. However, the majority of traditional spectroscopy techniques (e.g., UV-VIS, Fluorescence, Infrared, or Raman) currently utilized on modern spacecraft (e.g., Mars 2020 [2]), typically take spectra in a single dimension. As such, these techniques become severly limited in real-world situations where complex mixtures of minerals or chemical species are present at the same time and can give rise to absorptions/transmissions within the same bandwidth resulting in what is known as spectral confusion, and therefore it is impossible to identify unambiguously materials that are being studied. Typically laboratory measurements of analog samples are prepared to suggest likely candidates that resemble the original spectra. Though perhaps the idea of the StarTrek Tricorder seems a little bit far-fetched for the moment, there do currently exist multi-dimensional spectroscopy techniques capable of essentially asking the question: "Are any molecules that absorb at this frequency present here?"; the response of the molecules in question can either be a simple "yes/no" or *their entire spectral signature - leading to their unambiguous characterization.* Multi-dimensional spectroscopy holds many advantages over traditional techniques and will likely be widely utilized in future planetary science missions over the next few decades. Here, we will showcase one promising example, 3D-IR Raman spectroscopy [3,4], and briefly describe how it works, as well as some of the ways this could be benfitial with the context of planetary science.

How does 3D-IR Raman work: The principle of the technique builds upon that of traditional Raman spectroscopy. Here, a visible laser is typically used which excites a molecule into a virtual state. Though the majority if laser light is simply (Rayleigh) scattered, a small percentage (ppm – ppb) return at a slightly different frequency. Normal (or Stokes) Raman spectroscopy is where a molecule is initially in its ground state and then returns to a vibrationally excited state – the returning photon is red-shifted by an amount equivalent to the vibrational quanta involved (of note, fluorescence typically competes with normal Raman). Conversely, anti-stokes Raman spectroscopy requires for the molecule to be initially in an excited state and then upon interaction with the visible laser

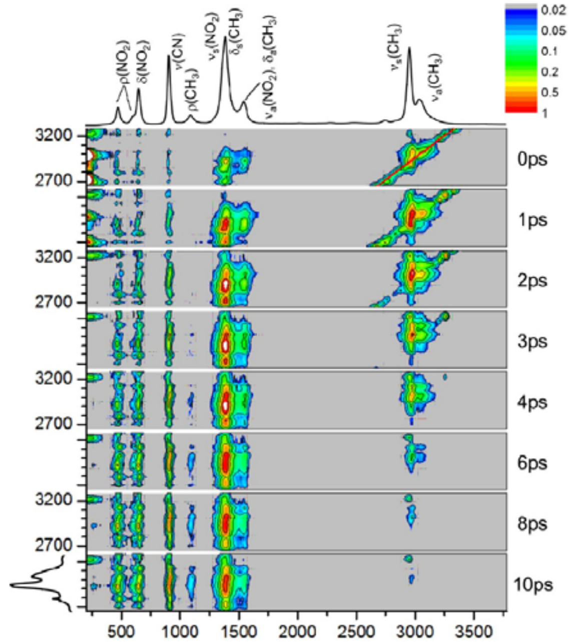

Figure 1: 3D-IR Raman spectrum of nitromethane with reference Raman (top) and IR (bottom left) spectra, taken from [4].

light it returns to a ground state, along with a corresponding blue-shifted photon (higher energy; no fluorescence competes). Because anti-stokes Raman requires populated vibrational states it is typically less commonly employed. However, modern tunable near- and mid-infrared lasers can be used to selectively 'pump' specific vibrational frequencies, or even overtones of fundamental frequencies and combination bands of several fundamental frequencies. The intramolecular, followed by intermolecular redistribution of vibrational states occurs in the following femto-pico-nanosecond timescales after the initial 'pump' excitation. However, an anti-stokes Raman 'probe' can be used to monitor these processes as they evolve. In addition, it is worth noting that by probing overtone or combination bands in the femto-pico second timeframes, the resulting spectra signature corresponds to the resulting population of fundamentals leading to unique unambiguous characterization [3,5]. The intra- and inter-molecular timescales provide additional information on the nature of the species being probed, and the surrounding environment, respectively [4]. Therefore, anti-stokes Raman spectra can be obtained as a function of the IR pump wavelength as a function of the temporal evolution after the initial pump. Figure

1 shows an example of a typical 3D-IR Ramn spectrum of nitromethane [4].

Application to Planetary Science: This technique is currently state-of-the-art and as such, no funding towards development of this technique to planetary science has been awarded thus-far, hence the benefits of this technique that will be presented are somewhat speculative.

A 3D-IR Raman instrument could potentially answer many of the high-priority questions across the entire range of missions and cross-cutting themes noted in the decadal survey [1]. We note that this is a non-destuctive technique capable of identifying trace-species unambiguously at parts per million (ppm) and is equally well-suited to probing liquids or solids, as well as minerals, resources, biomolecules (e.g., amino acids, lipids, sugars, nucleobases, etc.), volatiles, and even hypervolatile species such as O_2, N_2, and CO which may be incorportated in comets; see [6]. Therefore, such an instrument would represent an excellent choice for surveying sites for sample collection or resource utilization. In particular we note that for the proposed New Frontiers Cryogenic Cometary Sample Return (CSSR) mission, a required technology advancement stated was *"developing a reliable in situ method of determining that the sample contains at least 20% by volume of volatile ices and some fraction of organic matter"*. The 3D-IR Raman technique is capable of performing this task but in addition, it could search for biomarkers in situ as well as determine isotopic ratios of H/D $^{13}C/^{12}C$, $^{15}N/^{14}N$ and $^{18}O/^{16}O$. We note that determination of these isotopic ratios (besides H/D, and some instances of $^{13}C/^{12}C$) is typically beyond the resolution of traditional spectroscopic methods (differing by perhaps ~10 cm^{-1}), however, since the 3D-IR Raman can target highly excited hot-bands the frequencies of species become sufficiently separated (>30 cm^{-1}) that a near-IR laser can selectively excite one over the other (near-IR bandwidth ~ 25 cm^{-1}) [7]. Such additional isotopic information would be incredibly helpful in determining the origin of primitive bodies in the Solar System [8].

In addition, a high-priority for NASA over the next decades will be to search for evidence for life throughout the solar system. Therefore, it is desirable to utilize a non-destructive technique which is capable of detecting molecular species on each rung of the *"life detection ladder"* which includes chemical species such as amino acids, lipids, and indicators of metabolism. A commonly sought after biomarker is the detection of chirality within, for example, amino acids which is thought to be a strong indicator of life based on the *"Lego Principle"* [9]. The 3D-IR Raman is compatible with emerging microfluidic devices which are capable of separating molecular species based on chirality. Alternatively, this technique could additionally take advantage of the phenomoneon known as Surface Enhanced Raman Spectroscopy (SERS) or SERs tagging techniques [10,11]. Here, enhancements up to 10^{11} or 10^{12} have been demonstrated which would enable detection limits down to better than parts per quadrillion (ppq; 10^{-15}). However, enhancements of a more modest 10^6-fold enhancement are refularly achievable simply by the addition of gold/silver nanoparticles allowing for routine detection down to parts per billion (ppb) to parts per trillion (ppt) levels (10^{-9} to 10^{-12}). SERs tagging has been utilized to selectively enhance species based on their chirality [12], so it is very likely such tags will be developed for amino acids in the near future. The implications of these advancements suggest that 3D-IR Raman incorportated alongside a microfluidic detection scheme and/or equipped with SERS or SERs tags would enable life detection systems on missions searching for life on icy or ocean worlds, such as the Europa Multiple Flyby Mission (EMFM; a.a.k Europa Clipper) [1].

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PLANNING SCIENCE EXPERIMENTS ACCORDING TO THE MULTIHIERARCHICAL STRUCTURAL SYSTEM OF PLANETARY OBJECTS. *Szaniszló Bérczi, Eötvös University, Institute of Physics, H-1117 Budapest, Pázmány Péter sétány 1/a. Hungary (bercziszani@caesar.elte.hu)*

Introduction: According to my viewpoint in 2050 a planning and thinking method will be one of the coordinating activities in planetary science. This thinking will governed by the structural hierarchy of the material systems. The Multihierarchical Structural System of Planetary Objects gives synchronous view of the activities arranged by the structural hierarchy. This system gives benefits for both scientist and engineers. This method begins by teaching several scientific disciplines and results. This viewpoint uses the embedding sequence of structures.

From teaching planetary sciences to the planning experiments for planetary space probes:

Planetary sciences request integrated forms which may explain the complex operations. Here we exhibit a viewpoint which uses the embedding sequence of natural structures. Where the materials are considered as a complex systems this viewpoint needs analysis, needs definition of lower level units and building up of the structure from these units. This is the natural science research strategy. This method can be multiplied by decomposition of materials to lower and lower structural hierarchy levels.

The engineering viewpoint considers the materials as modular units for construction. Engineering builds up structures from these units, using up characteristic features of these elements. Engineering sciences represent strategies of construction. The construction can be also repeated to higher and higher complexity of system.

In the first approach we analyze materials by decomposition, searching more elementary building blocks, modular units and the relations which form structures from these units. Composition and structure appear as results of these analyzes. The decomposition may be carried out in several steps, reaching new and new structural levels as shown in the last centuries. Building up technologies produce new and new modular units, and in their work is concentrated to produce the requested characteristics of materials, in order to fulfill the requested function of the final product.

Planetary Science decomposes the Planets to structural hierarchy levels: a typical sequence:

I have a favorite example when I introduce NASA lunar samples in a course. This is a geological sequence of the representative structures. The decomposition of the structures is a natural step in geology, because it studies parallel larger and smaller material units then the size of the man. Larger units are the geological strata, the rock bodies forming the units of stratigraphy. Geologist goes to the field and takes a rock sample, delivers it to his/her laboratory and decomposes it: for example he/she makes a thin section from the rock, studies the texture. Texture in the optical microscope reveals the final structure: it decomposes rock texture to minerals. In another method geologist may decompose the rock to a powder, and the smaller mineral unit components can be identified by X-ray technology. This way an even smaller unit, the unit cell is revealed.

Another sequence of decomposition may result in chemical composition. The levels of the smaller and smaller hierarchy units are revealed and collected to libraries. Recently we use them as examples to show the structural hierarchy studies by geologist. But during the decompositional sequence several other disciplines were touched: mineralogy, radiation physics, chemistry. Structural hierarchy connects natural sciences. This makes it visible: structural hierarchy is an interdisciplinary subsystem in sciences. More detailed analyses can involve magnetic hierarchy from magnetic minerals, through magnetic domains to the magnetism of elementary particles (atoms, nucleons, electrons). Structural hierarchy helps to arrange decompositional levels into an integrated overview, where the main operation is the embedding sequence. We sketched this sequence in a geo, chemo, physico disciplinary line. We show a visual representation from the Earth, which is decomposed to its largest subsystems, the geospheres (Fig. 1.). Further decomposition continues with the subdivision of the lithosphere (in its surface regions) by stratigraphy. Taking one unit stratum from the stratigraphy, the decomposition continues from rock specimen to texture (in thin section), minerals, and subunits are represented by examples. (several branching can be involved if we consider other methods of decomposition in the sequence:- magnetic, chemical, radiation type).

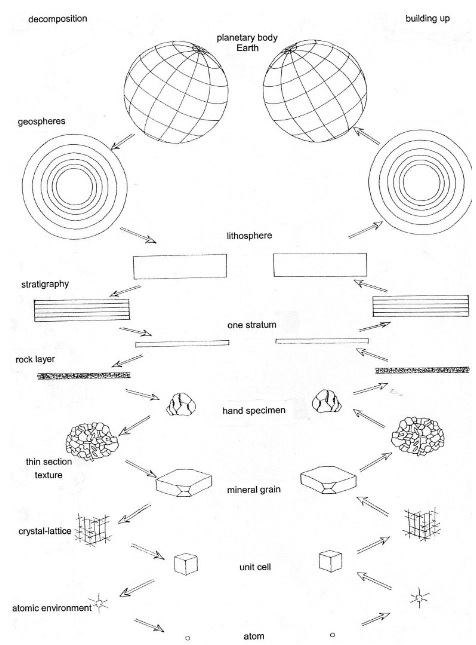

Fig. 1. A decompositional sequence (embedding sequence) of the planetary body Earth.

Permanencies of a structural hierarchy represent an embedding sequence. We may correspond various sets to the hierarchy levels (for example the Periodic table to the level of atoms, or the table of nuclides to the isotope level of the atomic nuclei). Moreover, the corresponding abundances of that set can be associated also with that level. In this sense our structural hierarhical table will be a large summary of that region of materials: not only the decompositional sequence is in front of us, but the variational sets, the cosmic, or terrestrial (or region specific) abundances. This system can be further extended by the observational methods and the technologies (instruments, production technology steps in the table: interdisciplinary tabulation is organized,). We show a decompositional sequence for a planetary body (Earth, Fig. 1.).

Structural hierarchy and the time sequence of the layers: Recognition of the multiple hierarchy levels of materials structures has a correspondence to the science event-history. We contracted this history into a figure, which explain the main events according to geology, where the startification is given as a linear sequence. (principle of law of sedimentation, Nicolaus Steno, 1669) Axiomatic geology started as a science of layers of rocks. (Dudich, 1997).. Fig. 2. demonstrates this series of steps. Actual application of the Steno principles in planetary geological mappings were for the Moon (Wilhelms, McCauley, 1971, Wilhelms, 1987):

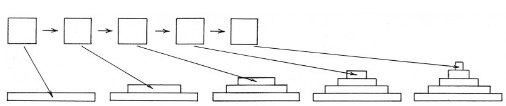

Fig. 2. The first law of Steno The sequence of events and the produced stratification of the corresponding layers according to the history sequence.

In his historical paper (written in Florence) Steno formulated another law: the law of embedding of the inclusions. If a rock includes another rock, then the included rock is isochronal or older, than the rock which embeds it (Steno, 1669).

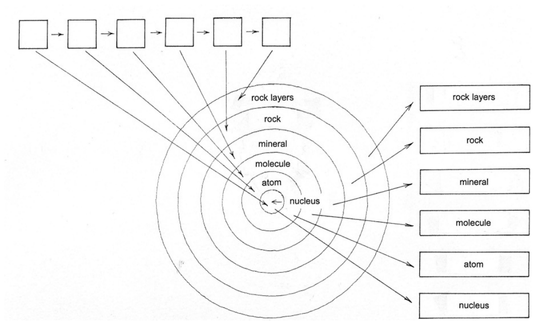

Fig. 3. The second law of Steno. In an extended form we sketch the inner structure of materials by this multiple structural hierarchy representation, using as many levels, as we can measure. The sequence of discovery as historical events of decomposition of this multiple hierarchical structure happened in a reverse direction as compared to the building up the sequence: mankind first discovered the mineral and molecular layers etc. to deep structure.

This embedding sequence forms a series of the inclusions which form a series in many respects similarly to the First law of Steno. However, in this second law the inclusions may be smaller – even with orders of magnitude – as compared to that one, which begins the inclusion's series. The inner structure of the real world materials is built up according to such a sequence, in the sense of Steno 2nd law. Sequence of events of embedding can be represented not only by the Fig. 2. style, but by the Fig. 3. style, formulated by concentric embedding circles, too. (Fig. 3.).

Connecting of two systems of disciplinary hierarchies: cooperation of geology and biology.

The advancing discoveries of geology happened in a joint work with biology while geologist recognized and reported the included fossils (paleontology). Fossils (belonging to another discipline) helped extension of the inclusion principle to a discipline running parallel, when the startigraphy of geological layers had been determined. Not only startification but the fossil assembly of a stratum helped in definition of a layering period. (fossil communities, Lyell and Smith) Changing of the assembly of the fossils - compared to the recent living forms - gave a series of fix points to biologist to identify a sequence, which was used to discover the law of evolution by Darwin (1859) and Wallace. Geology and biology helped them to recognize their mutual connections in identifying historical events in both disciplines. The geology and biology recognized the possibility of studying mutual dynamics of evolution of two structural hierarhical systems. This resulted in benefits for geology (the law of correlation) and for biology (evolution). Both disciplines worked together in clarification of the law of evolution.

Summary: If this multi-hierarchical structural systematics will be extended as a standard for the planetary science overview and experiments planning, than the fitting of the material levels will grow into the thinking almost automatically.

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The Terraforming Timeline. A. J. Berliner[1] and C. P. McKay[2], [1]University of California Berkeley, Berkeley, CA 94704, aaron.berliner@berkeley.edu, [2]Space Sciences Division, NASA Ames Research Center, Mountain View, CA 94075.

Introduction: Terraforming, the transformation of a planet so as to resemble the earth so that it can support widespread life, has been described as a grand challenge of both space sciences and synthetic biology [1,2]. We propose the following abstract on a Martian Terraforming timeline as a guide to shaping planetary science research over the coming century.

Terraforming Mars can be divided into two phases. The first phase is warming the planet from the present average surface temperature of -60ºC to a value close to Earth's average temperature to +15ºC, and recreating a thick CO_2 atmosphere [3,4,5,6] This warming phase is relatively easy and quick, and could take ~100 years. The second phase is producing levels of O_2 in the atmosphere that would allow humans and other large mammals to breath normally. This oxygenation phase is relatively difficult and would take 100,000 years or more, unless one postulates a technological breakthrough [6].

Pre-Terraforming: Before any terraforming begins, some basic questions must be addressed by robotic and human missions to Mars. These are: (1) The amount of H_2O present on Mars? (2) The amount of CO_2 present on Mars as gas, as ice, or absorbed on soil? (3) The amount of nitrate in the soil on Mars? (4) And, finally, the presence of life, alive or revivable, and the relationship of that life to Earth life. The answers will be crucial to planning any terraforming effort. However, there is also a fundamental question about terraforming itself that we must answered on Earth before terraforming can begin: . (5) What is the purpose and ethical approach for making Mars habitable? It may be impossible to arrive at a unanimous and definitive answer for this, but at the least we need an operational consensus.

Adequate inventories of water, carbon dioxide, and nitrogen (nitrate) present on Mars are key to the practicality of making a biosphere on that planet. We know that Mars has enough H_2O to supply clouds in the sky, rain, rivers and lakes. Presently, this H_2O is mostly in the form of ice in the polar regions and polar caps, but once Mars is warmed this will melt. Carbon dioxide is needed to provide a thick atmosphere to contribute to the warming and which will constitute the thick atmosphere at the end of the warming phase. While CO_2 may be present on Mars in vast quantities tied up in carbonate minerals, this form is not easily released as gas in the warming phase. Only the CO_2 that is easily released as gas as the temperature increases will contribute to the atmosphere during the warming phase. This includes the small amount of CO_2 in the present atmosphere, the CO_2 that is contained in the polar caps, particularly the winter South Polar Cap, and any CO_2 that is absorbed into the cold ground in the polar regions. Once the warming starts all this releasable CO_2 will go into the atmosphere. Thus, it is important to know the total before warming starts. Current estimates of the releasable CO_2 on Mars today range from a little more than the present thin atmosphere to values sufficient to create a pressure on Mars equal to the sea level pressure on Earth. Nitrogen is a fundamental requirement for life and necessary constituent of a breathable atmosphere. The recent discovery by the Curiosity Rover of nitrate in the soil on Mars (~0.03% by mass) is therefore encouraging for terraforming [7]. The current measurements only pertain to surface samples at the Curiosity site but include windblown sand and ancient sedimentary mudstones. For terraforming we need to know the total amount on the planet and given the high solubility of nitrate it may well be concentrated in specific locations.

The presence and nature of life on Mars will definitely affect plans for terraforming. If there is no life on Mars, then the situation is relatively straightforward. However, even after extensive exploration it may be hard to conclude that life is completely absent on Mars rather than simply not present at the specific locations investigated. If life is discovered, then the nature and relationship between the Martian life and Earth life must be determined. If Martian life is related to Earth life – possibly due to meteorite exchange --- then the situation is familiar and issues of what other types of Earth like to introduce and when must be addressed. However, if Martian life in unrelated to Earth life and clearly represents a second genesis of life then significant technical and ethical issues are raised.

The question of possible Martian life leads to the fifth question that must be addressed before terraforming begins. But the overarching question is why, and for who whom, are we altering Mars? If we are determined to make Mars like the present Earth – as implied in the word "terraforming" – then this requires certain levels of O_2 and places upper limits on toxic gases such as CO_2. Alternatively, if we are interested in making Mars a planet rich in life, but not necessarily a world in which humans can move about unprotected, then the presence of a thick CO_2 may be an adequate goal.

Warming Phase (~100 years): The primary challenge to making Mars a world suitable for life is warming that planet and creating a thick atmosphere. A thick warm atmosphere would allow liquid water to be present and life could begin. Warming an entire plant may seem like a concept from the pages of science fiction but in fact we are demonstrating this capability on Earth now. By increasing the CO_2 content of the Earth's atmosphere and the addition of super greenhouse gases we are causing a warming on Earth that is of order a many degrees centigrade per century. Precisely these same effects could be used to warm Mars. Warming the Earth was not the intended purpose of either the CO_2 release or the use of super greenhouse gases by humans and indeed we are now seeking to limit both effects. On Mars we could purposefully produce super greenhouse gases and rely on CO_2 released from the polar caps and absorbed in the ground. The result would be a thick warm atmosphere on Mars. The timescale for warming Mars after a focused effort of super greenhouse gas production is short, only 100 years or so. Effectively, greenhouse gases warm Mars by trapping solar energy. If all the solar incident on Mars were to be captured with 100% efficiency, then Mars would warm to Earth-like temperatures in about 10 years. However, the efficiency of the greenhouse effect is plausibly about 10%, thus the time it would take to warm Mars would be ~100 years. This assumes, of course, adequate production of super greenhouse gases over that entire time. The super greenhouse gases desired for use on Mars would be per fluorinated compounds (PFCs) as these are not toxic, do not destroy ozone, will resist dedgradation by ultraviolet life, and are composed of elements (C, S, and F) that are present on Mars [8]. Fluorine has been detected on Mars by Curiosity [9]. The Warming Phase on Mars results in a planet with a thick CO_2 atmosphere. The thickness is determined by the total releasable CO_2 present on Mars. The temperatures are well above freezing and liquid water is common. An Earth-like hydrological cycle is maintained. Photosynthetic organisms can be introduced as conditions warm and organic biomass is thus produced. A rich flora and fauna are present. A natural result of this is the biological consumption of the nitrate and perchlorate in the Martian soil producing N_2 and O_2 gas. While the pressure is high enough that humans do not need a space suit, they need a gas mask to provide O_2 and prevent high levels of CO_2 in the lungs.

Oxygenation Phase (~100,000 years): To alter the thick CO_2 atmosphere of Mars produced in the Warming Phase to allow for humans to breathe naturally requires that the O_2 levels be above 13% and the CO_2 levels be below 1% of sea level pressure. The high O_2 and low CO_2 levels on Earth are due to photosynthesis which uses light to power the following transformation [$H_2O + CO_2 = CH_2O + O_2$] Where CH_2O is a chemical representation of biomass. If all the sunlight incident on Mars was harnessed with 100% efficiency to perform this chemical transformation it would take only 17 years to produce high levels of O_2.

However, the likely efficiency of any process that can transform H_2O and CO_2 into biomass and O_2 is much less than 100%. The only example we have of a process that can globally alter the CO_2 and O_2 of an entire plant is global biology. On Earth the efficiency of the global biosphere in using sunlight to produced biomass and O_2 is 0.01%. Thus the timescale for producing an O_2 rich atmosphere on Mars is 10,000 x 17 years, or ~ 170,000 years. In the future, synthetic biology and other biotechnologies may be able improve on this efficiency, reducing this to about 100,000 years. The 0.01% efficiency of the biosphere represents an ecological constraint, averaging over oceans, deserts and forests. The intrinsic efficiency of photosynthesis in terms of a unit leaf is much higher, about 5%. If this could be utilized over the entire area of Mars (an unlikely possibility) then the timescale for O_2 production becomes a few hundred years [6].

Next Steps: Given the long-term timeline of a possible terraforming endeavor, we propose the development of a roadmap that outlines the technological processes and advancements required including: (1) adaptation of current and future robotic Martian missions for measuring specific elemental and mineral samples such that a geolocated Martian resource database can be constructed; (2) mathematical modeling of Martian terraforming such that both Martian and Terran resource costs can be calculated for a specific set of terraform-related reactions; (3) development of computational models for biological metabolism under specific conditions in line with the Mathematical terraforming conditions; (4) a focused synthetic biology initative for engineering organisms for Martian in-situ resource utilization; (5) Earth-based experimental systems for emulating Martian conditions for local testing of biological and chemical processes; (6) development of localized para-terraforming systems for evaluating processes in a controlled area on Martian surface and subsurface via probes; and (7) a planetary protection agreement describing restrictions of terraforming processes such that Mars can be maintained for future studies and terraforming can be explored beyond experimental and computational means. We realize that such a roadmap will require the input from many communitites within space scienes, astrobiology, geosciences, and biological sciences. Thus, we argue that, in light of the lengthy timeline outlined above, that we "might as well start now"[10].

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HARNESSING WATER AND RESOURCES FROM CLAY MINERALS ON MARS AND PLANETARY BODIES. J. L. Bishop, Carl Sagan Center, SETI Institute (189 Bernardo Ave., Suite 200, Mountain View, CA 94043, jbishop@seti.org).

Introduction: Clay minerals provide a source of water, metals and cations that can be harvested to provide resources for human exploration on Mars, asteroids and other planetary bodies. Planning how to access these resources from clays could be a vital component of future human exploration. Mark Whatney (*The Martian*) missed an opportunity to extract resources from the clays and other minerals on the surface of Mars. We need to prepare for this opportunity through experiments on clays and other minerals that represent potential resources for human missions.

Clay Minerals in our Solar System: Phyllosilicates are common aqueous alteration products on Earth, and are also present in thousands of locations on Mars and in a few meteorites, asteroids and comets. Clay minerals are readily detected from orbit or remote sensing by the distinctive OH and H_2O bands in near-infrared (NIR) spectroscopy [e.g. 1]. Clay minerals have been detected on the asteroid Ceres [2,3] and in some chondrites and Martian meteorites [4-6]. Nontronite clay was also detected at comet Tempel-1 using mid-IR spectra [7].

Clay Minerals on Mars: The martian surface is covered with clay mineral exposures wherever the ancient rocks are visible [e.g. 8-10]. Fig. 1 illustrates how these clays may have formed on early Mars when liquid water was present on the surface. The Mawrth Vallis region exhibits clay-bearing rocks that likely formed in such aqueous environments (Fig. 2). These phyllosilicates were buried over time and are exposed on the surface where the caprock is eroded. Clay minerals may have also formed in subsurface environments in some locations such as Nili Fossae [11].

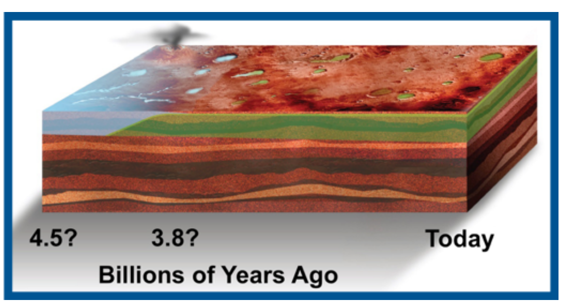

Fig. 1 Diagram of clay formation on Mars. Phyllosilicate formation was likely a pervasive process in aqueous environments on early Mars (<~4 Gyr). Subsequently, much of the phyllosilicate-bearing unit was covered and the water disappeared. Thus, phyllosilicates may be even more wide-spread just below the surface on Mars [12].

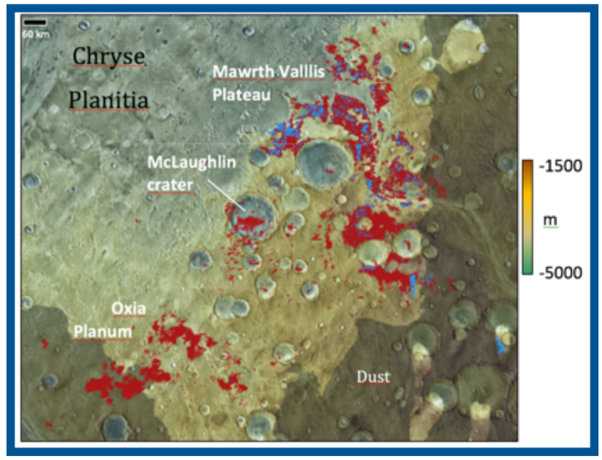

Fig. 2 Regional clay-rich outcrops across Chryse Planitia. Fe/Mg phyllosilicates are mapped in red over MOLA terrain and include nontronite, saponite, chlorite and serpentine. Al/Si-rich alteration products are shown in blue, and are comprised of kaolins, smectites, opal and allophane [1].

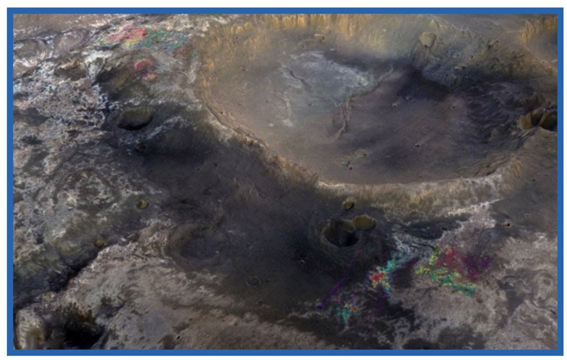

Fig. 3 View of light-toned phyllosilicate-rich material at Mawrth Vallis. This HRSC stereo mosaic shows the abundance of clay-bearing light-toned terrain exposed on the surface. CRISM parameters are overlain to indicate variations in the clay minerals and hydrated phases present [13].

Phyllosilicates on Mars are frequently observed in light-toned, layered outcrops, such as those in the Chryse Planitia region (Figs. 3-4). Typically Fe/Mg-smectite clays are present as a thick unit lower in the clay stratigraphy, while sulfates and Al/Si-rich materials are often present in upper units [e.g. 10, 12]. This stratigraphy is especially well documented in the Mawrth Vallis region. Poorly crystalline aluminosilicates (e.g. allophane, imogolite) exist at the top of the clay stratigraphy here (Fig. 4) [14] and are abundant surface components at Gale crater as well [e.g. 15].

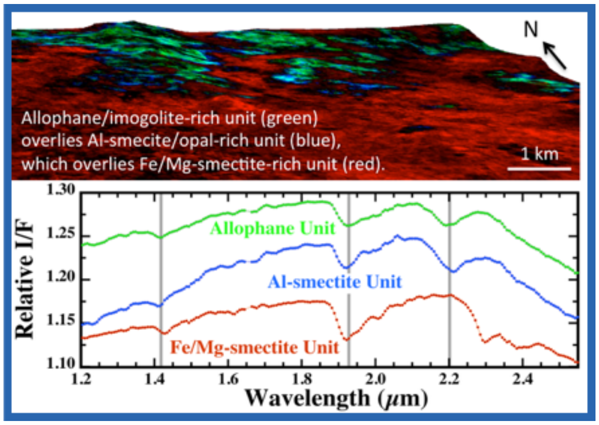

Fig. 4 Variations in clay units at Mawrth Vallis. This 3D view of CRISM image FRT0000AA7D displays the allophane/imogolite unit above the crystalline clay-bearing units with 5X vertical enhancement [14]. The spectra illustrate shifts in the bands for the allophane/imogolite-rich unit (1, green), the montmorillonite/hydrated silica unit (2, blue) and the Fe/Mg-smectite unit (3, red). Grey lines mark bands near 1.41, 1.92-1.93, and 2.19-2.20 µm.

Resources Available from Clay Minerals: Phyllosilicates are composed of sheets of FeO/OH, MgO/OH, or AlO/OH in octahedral configurations connected to sheets of connected SiO_4 tetrahedra (Figs. 5-6). Smectite clays have a layer of H_2O molecules bound to Na or Ca sandwiched in between the metal-bearing sheets and adsorbed H_2O on all surfaces. This adsorbed water is typically released ~100-150 °C and the bound water can be harvested by heating to ~300 °C [e.g. 16]. Retrieving water from poorly crystalline aluminosilicates is even easier because of the reduced structural integrity and high surface area [e.g. 17].

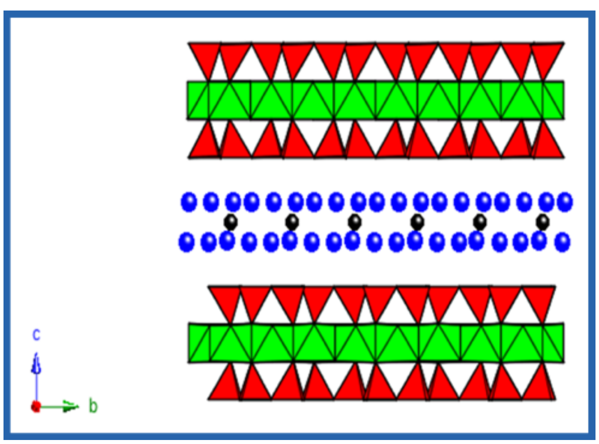

Fig. 5 Mineral structure of smectite clays. This diagram illustrates the water molecules (blue) and Na/Ca cations (black) in the interlayer region (blue), metal cations in the octahedral layer (red), and Si in the tetrahedral layer (green) [18].

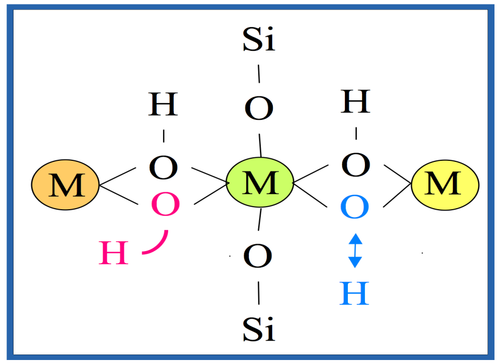

Fig. 6 OH bonds in phyllosilicate structures. This diagram illustrates the bonding configuration of the octahedral layer [from 18]. The OH stretching (blue) and bending (pink) motions have vibrational energies that depend on the type of metal cations (M) occupying the octahedral sites in the mineral structure.

What is Needed Now: Preparation for future human missions should include plans for harvesting resources from the surface rocks. Hydrated clay minerals and the associated poorly crystalline aluminosilicates are abundant at the surface and near surface on Mars. We need to document their global presence more precisely with future NIR imaging spectrometers (at least 1.2-2.6 µm) and characterize clays and associated hydrated phases at the landing site with VNIR spectroscopy (~0.4-4 µm). Lab experiments are also needed to determine optimal procedures for extracting water, cations and metals from clays and related minerals.

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THE ROLE OF ECONOMIC GEOLOGY IN THE FUTURE OF SPACE RESOURCES. Brad R. Blair[1], [1]NewSpace Analytics LLC, 60 Old Schoolhouse Rd, Canterbury, NH, 03224, <planetminer@gmail.com>.

Abstract: The field of economic geology is rich with experience for the space and planetary surface frontier. The industrial development of the mineral resources of the Moon, Mars, asteroids and comets could offer unprecedented access to scientific samples for tomorrow's planetary scientist and economic geologist. Productive and balanced geoscientific partnerships exist today between academia, industry and government research. The U.S. Geological Survey (USGS) and Minerals Management Service (MMS) facilitate advanced scientific research that bring new types of mineral wealth into the U.S. economic sphere. Impartial government and university research geologists partner with the mining and energy industries to gain intimate access to 3D information (mineral samples and geologic context) at minesites and boreholes across the U.S.A. and its terretorial waters. Experience from these successful public-private partnerships can inform future NASA science missions by making advanced methods and tools available that have worked well in the past. These include lessons learned for science valuation methods and can inform and calibrate program-level and architectural tradeoffs with real-world data.

Analogies will be offered that could illuminate a future leadership path for NASA that is based on historical USGS and industrial partnership experience. Commercial development of lunar resources offers advanced off-budget access to the space researcher that leverages private funding to dramatically increase scientific return. Indeed, a feasible path to the economic development of space mineral resources has been illuminated by decades of NASA-led scientific exploration, starting with the stellar Apollo human missions and precursor robotic programs.

To provide a context for discussing future roles for NASA, academia and private industry, conceptual scenarios will be offered as quad charts that visualize future mining and resource utilization on planetary surfaces, interiors, atmospheres, etc. This will be balanced by a year 2050 space infrastructure and customer forecast that includes orbiting shipyards, refueling nodes, tourism and colonization. Metrics will be offered in order to estimate commercial progress toward critical milestones in order to can calibrate schedules and adjust expectations. There will be a specific focus on the type and quantity of geologic data that will be associated with a planetary minesite based on mining industry practices and standards.

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DEFINITIVE MINERALOGY OF ROCKY AND ICY PLANETS AND PLANETESIMALS USING POWDER X-RAY DIFFRACTION. D.F. Blake[1] and P. Sarrazin[2], [1]Exobiology Branch, MS 239-4, NASA Ames Research Center, Moffett Field, CA 94035 (david.blake@nasa.gov), [2]SETI Institute, Mountain View, CA 94043.

Introduction: More than simple compositional analysis, definitive mineralogical analysis can provide information about habitability: T, P conditions of formation, present/past climate, water activity, the activity of biologically significant elements and the like.

Powder X-ray diffraction is a general purpose mineralogical technique that can provide definitive, quantitative mineralogical analysis of nearly any conceivable mineral assemblage without recourse to or dependence on other data or measurements. Definitive mineralogical analysis through the determination of crystal structure (i.e., powder XRD) is the standard to which all other techniques are compared. If an unknown phase (or an inorganic compound not classified as a mineral on Earth) is identified by itself or in a simple association, it can be fully characterized by structural (XRD) analysis without recourse to other data, because XRD relies on principles of atomic arrangement for its determinations. Chemical, optical, calorimetric or oxidation state data are seldom definitive because chemical compositions, optical emission/absorption features, calorimetric data or valence information can represent a range of substances or mineral assemblages.

Minerals are uniquely defined by their structure, and, as a result, cation valence states, site occupancies and bonding types (which are a consequence of structure and symmetry) can often be unequivocally determined. Redox-sensitive elements such as Fe and Mn can also often be quantitatively measured, independent of compositional data. Likewise, minerals that can have a variety of hydration states and are difficult or impossible to identify by other methods, have unique and easily distinguished XRD patterns (e.g., the $CaSO_4.nH_2O$ series anhydrite, bassanite, gypsum or the $MgSO_4.nH_2O$ series keiserite, sanderite, starkeyite, pentahydrite, hexahydrite, epsomite). Minerals that exhibit a solid solution between compositional end-members (such as the olivine series forsterite-fayalite ($MgSiO_4$-$FeSiO_4$)) can be identified and the degree of cation substitution established using diffraction data. Polymorphism such as occurs in the SiO_2 system and order-disorder relationships such as occur in the potassium feldspar series can be identified and quantified. These structural and compositional variants, once identified, can be related to environments of formation that can be used to assess present or past habitability.

On icy planetesimals and the Ocean Worlds such as Europa, XRD can uniquely identify type I and II water ice clathrates [1], amorphous, cubic and hexagonal water ice [2] in addition to simple gas hydrates.

Modern XRD methods are able to quantify the abundances of all minerals in a complex mixture using full-pattern fitting methods such as Rietveld refinement [3]. When X-ray amorphous material is present, other full-pattern fitting methods such as FullPat [4] can be used to quantify the relative amount of amorphous material. When combined with XRF data, these types of analyses will yield as complete a characterization as is possible, by any spacecraft-capable technique.

The CheMin instrument on MSL: CheMin, the first XRD instrument flown in space, has been operating on Mars for more than 4 years as one of MSL's laboratory instruments. CheMin data were used to establish the quantitative mineralogy of the Mars global soil [5,6], to discover and characterize the first habitable environment on another planet [7,8], and to provide the first in situ evidence of silicic volcanism on Mars [9]. The instrument is now being used to systematically sample and characterize the depositional and diagenetic environments associated with the mudstone sediments that comprise the lower strata of Mt. Sharp.

Sample preparation for X-ray Diffraction: Conventional powder XRD requires a sample comprised of a myriad of small grains (ideally $>10^6$ grains with a grain size <10 µm) presented in random orientations to the X-ray beam. In CheMin, sample cells are vibrated at sonic frequencies that cause loose powder held between two X-ray transparent windows to pass through a 50 µm diameter X-ray beam in random orientations over time. This turbulent grain motion relaxes the requirement for a large sample because individual grains can pass through the beam many times in different orientations, and allows powders ≤ 150 µm to be analyzed. Nevertheless, a CheMin geometry instrument still requires mechanisms to collect, crush and sieve samples before analysis. However, other diffraction geometries are possible and have been designed to require little to no sample preparation prior to analysis.

Alternative XRD geometries: In the early days of X-ray diffraction when only film methods were available, a large number of camera designs were developed with special geometries for particular purposes. Many of these geometries can be realized using the same three basic elements present in CheMin – X-ray source, sample holder and CCD imaging detector.

Guinier XRD. A high-resolution, high-throughput XRD instrument based on a Guinier camera design using parafocusing geometry is being prototyped (fig. 1). As shown in fig. 2, the instrument can be built for both reflection and transmission geometries. While sample preparation is still required, the advantages of this geometry are improved XRD resolution from the focusing of the diffracted signal on the cylindrical detector and rapid data collection because a larger sample area can be analyzed without directly affecting 2-theta resolution. The main challenge in the development of this geometry is the requirement for a cylindrical 2D X-ray detector. Several designs are currently being investigated based on bent CCDs or X-ray optics.

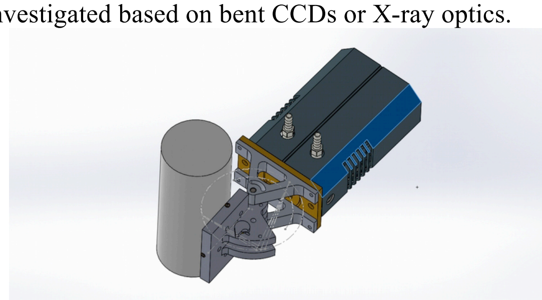

Fig. 1. Prototype Guinier XRD instrument built with COTS parts.

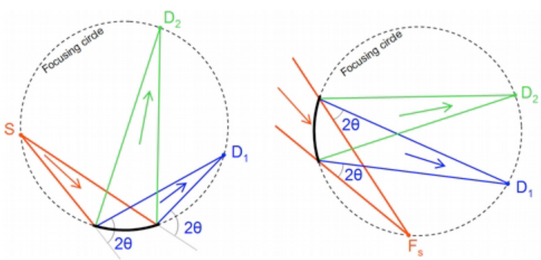

Fig. 2. Reflection and transmission geometries of a Guinier XRD.

XTRA (Extraterrestrial Regolith Analyzer): XTRA [10] (fig. 3) is designed to analyze fines in surface regolith without sample preparation. Fine-grained regolith coats the surfaces of most airless bodies in the solar system, and because this fraction is typically comminuted from the rocky regolith, it can often be used as a proxy for the surface as a whole.

Hybrid XRD. The hybrid instrument is designed to be placed on a rock or soil without a requirement for sample preparation. CCDs placed in a hemispherical arrangement collect diffracted photons (fig. 4). If the material is fine-grained enough, a powder XRD pattern is obtained, similar to CheMin or XTRA. With coarse grained crystals, the bremsstrahlung radiation striking the sample is diffracted into Laue patterns. The Laue spot energies are measured by the CCD and dedicated crystallographic software allows identification the minerals responsible for the diffraction (fig. 5).

Toward a high TRL tool-kit: the various geometries presented above all rely on similar basic components arranged and used in different fashions: a micro-focused X-ray tube and its high voltage power supply, a collimator or X-ray optics, a cooled CCD detector and its low noise driving electronics, and the software to extract crystallographic data from raw CCD frames. All basic sub-systems have been, or are being developed in partnership with the space systems and X-ray analytical industries. This approach enables quick turn-around and reduced cost in the development of future space-deployed XRD instruments.

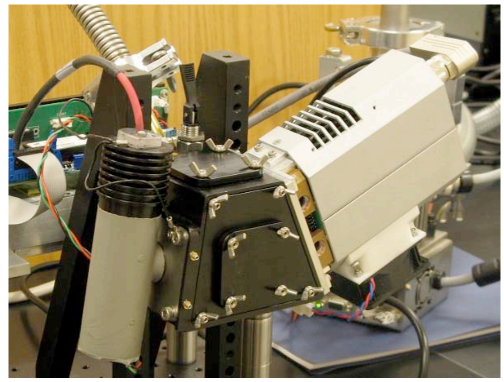

Fig. 3. Reflection geometry XTRA prototype instrument for use with unprepared regolith samples on airless bodies.

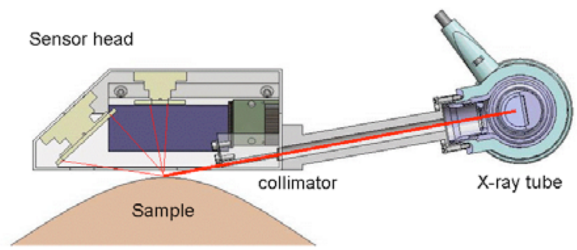

Fig. 4. Arm-mounted contact Hybrid XRD.

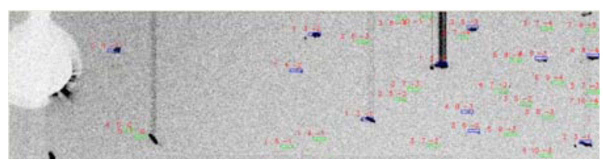

Fig. 5. Laue image of olivine marked with Miller indices found by the analytical software. Vertical lines result from spreading of X-ray signal during CCD readout at positions of intense diffraction.

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THE IMPORTANCE OF PARTICLE INDUCED X-RAY EMISSION (PIXE) ANALYSIS AND IMAGING TO THE SEARCH FOR LIFE ON THE OCEAN WORLDS.

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Introduction: Microbial life exploits microscale disequilibria at boundaries where valence, chemical potential, pH, eH, etc. vary on a length scale commensurate with the organisms themselves - tens to hundreds of micrometers. These disequilibria can exist within cracks or veins in rocks and ice, at inter- or intra-crystalline boundaries, at sediment/water or sediment/atmosphere interfaces, or within fluid inclusions trapped inside minerals. Detection of accumulations of the biogenic elements C,N,O,P,S at appropriate concentrations on or in a mineral substrate would constitute permissive evidence of extant life, but context is also required. Does the putative biosignature exist in a habitable environment? Under what conditions of P, T, and chemical potential was the host mineralogy formed?

In searching for evidence of life on Ocean Worlds, detection and/or quantification of the biogenic elements C, N, O, P, S, as well as the cations of the rock-forming minerals (Na, Mg, Al, Si, K, Ca, Ti, Cr, Mn, Fe) and anions such as Cl, Fl are important in establishing permissive evidence for life and context. In both terrestrial laboratories and landed planetary missions, these measurements are typically made with X-ray Fluorescence (XRF) or Particle Induced X-ray Emission (PIXE). While either an X-ray tube source (XRF) or a radioisotope source such as ^{244}Cm (XRF/PIXE) can be used for fluorescence, ^{244}Cm (used in all of the Alpha-Particle X-ray Spectrometer (APXS) instruments to date [1-4]) is preferred because the γ-rays at 14 and 18 KeV fluoresce the mid-range elements Ca – Mo, and the α-particles at 5.8 MeV strongly fluoresce the lower atomic number elements including C, N and O. With such a source, a florescence analysis would yield the biogenic elements C, N, O, P, S, as well as the cations and anions important for providing contextual mineralogy or chemistry. By comparison, an X-ray tube source operating in the 30 KeV range is typically very efficient at fluorescing higher Z elements but much less so for lower Z elements.

For spaceflight XRF applications, the use of a radioisotope source eliminates the high cost, complexity, risk, power requirement, thermal and vibration sensitivity and mass of an X-ray tube and HVPS – but brings with it the risks and safety precautions associated with handling ionizing and cancer-causing substances. The specific requirements of a particular space mission will dictate which source type would be more appropriate.

Scaling sources to meet science requirements: The fluorescent sources must be chosen and scaled to meet the science requirements of the application: Sufficient flux to meet detection limits for minor elements and accuracy/precision limits for major elements. Empirical measurements utilizing an XRF test fixture and modeling utilizing PyMCA [5], XMIMSIM [6] and GEANT4 [7] were used to determine source flux requirements for a variety of test cases. Fig. 1 shows a comparison of measured vs. modeled fluorescence of a NIST basalt standard with a 30 mCi ^{55}Fe source.

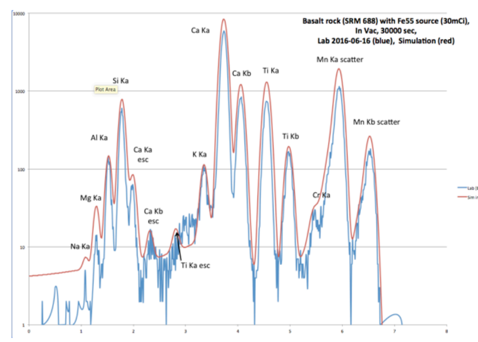

Fig. 1. XRF spectrum of NIST Basalt 688 obtained using a 30mCi ^{55}Fe γ-ray source measured in vacuum in an XRF test fixture (blue) vs. XMIMSIM simulation (red).

Figure 2 shows a comparison of modeled vs. measured fluorescence from a basalt sample using 30mCi ^{244}Cm. Modeled α-particle excitation is shown in blue in fig. 2a, illustrating the strong fluorescence of low-Z elements afforded by PIXE.

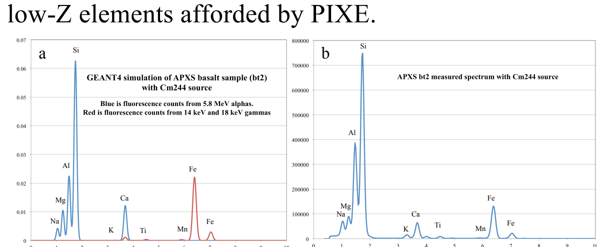

Fig. 2. Comparison of fluorescence from basalt sample bt2 using: (a) 30 mCi ^{244}Cm source with 5.8 MeV α-particles (shown in blue), 14 and 18 KeV γ-rays (shown in red) modeled with GEANT4 vs. (b) published fluorescence data from the APXS instrument.

Calculation of k-values for detection and quantification of elements of interest: We used GEANT4 to model fluorescence of the biogenic elements and cations of the rock forming minerals with a 30 mCi ^{244}Cm source. Calculations shown in Tables 1 and 2 assume integration over a sample area of 2 cm X 2 cm and an accumulation time of 10^4 sec (~3 hours). The accumulation time for Table 3 was increased to 10^5 sec (~28 hours).

We calculate the significance level k as the number of counts in a characteristic peak divided by the square root of the background below the peak. k>2 signifies successful detection at the 95% confidence level, k>10 signifies successful quantification. Tables 1a and 1b show results for rock matrices and Tables 2-3 show results for ice matrices.

Element	Energy (KeV)	k-value (Basalt Matrix)	k-value (Silica Matrix)
P Kα	2.02	1.9	1.9
S Kα	2.31	3.8	4.2
Cl Kα	2.62	3.0	4.2
K Kα	3.31	3.5	3.9
Ti Kα	4.51	1.4	3.9
Cr Kα	5.41	2.3	5.6
Mn Kα	5.90	1.7	8.4

Table 1a: Significance level k of Kα peaks in two different rock matrices for trace element detection @ 100 ppm; k>2 indicates detection at 95% confidence level. 30 mCi ^{244}Cm source, 10^4 sec run time.

Element	Energy (KeV)	k-value (Basalt Matrix)	k-value (Silica Matrix)
Na Kα	1.04	140	170
Mg Kα	1.25	140	260
Al Kα	1.49	X	220
Si Kα	1.74	X	X
Ca Kα	3.69	240	210
Fe Kα	6.40	X	560

Table 1b: Significance Level k of Kα peaks in two different rock matrices for quantification of selected major elements, quantified to 1.0% ±0.1; k>10 indicates successful quantification. (X=when an element is present in significant quantity in the matrix, k can't be calculated by this method.) 30 mCi ^{244}Cm source, 10^4 sec run time.

Element	Energy (KeV)	Weight %	k-value
C Kα	0.282	0.1%	8.3
N Kα	0.392	0.1%	18
Na Kα	1.04	0.1%	23
Mg Kα	1.25	0.1%	33
P Kα	2.02	0.1%	80
S Kα	2.31	0.1%	72
Cl Kα	2.62	0.1%	57

Table 2. Significance level k for detection and quantification of biogenic and other low-Z elements present at 0.1% in a water ice matrix. 30 mCi ^{244}Cm source, 10^4 sec run time, k>10 indicates successful quantification.

Element	Energy (KeV)	Concentration	k-value
C Kα	0.282	1 microbe / 100X100 µm pixel	28
N Kα	0.392	1 microbe / 100X100 µm pixel	11

Table 3. Significance level k for detection and quantification of C and N on a zero background filter through which melted Europa ice has been filtered. 1 microbe per 100X100 µm pixel over a 2 cm X 2 cm area. 30 mCi ^{244}Cm source, 10^5 sec run time, k>10 indicates successful quantification.

Discussion: Monte Carlo simulations of ^{244}Cm (PIXE) fluorescence of the biogenic elements in rock and water ice matrices demonstrate the value of this technique to landed science on Ocean Worlds. Monte Carlo simulations of fluorescence using X-ray tube and/or radioisotope sources with γ-radiation only are shown to be inadequate for this application.

Historically, ^{244}Cm sources have only been manufactured in Russia, and an informal query of NASA centers indicates that a source of this type does not exist within the agency. To date, all quantitative elemental analyses on Mars since Viking have been obtained with ^{244}Cm sources, utilizing instruments contributed by other countries. We suggest that it is of strategic importance for NASA to develop such a source. Development will require the manufacture of a suitable curium compound (e.g., curium silicide), the development of an NRC-approved capsule having a thin foil cover to allow transmission of α-particles while blocking fission-induced sputtering of the material, testing the source and obtaining an NRC license for its use. Since the half-life of curium is 18 years, the sources can be manufactured and stored for long periods without loss of activity.

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Acknowledgements: This research was supported and sponsored by NASA/ARC's Center Innovation Fund (CIF) and NASA's PICASSO program (grant# NNX14AI28A).

PLANETARY EXPLORATION, HORIZON 2061: A JOINT ISSI-EUROPLANET COMMUNITY FORESIGHT EXERCISE. Michel Blanc[1], Ari-Matti Hari[2], Rafael Rodrigo[1], Norbert Krupp[2], Karoly Szego[2], John Zarnecki[1], the H2061 W.G., Air and Spaee Academy[4] and the Planetary Exploration Horizon 2061 team[3]. [1](International Space Science Institute, Bern, Switzerland, blanc@issibern.ch), [2](Europlanet Research Infrastructure), [3](http://www.issibern.ch/forum/europlanetforum/), [4](http://www.academie-air-espace.com/).

Introduction: We present the preliminary results of a foresight exercise initiated by the Air and Space Academy (Toulouse, France) and jointly implemented by the Europlanet Research Infrastructure project of the European Union and by the International Space Science Institute (ISSI). The objective of this exercise is to produce a community Vision of Planetary Exploration up to the 2061 horizon, which we will name H2061 for short. 2061 was chosen as a symbolic date corresponding to the return of Halley's comet into the inner Solar System and to the centennial of the first Human space flight: this date connects particularly well science and exploration. This Vision will be built on a concurrent analysis of the four "pillars" of planetary exploration:

(1) The **key priority questions** to be addressed in Solar System science;
(2) The **representative planetary missions** that need to be flown to address and hopefully answer these questions;
(3) The **enabling technologies** that will need to be available to fly this set of ambitious missions;
(4) The **supporting infrastructures,** both space-based and ground-based, to be made available.

In this fully science-driven approach, we will build our Horizon 2061 Vision in three following steps. In step 1, **an international community forum convened in Bern, Switzerland on September 13th to 15th, 2016 by ISSI and Europlanet identified the first two pillars: key questions and representative planetary missions**. In this forum, over 35 selected international planetary science experts met during two days with 9 international technology experts from space agencies and major industrial groups to identify the contents of these two pillars. The outputs of step 1 will be used as inputs to step 2, an open community meeting focusing on the identification of pillars 3 and 4 which will take place around the end of the year 2017. Finally, the four pillars identified by steps 1 and 2 will be discussed and compared in the "synthesis" meeting of step 3, which will take place in Toulouse, France, on the occasion of the European Open Science Forum 2018 (ESOF 2018). In this contribution we report solely, and for the first time, on the preliminary results of step 1.

Planetary Exploration Horizon 2061: scientific approach. Since 1995 and the discovery of the first exoplanet orbiting a main sequence star, we are living a revolution in planetary science: as of today, over 3000 exoplanets have been identified by a diversity of techniques, first by ground-based telescopes and more recently by space missions like Corot and Kepler. Many more are to come in the few decades ahead of us, bringing to our knowledge an ever larger number of exoplanets. Outstanding progress is expected not only in their detection, but also in their characterization. The continuously expanding sample of exoplanets to which we have access from our Earth-based observing point contains today more than 500 exoplanetary systems (e.g., systems displaying at least 2 exoplanets). This figure can be compared to the number of planetary systems we can explore in our Solar System: one can count five, one being the Solar System as a whole, and four others being the satellite systems of our giant planets, which are sort of "small solar systems in the large one". While the "exploration" of exoplanetary systems will remain the privilege of space-based telescopes and remote sensing techniques for a long time, space exploration opens a far more detailed access to a far more limited number of systems and of constituting objects in the Solar System. Linking these two uniquely complementary lines of research lays the foundations of a new type of comparative science: the science of planetary systems. Our foresight exercise is a contribution to this perspective.

Overarching goal of the study of planetary systems. We propose the following overarching goal to the comparative science of planetary systems and to the associated set of space missions:

Study the formation and evolution processes leading to the growth of complexity, and ultimately to the possible emergence of life, across the diversity of planetary systems.

More explicitly, we propose to study the emergence of life as a "close encounter of the most important kind" between (1) the growth of molecular complexity, from the Interstellar medium (ISM) to planetary and moon environments, and (2) the growth in complexity of planetary environments themselves, and the conditions under which their evolunationary paths may lead them to enter the "triangle of habitability"and to become "habitable".

Top research objectives. To address this goal, we propose to identify five complementary objectives: (a) study the initial conditions of planetary systems formation (in the ISM and during star and proto-planetary disk formation); (b) retrieve the different formation and evolution scenarios leading to the presently observed architectures of planetary systems, and particularly the formation of the different categories of objects (giant planets, terrestrial planets, small bodies/debris disk objects) and the resulting architecture; (c) develop a comprehensive study of the coupling mechanisms operating between the central object(s) and the different planets/satellites: gravitational/tidal interactions and their effects on the long-term evolution of the interiors and orbits of planets and satellites, electrodynamic interactions and their effects on planetary environments, with a special emphasis on the role of magnetic field and coupling processes at the level of astrospheres and magnetospheres; (d) study the respective effects of the intrinsic properties of planetary bodies and of their forcing by the planetary system coupling processes (just described) on the emergence of habitable zones and potential habitats; (e) implement strategies for the detection of life in the diversity of candidate habitats: surface habitats (e.g. on Earth-like planets in habitable zones) and deep habitats (e.g. in the sub-surface oceans of icy moons).

Setting the stage for exploration: the exoplanet context. The main objective of our H2061 foresight exercise will be to develop an implementation plan to address our five top objectives in the Solar System. We will do it by first placing Solar System exploration in the broader context of the comparative science of planetary systems. We will summarize the perspectives of exoplanet research for the coming decades and how they will address our five top objectives: from the initial focus on detection of new objects, exoplanet research will develop and use a diversity of techniques of increasing complexity to characterize planets to higher and higher degrees of detail, from "simple" estimates of their masses and radii to sophisticated diagnostics of their physical and chemical properties. Along this line the characterization of their atmospheres will benefit first from the spectacular on-going progress of high-resolution and multi-wavelength spectroscopy, while a characterization of their surfaces will wait for the emergence of new imaging techniques giving access to the needed very-high angular resolutions.

From research objectives and detailed measurement objectives: Solar System exploration. Space exploration offers a unique diversity of measurement techniques to address our five top objectives at three complementary hierarchical levels: individual objects, giant planets systems, and finally the Solar System itself with its gravitational mechanisms (overall system dynamics) and its electrodynamic mechanisms (heliospheric and magnetospheric interactions). We will tentatively identify the different measurement objectives to be assigned to an ideally coherent suite of planetary missions:

- critical measurements providing improved constraints on the origin and formation scenarios of the System and its components;
- measurements or suites of measurements leading to a detailed characterization of the structure and dynamics of the surfaces and interiors of planetary bodies;
- their counterparts for the characterization of their fluid and plasma envelopes ;
- critical measurements leading to the characterisation of surface or sub-surface habitats, with a focus on terrestrial planets and Ocean Worlds;
- and finally, strategies for the detection of extinct or extant life in these habitats.

Drawing the contours of a strategic framework for Solar System exploration. Space exploration tools offer to us a rich diversity of mission scenarios to perform these key measurements. In order of increasing complexity, one can identify the following "elementary" mission types:

- planetary and/or satellite fly-bys;
- planetary and/or satellite orbital reconnaissance;
- atmospheric descent probes and surface scientific stations;
- mobile vehicles at planetary surfaces;
- sample return missions.

We will conclude our study by associating these different types of missions to the requirements generated by the different measurement objectives: the result will be the description of the "left-hand-side columns" of a simplified Traceability Matrix describing an integrated framework for a science-driven approach to planetary exploration, up to the 2061 Horizon.

Acknowledgements: the authors of this contribution wish to extend their deep gratitude to the three institutions which made it possible to elaborate our H2061 planetary exploration perspective: the Europlanet Research Infrastructure project (a component of the Horizon 2020 framework programme of the European Union), the International Space Science Institute (ISSI) and the Air and Space Academy (AAE/ASA).

LONG TERM ENVIRONMENTAL MONITORING: NECESSARY STRATEGY AND INTEGRATED TECHNOLOGIES TO ENSURE SUCCESSFUL SCIENCE RESOURCE UTILI ATION AND PLANETARY PROTECTION DURING HUMAN EXPLORATION.

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Introduction: Within the next several decades humans are likely to be exploring planetary surfaces beyond low Earth orbit. A number of scenarios exist within human exploration architectures for both NASA and other space agencies that are relevant to the International Space Exploration Coordination Group (ISECG) [1]. NASA's human exploration focus is currently the Journey to Mars, with plans including repeat visits by human crews, a single location of habitation involving long duration stays, and a range of human exploration via traverses with pressurized rovers on the order of ~ 100 km from the primary habitat (currently called the Exploration Zone, or EZ) [2]. Even if the grand vision of the Journey to Mars is not fully realized, the likelihood of humans operating on the surface of planetary bodies to achieve scientific goals is high. Such an endeavor involving *in situ* human operations, especially on the surface of a planet with the possibility of past or extant life, will require an unprecedented collaborative effort between NASA's science, *in situ* resource utilization (ISRU) and planetary protection communities, the goals of which are sometimes seemingly contradictory.

Successfully enabling human-conducted science and resource utilization while maintaining planetary protection protocols will require new strategies and technologies. To fully address this topic requires discussion of policy and international agreements. *Here we discuss an element to this topic, long term environmental monitoring, which we consider to be a necessary approach to responsible human exploration of the Solar System*.

Rationale: Human exploration *in situ* on the Martian surface will enable unique scientific opportunities [3]. Humans will likely utilize local materials such as water to produce resources. However, the presence of water establishes Special Regions on the surface or sub-surface that could harbor extant or past life, requiring protection from human contamination. A human presence will alter the local Mars environment, as demonstrated by the Apollo Cold Cathode Gauge Experiment that showed elevated gas concentrations (2 order of magnitude) during the lunar daytime associated with human surface operations [4]. Current ISS testing includes characterization of gas and microbe leakage both from the ISS and from astronaut's space suits during EVA [5]. Thus, fully characterizing the pristine Mars environment prior to humans is a baseline requirement to which measurements can be compared after the human presence is established. Long term monitoring that begins prior to human operations will enable the most accurate understanding of the atmosphere, the surface mineralogy and geochemistry coupled with that atmosphere, and ultimately the response of the local environment to the human operations.

Strategy: The mineralogy and geochemical character of the exploration zone (EZ) tells part of the story about the habitability potential of the Martian environment for human explorers and possibly other accompanying Earth life. Physical aspects to the Martian environment that are also important— diurnal variation in ground and air temperature, cosmic radiation, solar irradiance, wind velocity and variability, atmospheric pressure cycles, surface stability with respect to hardness, slope, porosity, permeability, magnetic character and electrostatic charging are examples.

Any approach for human exploration must also include a comprehensive plan for monitoring both chemical and physical environmental dynamics as humans invariably alter the exploration zone, even if the goal is to alter that environment only minimally. We propose a long term interrogation of proposed landing sites from the perspective of the ease with which the integrated set of environmental monitoring measurements can be deployed in semi-permanent array at intervals around the exploration zone, with outward looking observation posts that extend the data set to include data relevant to human safety and environmental preservation at larger spatial scales. This requires the development of integrated instrument packages that are inclusive of needs from science, ISRU, and planetary protection.

Monitoring stations must be deployable robotically, well in advance of the human operations. The style of human-robot interactions is an ongoing topic of discussion, including operations by crew members in Mars orbit that can take advantage of low-latency operations [6, 7]. It should be stated that the goal of this strategy is to develop a robust monitoring package that can be replicated and deployed throughout the EZ and across multiple potential or actual EZs. Here, the goal is to recognize what level of detail is "good enough" for long term monitoring and focus funding on the development of numerous packages as opposed to a single instrument or instrument suite. Ideally, monitoring stations would not require physical interaction with humans but would monitor changes throughout the EZ as human operations commence. Furthermore, the ability to augment this effort by adding stations would enable a response to environmental changes. Distributed sensor networks can be piggybacked onto communication relay nodes that also enable global positioning, meeting three requirements for minimizing the risks associated with a sustained human presence at Mars.

Technologies: Because of existing datasets from Mars Science Laboratory's Rover Environmental Monitoring Station (REMS) [8] and what will have been acquired by ESA's ExoMars [9] and MEDA on NASA's Mars 2020 [10] missions (as well as potential TBD precursors), we have a good idea of the range of measurements that are relevant to the characterization of environmental dynamics. Ground and air temperature, relative humidity, atmospheric pressure, and variation of ionizing radiation are key measurements to make at a frequency of at least a few minutes per hour. Dust characterization and atmospheric loading and the presence and heading of dust devils are also important, as is monitoring the approach of dust storms. An upward looking observatory for tracking tau and other astronomical observations would also be important for understanding relationships between the dynamical elements of the environment. Monitoring surface sample chemistry and mineralogy as related to changes in the atmosphere (phase changes) will be critical and should be done in such a way as to enable routine evaluations of the toxicity of materials in the surface soils.

The physical response of the local geology to human operations must also be understood. ISRU processing could potentially redistribute significant surface mass as ice is converted to liquid or gas and transported to other locations. Offloading surface mass on Earth can create a seismic response, thereby requiring monitoring of seismicity. Futhermore, processing of frozen volatiles can create surface runoff or subsurface migration of liquids, which could lead to surface instability. Both cases could pose unforeseen hazards to human habitats, especially if seismicity is powerful enough to damage structures or initiate mass movements. Furthermore, liquid and gas release and migration should be monitored to assess plume migration and related surface/atmospheric chemistry variability.

Conclusions Other Considerations: Long term environmental monitoring of any planetary surface on which humans plan to operate should be a requirement of responsible human exploration [see also 11]. A challenge to this strategy is that this type of technology development can fall between funding programs, potentially leading to inadequate support or neglecting important concerns. It is critical that the science, ISRU and planetary protection communities continue interacting as has recently been initiated through numerous workshops inside and outside of NASA.

To support human survival, the Mars system should be considered in much the same way that the Department of the Interior and U.S. Geological Survey consider geologic frameworks as they relate to responsible land-use strategy for the United States of America. Resources must be responsibly used and proper protections put in place to ensure that harmful pollutants and human impacts do not impede the achievement of the science goals that motivated humans to go to Mars in the first place. It is possible that a changing environment could necessitate changing boundaries in special or protected regions. Hazard assessments might also change in real time. This will include new approaches to mapping and interrogation of the subsurface to ensure that Mars is not made less habitable upon the arrival of humans. Instruments exist to address these issues now or could be modified from existing hardware, and the Earth serves as a case study for properly conducting this approach elsewhere. Global communication and positioning will be key enabling infrastructure to ensure astronaut safety and mission success.

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PLANETARY SCIENCE TRAINING FOR NASA'S ASTRONAUTS: PREPARING FOR FUTURE HUMAN PLANETARY EXPLORATION. J.E. Bleacher[1], C.A. Evans[2], T.G. Graff[2,3], K.E. Young[2,3] R. Zeigler[2], [1]NASA's Goddard Space Flight Center, Greenbelt, MD, 20771 (jacob.e.bleacher@nasa.gov), [1]NASA's Johnson Space Center, Houston, TX, 77058, [3]Jacobs/JETS Contract, NASA JSC, Houston, TX,

Introduction: The scientific success of the Apollo Missions is a testament to the scientists, engineers and managers who developed the exploration architecture that accomplished their goals. There will be numerous differences between the Apollo Program and HEOMD approaches to surface science during future human exploration of the Solar System. However, many similarities will likely exist. The Apollo Program approach to preparation for science operations included extensive geology training, including over 1000 hours per crew member during the J-Missions [1]. Fielding well-trained crew members, particularly for those who do not possess a science background, was considered a major influence on the science success of those missions [1-4]. Although the Apollo geologic training program was discontinued in 1972, Space Shuttle crew-members received 40-50 hours of limited training in Earth observations prior to their flights [5]. In 2008, it was decided to revamp the geologic training curriculum to include more thorough classroom work and geologic mapping to improve the astronaut's observations skills and understanding of basic geological concepts. The two most recent astronaut candidate classes (2009 and 2013) received this improved geology training, and the Astronaut Office has also involved senior members in short field geology mapping courses and field assistant programs. The training curriculum and timeline are currently in development for the next class of astronauts to be selected in 2017, which includes geoscience based on lessons learned from the prior to classes. Here we discuss the current status of astronaut planetary science training and how this training will enable future planetary exploration.

Background: The current exploration vision within NASA involves development of hardware to carry humans to a series of possible destinations, with a long range vision of humans at Mars. One purpose of delivering humans to these destinations is to conduct scientific research, including planetary science involving *in-situ* field studies. As such, planetary science training at this time is primarily focused on basic geologic concepts as a means of enhancing observations and science that might be conducted from the ISS. The goal is not to train astronauts in lunar, asteroid or Mars science, but to begin training the mindset that all astronauts should know the scientific value of, and routinely consider the observations they can make from their unique vantage point. We plan to help develop a Crew Office within which consideration for science operations is the norm for all decision making steps during the development of the human exploration architecture.

Geology Training: Geology training for the astronauts can be generally divided among three main approaches, including: 1) class room teaching and field exercises, 2) a field assistant program, and 3) integrated analog field tests. Classroom and field exercises incorporate an "outcrop to orbit" perspective; whether the subject is structural geology or volcanology, all topical training integrates orbital observations. The field component of geology training is also integrated with a Crew Office requirement to routinely provide expeditionary training and team building experiences.

: Classroom training and field exercises are the primary mechanism for training during astronaut candidacy. The curriculum includes input from > 30 geologists both within and outside of NASA. Classroom training is focused on basic field geology concepts and for the 2013 class involved three weeks of classroom activities. Discussion of target specific science was provided in an historical context with respect past or currently active missions, such as Apollo, MER and MSL.

The approach to classroom training involves a daily focus on a single geologic discipline. Typically the crew are presented with a perspective of what they can expect to see from ISS, essentially a regional to global perspective from orbit. Lectures and activities become more focused on details within each discipline. The details are not presented as material to be memorized and retained but in a manner that enables the crew to understand why the observations they can make from ISS are important to scientists on the ground. For example, the crew are trained not to necessarily interpret that a volcano is rhyolitic but to explain that they see a volcano with steep, light toned flanks and a dark colored plume. The goal is to train scientific observational skills and an understanding of the value of those observations.

During classroom training each crew member constructs a preliminary geologic map of the field exercise area, a volcanic region of about 140 km^2, from remote sensing data. Most days are concluded by revisiting and revising the map on the basis of the geologic lessons that day. The end result is a well-constructed remote sensing map from which they develop field-testable hypotheses and plan their field activities.

Shortly after completion of classroom training the crew are taken into the field. Although the primary objectives are geological, living and working outdoors also provides opportunities for expeditionary training. With preselected field targets and their preliminary maps in hand, crew member pairs and a field geologist conduct geologic mapping, sample characterization and collection, and data collection with a range of geologic instruments. A geologic map and cross section that integrates both remote sensing and field observations are the final team products of these efforts. Results are later compared with published interpretation(s) for the site. Upon requests from the Crew Office, a similar approach has been adopted for senior members who joined the Astronaut Corp prior to the 2009 class. Field training exercises for this purpose have been conducted several times in the last few years with the intent of providing a baseline level of geologic training and experience for the entire Crew Office.

: Classroom training and field exercises provide a large group with a basic level of geologic knowledge. However, basic field exercises can lack a sense of "doing new science". To address this the field assistant program was developed. In this program members of the geology training team provide opportunities to the Crew Office for crew members to take part in small, basic field research projects. As field assistants the crew members are given an opportunity to experience the reality of testing multiple working hypotheses and dealing with the real-life difficulties of doing so. The participants are exposed to situations where field geologists disagree while discussing their observations in the field. This provides the field assistants with a realistic view of how geologists communicate and present their observations and develop testable hypotheses. The emphasis complements the goals of the classroom/field activities in which training observational capabilities is the goal. Because many of these projects are related to planetary analogs, the astronauts who participate are also given a chance to gain relevant planetary science knowledge, which they typically present to the Crew Office through briefings.

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The program described above has been in place informally since 2008, has trained two successive classes of astronauts, as well as having exposed engineers and managers to geologic field work, and is currently in place for the 2017 Candidates upon selection. In addition to geoscience training, the broader Astronaut training effort is utilizing field geoscience opportunities to expand and continue teamwork and management skills training. The popularity and success of this program supports the notion that geologic astronaut training be formally included in the astronaut training program. This is especially critical as a number of key members of the current training experts are nearing retirement age.

As the Planetary Science Vision develops and human exploration capabilities beyond LEO are realized it is imperative that the new scientific goals and technologies are integrated into the training program. The Crew Office has recognized the value and requested an increase in astronaut interactions with science instruments and tools, both to support ongoing objectives on ISS as well as preparation for future geoscience activities. The current training effort is designed to be highly flexible and responsive to the needs of the Astronaut Office in a rapid manner. This flexibility will also be critical moving forward with regard to the evolving Planetary Science Vision.

Conclusions: Field geology training was a fundamental aspect of the success of the Apollo Program. Astronauts of the Shuttle Program era received roughly one week of training related to orbital observations of the Earth. LEAG and CAPTEM recently recommended an increase in this training and the development of an official geology training program to ensure the science success of future human exploration programs. Geology training that was developed and implemented within NASA for the 2009 and 2013 astronaut classes included NASA personnel, US and State Geological Surveys and participants from academia. This effort builds upon the Apollo geology training, is reestablishing the links between NASA and professional geologists outside of NASA, and has exposed several early career participants to the institutional Apollo knowledge base that is now retired or might be retired over the next decade. The goals of the training program are to develop a Crew Office with a healthy understanding of how science fits within human exploration of the Solar System and to put in place and provide experience for the next generation of astronaut geology trainers.

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Origins and Life, The Next Steps Beyond the Initial Survey of Our Solar System. S. J. Bolton[1], T Owen[2], and J. H. Waite, Jr.[1], [1]Southwest Research Institute, [2]University of Hawaii.

Introduction:

These are the themes of the conference that this abstract focuses on:

ORIGINS — understanding formation and evolution of solar systems (including exoplanetary systems)

WORKINGS — understanding how the processes in our solar system operate, interact, and evolve

LIFE — improve our understanding of the origin and evolution of life, including Earth analogs, to guide our search for life elsewhere

Origins:

From Viking and Voyager, followed by our initial survey of nearby comets and asteroids and the outer planets, we have learned that our simple concept of how the solar system and life began is fraught with unanswered questions. A plan and outline for the next decades of key measurements within the solar system necessary to determine these fundamental truths is presented. We start with an overview of the importance of water throughout the universe, encompassing both the origin of life as well the more fundamental aspect of the fact that oxygen is the third most abundant element (of ordinary matter) in the universe following only Hydrogen and Helium. The importance and dilemmas of isotopic ratios and noble gases will be presented.

Abundance of Water on Jupiter: Implications

- Oxygen is the remaining key element abundance “unknown” from the Galileo Probe
- Oxygen discriminates among theories on how Jupiter’s heavy element enrichment occurred.
- Oxygen constrains mass of Jupiter’s molecular envelope

Giant Planets After Juno, Galileo and Cassini

To understand the origin of the Solar system we have to understand the origin of the Giant planets. We have a large amount of information about Jupiter and we are gaining more with mission Juno. To understand this fully we need a context and that means we need to study the Gas Giant and Ice Giant planets with the same level of detail. Understanding the atmospheric composition (enrichment of heavy elements) and the interior structure of the Saturn, Uranus and Neptune is essential.

We propose to use orbiters with probes. This would be essentially a combination of the Galileo probe carried by an orbiter with a payload similar to that of Juno. Sucha mission will satisfy our goals. To complete the picture of Giant planet origins we will need comparable missions to Saturn, Uranus and Neptune. We could reduce costs by developing a common spacecraft for missions to all three giants. Comparing the planets with more composition of the multiple asteroid, dwarf planets, and comet populations is required.

Small Bodies after Rosetta, Dawn and Deep Impact

To complete the picture of the Giant plant origins we need to know the composition of the planetesimals that form their cores. This means we have to study the asteroids, comets and the small icy bodies presently in orbit around the Sun. We now know that all comets are not alike and we have to gain an understanding of the variety of these objects.

The concept is to develop a fleet of small spacecraft/cubesat investigations to comets, asteroids, Trojans, Centaurs even KBOs – these investigations carry out as single purpose sentinels with specialized techniques for both remote sensing and in situ capabilities. For example, one could have a small s/c that performed long distance surveillance looking for volatile release. Results from the volatile survey govern decisions to deploy additional s/c for volatile investigation and mineralogical surveys. This would provide an efficient survey of a large number of small bodies, which is essential for determining the statistical variance of small bodies.

We therefore propose the development of three small spacecraft outfitted with three different instrument compliments. The first is a long range surveyor that contains a wide angle camera and a microwave/submillimeter for volatile detection and determination of the D/H ratio in water. The other two small satellites will provide the detailed reconnaissance of the identified targets. One of the small satellites contains an infrared camera primarily for detailed mineralogical analysis and the other small spacecraft contains a mass spectrometer for detailed volatile isotope and noble gas analysis of bodies identified by the surveyor as outgassing volaitles. Ideally the survey should permit visits to multiple targets (five comets and five asteroids).

Small bodies of major interest identified through this initial investigation can then be visited by a spacecraft with greater payload or sample return capability as warranted. In recent years, the concept of asteroids being rocks and comets being iced has been demonstrated to be incorrect. We now know there are main belt comets and asteroids that have volatile outgassing. It is essential to inventory the composition of all of these types of small bodies.

Future Missions and Science Goals

- Juno w/Probes at Saturn, Uranus and Neptune
- Missions that can obtain a Survey of Small Body Volatiles (survey D/H and isotopes at many comets, dwarf planets, and asteroids)
- Eventually, Sample returns of various categories and populations of Small Bodies

WORKINGS:

This topic overlaps with Origins, but it specifically covers the question of delivery of volatiles to the inner planets by small bodies. This requires the harvest of isotope information for hydrogen, oxygen, nitrogen and the noble gases as described above. It also covers the question of heavy element incorporation into the giant planets and how this changes as a function of heliocentric distance.

LIFE:

Mars Strategy

Search for life in regions that currently have liquid water. At Mars, we propose to search "damp" locations, collect samples for analysis in ultra-clean laboratories on Earth.

This approach to finding life on Mars has two fundamental improvements over previous attempts:

a. Samples have recently been in contact with Mars water.
b. Samples are analyzed by the most sensitive protocols on Earth.

Europa Strategy

Is there an ocean of liquid water beneath Europa's icy crust? If there is, is it possible that life has begun and survived in this environment?

Send a bomb to break a hole in the ice with a "chase plane-s/c" that follows it and takes movies of what happens. The chase plane could be equipped with an high resolution mass spec (i.e. MASPEX) to analyze the plume produced by the explosion. At that point, scientists can assess the situation and decide on the next step. This is the bottom rung of the ladder used to detect life on other worlds.

LIFE DETECTION IN BRINY ENVIRONMENTS: AN INTEGRATED APPROACH FOR ACCESSING AND DETECTING BIOMARKERS ON MARS AND IN THE SOLAR SYSTEM R. Bonaccorsi[1,2] , David Willson[2,3], A. Davila[1,2], C.R. Stoker[2], C.P McKay[2].
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Introduction: The upcoming NASA 2020 mission will seek evidence of fossil past life on Mars. Yet, no actual life detection mission has been planned for the next decade. The NASA vision for Space Exploration involves robotic missions to prepare for humans safely living and working on the Martian surface. Understanding if Mars is currently inhabited by dormant microorganisms, which may become active under transient conditions, and represent a potential biohazard for astronauts, should be a priority in the context of planetary protection.

Our 2020-2050 vision: Our vision for the late 2020's involves a suite of life-detection tools able to detect life in a variety of terranes, environments, and complex geological matrices (e.g., lab-on-the chip assays, microscopes, etc for life detection of indicators of metabolically active life (ATP, ADP, RNA, LPS, and maybe other universal poliphosphate biomarkers, etc). In this vision there are several keys aspects: 1. Mitigating recurring *life detection issues* arising from the analysis of complex geobiological samples (false negatives, low signal to noise ratio, etc); and 2. Addressing *site accessibility issues* by developing and integrating multi-component platforms (mini-rovers, quadcopters, crawling jumping drones, etc), cubesat miniaturization technology that could carry, deploy, and retrieve life detection labs. Such a package will enable robotic and drone-assisted human explorers to analyze and retrieve environmental samples from icy and rocky terrains otherwise very difficult to access, e.g., steep slopes of craters, mounds, and trenches. In parallel with the search for Martian life - including terrestrial microbes that could be accidentally introduced by humans - the vision continues into the 2030s with the development of quadcopters and mobile integrated platforms for exploring Saturn's and Jupiter's ocean worlds Enceladus and Europa. This extends to high pressure and cold regions on Titan in the 2040's, and later in the 2050's exploration of Venus' surface and atmosphere.

In support of one specific aspect of this vision (Item 1 above) we offer here just an example of successful detection of metabolically active life in briny environments challenging to analyze.

Life detection on Mars: The next frontier for life detection (as we know it and/or Earth-like) on the surface of Mars could be briny environments with magnesium, sodium chlorate and perchlorate salts lowering the freezing point, thus enabling the presence of transient liquid water even today [e.g.,1]. A promising target for life detection could be the recurring slope lineae (RSL) where briny water seeping down steep slopes (25 to 40°) has been remotely observed. It is thought that the SRL could form in different Martian regions by melting surface/subsurface ice, deliquescence of salts, or by the seasonal discharge of a local aquifer [1 and refs. therein], which could lead to habitable conditions, or even actual habitation. The RSLs are very difficult and dangerous to explore by both rovers and astronauts wearing space suits and backpacks. Either they must climb up the slopes or rappel down, which are high-risk activities.

Background: The search for Life as we know it in the Solar System and beyond begins here on Earth. Field research in extreme environments enables us to expand our knowledge about the extreme limits for life, and testing opportunities of technologies, system interactions, and analytical protocols for life detection in geobiological materials. Over the past few years we have learned that terrestrial briny environments can be habitable and conducive to life. For instance, the deliquescence of hygroscopic salts in the hyperarid core of the Atacama Desert (Chile) provides a shallow surface habitat for active halophylic prokaryotes [2-3]. Hypersaline ponds, lakes, shorelines and salt flats can also shelter complex microbial communities as well as eukaryotic life [4].

Life detection and analytical gaps: The detection of molecular proxies for life (as we do know it) in planetary environments depends on four conditions: (1) their initial presence due to current and past biological production; (2) their concentration in measurable amount in target environments; (3) their long-term preservation within the geological material; and (4) the analytical ability of payload instruments to detect and identify them. The analytical requirement is a very key one. False negatives (null or incomplete recovery) can result from the analysis of both biologically lean and biologically rich materials.

Approach: Briny water and sedimentary materials were collected from high-altitude hypersaline evaporitic lakes (Figure 1) in the Leh-Ladakh region of the Himalayas (India) [5]. Samples were collected using sterile tools and analyzed a few hours after collection with a portable luminometer instrument detecting the Adenosin Triphosphate (ATP) biomarker for active life. To test effectiveness of life detection assays samples were additionally analyzed for lipopolysaccaride (LPS) Lipid A using lab-on-the chip / wet chemistry assay. Water samples were diluted x10, 100, and 1000 to mitigate chemistry-related interfering factors. For each sample up to 10-12 sub aliquots (same weight or dilution) were analyzed to address the occurrence of false negatives.

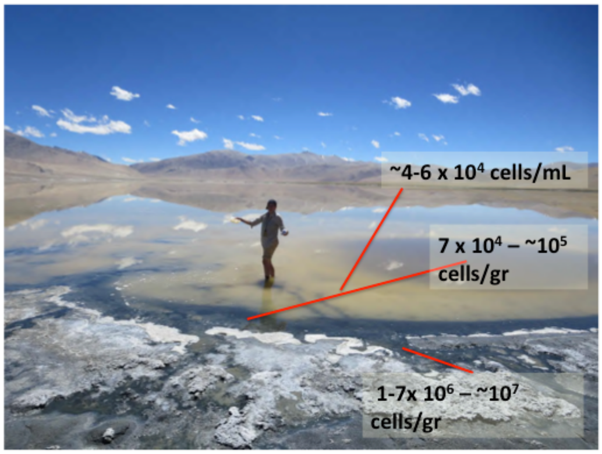

Figure 1. Briny environments sampled at Tso-Kar Lake

Results and Discussion: Overall, the LPS- and ATP-based biomass of freshwater, saline, and hypersaline samples range from 10^2 cells/gram to 10^9 cells/gram and cells/mL (not shown here).

Up to 10-12 trials were required to detect the biomarker analyte in reproducible amounts (Figure 2). The most common issues related to the analysis of briny samples are: 1. False negatives; 2. Poor yields in non-diluted briny samples; 3. quenching effects (for nanophase clay- and pigment-rich brines); and 4. Large intra sample variability. Only averaged positive values are outlined in Figure 2.

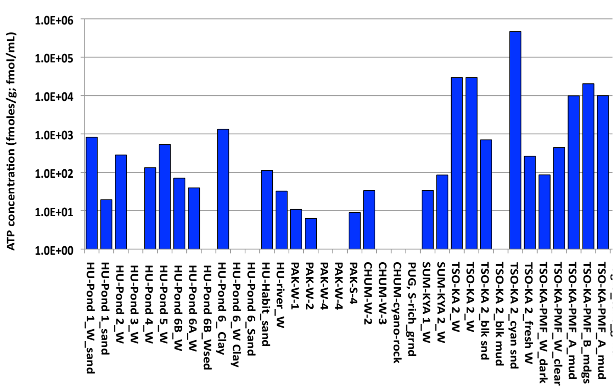

Figure 2. ATP concentration in periglacial environments of the Leh-Ladakh Region. The highest concentrations of ATP were measured in water and sediment samples from the hypersaline Tso-Kar Lake (i.e. ~5 x 10^5 fmoles of ATP per gram, or per milliliter.

Conclusion and Applications: Failing to detect life in modern terrestrial environments that we know have abundant life is a chief concern for our ability to detect life on Earth and other planets as well.

In geological and water samples the detection of LPS and ATP biomarkers can be affected by the mineralogical (i.e. clay minerals, nanophase iron oxyhydroxides) and physico-chemical composition (salts, pH, T, organics) of the media. Dilution is a key for a successful life detection in saline and hypersaline samples and can increase the signal to noise/ratio up to 3 orders of magnitude.

To boldly go beyond Mars: Beyond Mars, the near future search for life will target the Ocean Worlds Enceladus and Europa where subglacial oceans potentially harbor life. Afterward, Titan and Venus could be next target as they may host life as we do not know it yet. Learning how to assess and mitigate matrix-related interferences can be applied to future life detection missions to our Solar System.

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FROM RUBE GOLDBERG TO TRICORDERS: ASTROBIOLOGY TECHNOLOGY NEEDS.
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Introduction: The hunt for life in extraterrestrial environments and in extreme environments on Earth presents challenging problems in strategy, science, and engineering [e.g 1]. Much of the astrobiology community comes from the science side of the house, with some notable exceptions, so it is to our benefit interest more engineers, makers, and innovators in astrobiology-related technology needs.

Biology and the various disciplines of engineering can overlap in a wide variety of ways. These include design inspired by biological entities and subsystems, the actual use of biological materials as components, what we have come to know as genetic engineering, synthetic biology, and other engineering that is in service to biological systems in a variety of ways. Technology for astrobiology purposes could fall within one or more of these categories.

Some of the most severe constraints on built items in space and in challenging planetary environments involve robustness, fault tolerance, and the potential for self-repair. Interestingly, these are challenges that biological entities also face and their solutions to these problems have been tested in the laboratory of evolutionary time and selection to provide many approaches of use to us in solving our astrobiology needs.

Fruitful interactions between the innovation community, and enthusiastic astrobiology customers can result in major capability leaps as we go forward to explore the Solar System and beyond. There are already many meetings and reports that have addressed life detection needs, but there is a broad community of expertise and creativity that has not yet engaged in astrobiological arenas that may be tapped for fresh perspectives There are five major problem areas that come to mind, which could benefit from such efforts.

Problem 1 – Simultaneous Measurements: The ability to interrogate a sample simultaneously in a wide variety of ways is of great value in the task of unequivocally demonstrating that something is alive [2]. Our current payloads have much to commend them, but they are largely focused on static or serial measurements that are often hard to translate into what we think of as ongoing life processes. The discontinuity and failure to close logical loops between datasets is a conundrum that must be solved if we are to claim definitive evidence of ongoing extant life. We are often faced with incompatibilities of methods that we would like to bring to bear on the same samples at the same time. A move towards minimally invasive or non-invasive techniques could help to advance us towards the goal of simultaneity.

Problem 2 – Long-Term Observations on Landed Missions: The ability to follow natural phenomena for protracted periods of time is very difficult to do in the mission context, but life is an ongoing process whose pace depends on many factors and can be very slow [1,3]. Our ability to successfully detect and characterize phenomena as truly life may depend upon our coming to grips with this problem.

Problem 3 - Access to Challenging Terrain: Many sites on Earth that may represent some aspects of astrobiologically promising sites on other Solar System bodies are very difficult to access even with human expertise and equipment. This task becomes even more daunting when we contemplate the robotic and sample handling needs involved. Access to chasms, caves, liquid bodies, through ice shells, dense gas oceans, and more are awaiting our creativity [e.g. 4].

Problem 4 - Seeing Like a Human: Our own evolutionary history has made us into excellent pattern recognition machines with great subtlety and the ability to make intuitive leaps of logic and interpretation. While machine learning and automatic pattern recognition are fields gaining much attention [5, 6] we still have a long way to go to sufficiently emulate humans.

Problem 5 – Affordable & Implementable Planetary Protection: The *sine qua non* of astrobiology missions to potentially inhabited parts of bodies like Mars [7, 8] and the ice-shell liquid interior moons of the Outer Solar System [9] is Planetary Protection. The justification for this is solidly based in protection of life detection science to provide unequivocal results and must be responsive to our international treaty obligations. Considering that the Viking landers were completely heat sterilized prior to their launches, this is a mission need that we can solve with a combination of new technology and smart systems engineering. Multiple methods of sterilization are available ranging from heat, steam and pressure, sterilant gases, ultraviolet light, and various types of hard radiation.

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EXPLORING PLANET MIGRATION AND EARLY SOLAR SYSTEM BOMBARDMENT. W. F. Bottke, D. Nesvorny, S. Marchi, H. Levison, R. Canup. Southwest Research Institute and NASA's SSERVI-Institute for the Science of Exploration Targets (ISET) Team, Boulder, CO, USA (bottke@boulder.swri.edu)

Introduction: One of the recent revolutions in our thinking about how our Solar System formed, driven in large part by the orbital properties of Pluto and Kuiper Belt objects, is the concept that the orbits of the outer planets migrated substantially after their formation. The dynamical causes and timing of this globally-important process are a topic of active work and debate, with broad implications for planet accretion models, early solar system dynamical stability, volatile delivery to the terrestrial planet region, and the early impact rate throughout the solar system.

A quantified and well-developed description of this behavior is provided by the "Nice model" [1-2]. The Nice model is an umbrella term for a broad class of dynamical models in which the giant planets experienced a dynamical instability that led to a violent reorganization of the outer planets. Specifically, Uranus/Neptune entered into a large disk of small icy planetesimals (i.e., comets) residing between ~20 and 30 AU and flung its members throughout the Solar System, while the migration of Jupiter/Saturn drove portions of the primordial asteroid belt onto planet-crossing orbits. Even more intriguingly, current models indicate our Solar System once had 5 giant planets: Jupiter, Saturn, and three Neptune-like ice giants. One ice giant was lost via an encounter with Jupiter, but not before producing Jupiter's Trojans/irregular satellites and implanting comets into the asteroid belt [e.g., 3].

The Nice model is potentially powerful because it not only explains the current orbits of the giant planets but also the dynamical state of small body populations across the solar system. Questions remain, however, about how/when (and for some, if) it happened.

One potential way to test the Nice model is to better understand the heavily cratered surfaces on the Moon and Mars. They were both battered by an intense bombardment during their first billion years or more but the timing, sources, and dynamical implications of these impacts are controversial. We argue getting the ages of the most ancient surfaces and basins on Moon/Mars should be a key goal of planetary science in 2050. These worlds are also key targets for human exploration, and as such their future study will likely involve joint involvement from both NASA's science and exploration programs (and help from SSERVI-ISET).

Testing Early Bombadment. Here we define the "Late Heavy Bombardment" (LHB) as those impact events that occurred after stabilization of planetary lithospheres such that they could be preserved as craters and basins. So far, lunar melt rocks and meteorite shock ages point toward a discrete episode of elevated impact flux between ~3.5 to ~4.0-4.2 Ga, relative quiescence between ~4.0-4.2 to ~4.4 Ga, and elevated impacts > 4.4 Ga [4, 5].

Dynamical models have so far concentrated on examining populations residual from primary accretion and destabilized by giant planet migration. Either one can potentially account for the available observations, although all have pros and cons. We believe the best solution thus far to match constraints is a hybrid model with discrete early, post-accretion and later, planetary instability-driven populations of impactors.

A key problem, though, is that we do not know whether the Nice model instability occurred after a delay that was tens of Myr after CAIs or as long as many hundreds of Ma. <u>Only the latter case would be capable of producing a late uptick in impacts across the solar system.</u>

The Oldest Surfaces on the Moon and Mars. A fundamental problem in testing any model of early bombardment is determining the crater or basin retention ages of the oldest lunar and martian surfaces. For example, the Moon's oldest surface could be as young as 4.35 Ga, which may date a global magmatic event [6], or as old as ~4.4-4.5 Ga, the putative age of the Moon itself (**Fig. 1**) [7]. For Mars, it is possible the oldest surfaces correspond to the age of Borealis basin, which defines Mars' global topography (**Fig. 2**) [8]. The available evidence suggests this basin formed > 4.5 Ga, but a younger formation age and more recent resurfacing cannot be ruled out. It is also possible that large basins would not be retained for some interval after Borealis formation, though this time period may be as short as a few tens of Myr.

Obtaining the Ages of Ancient Basins. Lunar data from the Apollo/Luna programs and lunar meteorites provide compelling evidence that the LHB extended back in time to at least 4.2 Ga and possibly before [9]. The problem is that nearside region of the Moon seems to have been comprehensively resurfaced by ejecta from Imbrium basin, and this has biased our view of the Moon based on the Apollo samples. The lack of absolute ages, especially for the older lunar basins, and solid constraints on the mass vs. time flux of impactors across the inner solar system, is a significant impediment to resolving the nature of the LHB.

We suggest that obtaining solid ages from several lunar and martian basins would go a long way to helping us resolve the timing and nature of the LHB. The two oldest basins on the Moon and Mars, respectively, are South-Pole Aitken and Borealis (**Fig. 1-2**), but each have an unknown age. Obtaining the ages of basins like Nectaris (Moon) and Hellas (Mars) would also bring clarity to early bombardment history. Each represent a key basin that is located at the beginning of a geologic epoch (i.e., the beginning of the Nectarian-era and Noachian-era, respectively). Their ages would help us determine whether a "lull" in the basin-formation epoch really existed between 4.1-4.4 Ga.

Archean Era Bombardment. The earliest history of Earth is poorly understood because few rocks older than 3.9 Ga exist. Even in the Archean, which lasted between 2.5-3.7 Ga, there are very few existing outcrops of non-metamorphosed rocks. Thus, even though this was a formative time for life on Earth, we lack key information on the terrestrial impact rate.

An oft-neglected constraint comes from terrestrial impact spherule beds. When a large impactor strikes the Earth, it produces a vapor-rich ejecta plume containing numerous sand-sized melt droplets, most of which rise above the atmosphere. Eventually the droplets cool and fall back, forming a global layer that can be several mm to many cm thick for Chicxulub-sized or larger impact events. These layers tell us about large ancient impact events, even if the crater has been lost.

Multiple spherule beds have been found in Archean and early Proterozoic terrains, with the oldest spherule deposits at 3.47 Ga [e.g., 5]. Models show that their age distribution likely corresponds to 70-80 craters with D > 150 km forming on Earth between 1.7-3.7 Ga [5]. Collectively, they suggest the LHB had a long-lived tail that lasted to ~2 Ga for Chicxulub-sized impact events on Earth, with the LHB endgame taking place during the Great Oxidation Event, Snowball Earth events, etc. The problem is how to test whether impacts mattered when the flux is uncertain.

One method to get the Archean impact flux is to determine the ages of several D > 50-100 km lunar impact craters formed between 1.7-3.7 Ga. Given that the likely impact ratio between the Earth and Moon is ~20, we can use their ages to predict the Archean-era terrestrial flux for larger impacts with some precision. The critical issue will be to identify and date craters with a range of superposed crater spatial densities in order to fill in the gaps of our crater chronolgy. The precise number needed will require an analysis of LRO data combined with geologic mapping work.

Similarly, the evidence suggests Mars also had a long bombardment tail that ended in the Hesparian-era. The formation time of these large craters is highly uncertain, partly because of erosion but also because their ages are benchmarked to Apollo-derived crater chronologies whose accuracy may be is questionable [9]. Interestingly, these impacts occurred when Mars was experienced substantial water activity, which could suggest a link.

Method for Getting Ages. We suspect the most cost effective method to determining the ages of these surfaces is *in situ* dating using some combination of flyers/rovers that can reach intact outcrops of impact melt on Moon/Mars. Mobility for a single mission may be valued, given that multiple missions are costly.

Our 2050 Goals. We would like the ages for:

- **The oldest lunar and martian surfaces to determine basin retention ages.**
- **The oldest basins South Pole Aitken (Moon) and Borealis (Mars).**
- **Basins at changes in geologic epochs: Nectaris (Moon) and Hellas (Mars)**
- **Middle aged craters on Mars/Moon to fully compute crater chronologies for each world.**

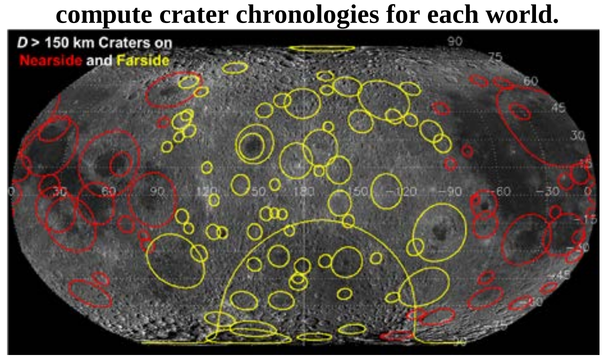

Fig. 1. A map of all D > 150 km diameter lunar craters on the lunar nearside (red) and farside (yellow). The largest yellow circle is South Pole Aitken basin.

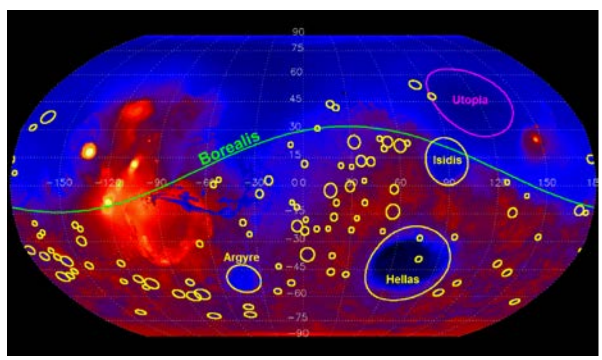

Fig. 2. A map of all D > 150 km diameter Martian craters. The green circle is Borealis basin.

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THE INTERSTELLAR PROBE MISSION: HUMANITY'S FIRST EXPLICIT STEP IN REACHING ANOTHER STAR. P. C. Brandt[1], R. McNutt[1], G. Hallinan[2], M. Shao[3], R. Mewaldt[2], M. Brown[2], L. Alkalai[3], N. Arora[3], J. McGuire[3], S. Turyshev[3], A. Biswas[3], P. Liewer[3], N. Murphy[3], M. Desai[4], D. McComas[5], M. Opher[6], E. Stone[2], G. Zank[7], L. Friedman[3], [1]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA (pontus.brandt@jhuapl.edu), [2]California Institute of Technology, Pasadena, CA 91125, USA, [3]Jet Propulsion Laboratory, Pasadena, CA 91109, USA, [4]Southwest Research Institute, San Antonio, TX 78238, USA, [5]Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA, [6]Boston University, Boston, MA 02215, USA, [7]University of Alabama in Huntsville, Huntsville, AL 35899, USA.

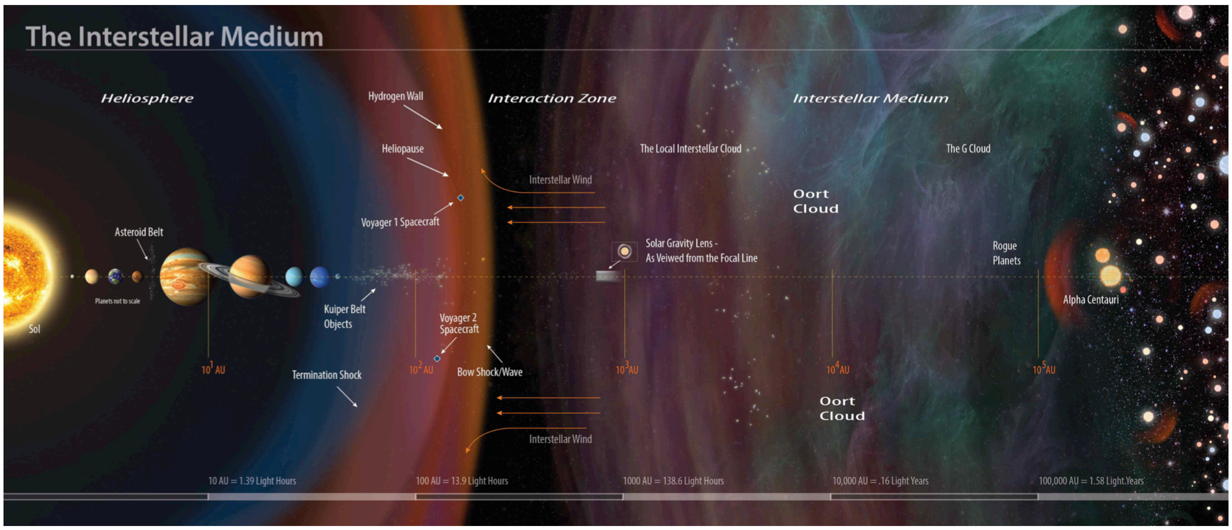

Figure 1: An Interstellar Probe Mission to the Interstellar Medium (ISM) would be daring, challenging and inspirational to the public and will be a rationale first step before attempting to reach another star.

Introduction: As the Voyagers are crossing in to the ISM (Figure 1) and the Kepler Mission has unveiled an abundance of Earth-like planets around other Suns, inevitably, we are faced with the question of how humanity will venture out through the vast space between our star and other potentially habitable planetary systems. Here, we discuss an Interstellar Probe Mission concept that would represent the first explicit step scientifically, technologically and programmatically on that path. The concept presented follows the work from two workshops led by Dr's E. Stone, L. Alkalai and L. Friedman.

Science Rationale: Venturing on to an escape trajectory will offer science discoveries of different proportions that will naturally bridge planetary, heliophysics and astrophysical disciplines by putting our own planetary system and magnetic bubble in the context of the increasing number of other exo-planetary systems and astrospheres detected and characterized. The following topics illustrates the ground-breaking science that could be achieved with an optimized payload on board an Interstellar Probe to the ISM.

Evolutionary History of Planetary Systems: The evolution of a planetary system is manifested in part by the large-scale distribution and motion of dust. Although dust emits in the infrared wavelengths, from a vantage point inside the solar system it is intrinsically difficult to determine its large-scale distribution. On its way outward, the Interstellar Probe will measure and determine the radial, compositional and size distribution of dust and provide quantitative picture of the dust distribution that could be directly compared to the IR observations of dust characterizing exo-planetary systems.

Diversity of KBO's: As the New Horizons Pluto flyby has shown, this extended part of our solar system holds a diversity of worlds, which should unlock many of the secrets of the evolution of our solar system, but would more importantly put the evolution of other exoplanetary systems in context. At 40-50 AU, conveniently lining up with the nose direction of the heliosphere of a flyby in the ~2030's, lies the dwarf planet Quaoar (Figure 2) that is in the last stages of loosing its methane atmosphere. Surprisingly, crystalline ice has been detected on the surface implying cryo-volcanism active in the immediate past or even still active. Quaoar therefore represents one of the possible targets that could unveil yet another unexpectedly exotic world of a KBO with critical implications for planetary formation.

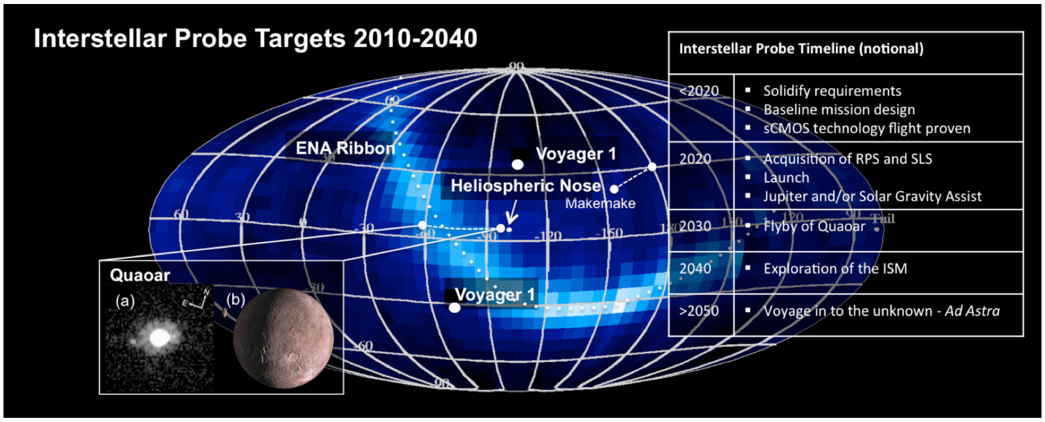

Figure 2: The Interstellar Probe targets include the dust distribution of our solar system, a flyby of KBO Quaoar and unveils the global nature of our own astrosphere before continuing its voyage in to the unknown ISM.

Global Nature of Astrospheres: Planetary systems are encased in a magnetic bubble spanned by the outward stellar wind of its parent star. The global shape and nature of this astrosphere as it plows through its surrounding ISM, is directly constrained by the properties of the stellar wind and therefore reveals the habitable conditions governed by stellar-wind interactions responsible for the loss of planetary atmospheres. The quest to understand the global nature of our own astrosphere have illuminated large gaps in understanding the exotic plasma-physical processes that take place in this boundary region of astrophysical scales: The in-situ exploration by the Voyagers points to an unexpected heated plasma population (not directly measured) dominating the forces here. The glaring absence of the anticipated acceleration region of Anomalous Cosmic Rays also came as a dramatic surprise. Energetic Neutral Atom (ENA) images obtained by the Interstellar Boundary Explorer mission have revealed a completely unpredicted pattern of a thin "ribbon" across the sky that is believed to be organized by the interstellar magnetic field. As it traverses our heliospheric boundary into the pristine ISM, the Interstellar Probe will probe the exotic plasma physics governing this unique astro-plasma physical region and conduct remote ENA imaging of the enormous three-dimensional boundary from multiple vantage points to pinpoint the location and physics of the ribbon. As the Probe eventually leaves our heliosphere behind, it will lay claim to historical external views of the heliosphere allowing us to extrapolate and understand other astrospheres and the habitability of the planetary systems they harbor.

Mission Requirements: A key-enabling component is the availability of a heavy launch vehicle such as the SLS. One of the trajectories studied relies on an SLS launch in the 2020's, followed by a Jupiter Gravity assist. A daring solar-gravity assist is also under consideration, which would enable the Probe to reach the ISM quickly and put it at solar-system escape velocities of 13-19 AU/year at 200 AU in 20-30 years. Beyond 550 AU the Solar Gravity Lens would open up breathtaking possibilities for a larger mission for direct exoplanetary imaging. A series of community workshops solidifying the key requirements for the Interstellar Probe should be conducted in this decade.

Technological Developments: A critical design driver is to develop a highly integrated spacecraft system and instrument architecture in order to reduce resources that will directly translate to increased energy to reach the ISM. Power generation can be achieved with known radioisotope power system (RPS) technology. Use of Multi-Mission Radioisotope Thermoelectric Generators will require lifetime extension based on ongoing successful developments of new materials, or reclamation of the Si-Ge technology used by several missions. Communication challenges could be addressed by using optical communications combined with an optical and IR telescope that would rely on new sCMOS state-of-the-art technology that will be tested in flight 2017. Although no new technology development is required for the heliophysics instrumentation, trade studies are needed to develop an appropriate instrument suite. A cube-sat sized Quaoar impactor could provide an unprecedented glimpse in to the interior of the KBO science.

Programmatic Transformation: The almost indefinite nature of an Interstellar Probe mission, necessitates a transformation in how such endeavors are supported and managed: How is continual funding ensured that goes beyond changing political administrations? How will NASA SMD handle such a mission that naturally brings together three Science Divisions? How will requirements on component and subsystem be crafted to support such a mission?

LABORATORY STUDIES OF EXTRATERRESTRIAL ICES – SAMPLE RETURN FROM ICY BODIES

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Introduction: The last decades of space exploration revealed the widespread occurrence and underlines the importance of Ices throughout our Solar System [e.g. 1, 2, 3]. Without a detailed knowledge of Ice formation and evolution a comprehensive model for the development of habitable environments is impossible.

Ices are unique carriers of a number of different chemical tracers, which include isotopic signatures of hydrogen, carbon and oxygen, noble gases, trace element and REE patterns, to mention a few. Furthermore ice can capture, store, preserve and protect organics for extraordinary long time spans [4].

Whereas terrestrial ices are studied in great detail [e.g. 5], despite its importance, comparably little is known about extraterrestrial ice.

However, rapid technical developments in laboratories on Earth will enable a comprehensive analytical study applying traditional as well as novel techniques.

Ice sample return: Ice is one of the main components of comets. It also exists in dwarf planets [2], at the poles of Mars, in shadow regions of the Earth´s moon [6], Mercury [1], it forms the crust of several moons of Jupiter, etc. Beside the sampling procedure itself the main challenge in ice sample return studies is to keep the ices at very low temperature during capture, transport, re-entry, storage and analyses without ever interrupting the cooling chain.

Analogue experiments: Analogue studies on terrestrial ice already overcome some of these challenges, which include ice core sampling in the Antartica, transport, storage and electron back scatter diffraction (EBSD) studies using SEM [e.g. 7, 8, 9].

Analytical Techniques: Non-destructive measurement techniques, like low dose SEM, ESEM, synchrotron XRD and XRF, are scarce. Even if these techniques are applied under the most gentle conditions available, ices - beside organics - remain the most delicate samples due to their very unstable nature.

Cryo Electron Backscatter Diffraction (cryo EBSD) of Ice: EBSD turns out to be among the most powerful analytical techniques that SEM introduced to Earth and Planetary sciences about 20 years ago [10]. Just recently it became a routine technique to study water ice [7], applying several appropriate strategies for reducing beam damage. EBSD allows to determine the structural state, identifying the crystal structure and its respective orientation (LPO) down to the nanometer scale. Based on these data, deformation mechanisms, which control the dynamics within glaciers, Ice shields and the icy crusts of planetary moons, can be identified.

Synchrotron Techniques: Synchrotrons around the globe were used to study tiny particles of cometary [11, 12] and interstellar sources [13, 14, 15] collected during NASAs Stardust mission. Although due to the sample collection procedure it did not include the study of ices yet, it was demonstrated that synchrotron sources are valuable tools to measure the main and trace element content of even the tiniest extraterrestrial particles. The use of synchrotron sources to study terrestrial ices is already established [e.g. 16]. It enables the study of very tiny inclusions of fluids and solids trapped within the ice.

The development of new analytical approaches to measure REE-patterns in sub-micron inclusions applying confocal XRF set-ups and energy-dispersive X-ray imaging detectors [17] represent ongoing work in the framework of a long-term project of our group at the PETRA-III synchrotron facility (Hamburg, Germany).

Neutron Techniques: Pilot experiments to use neutron diffraction to constrain the kinetics of low temperature phase transformations in water ice, at ambient pressure is part of an ongoing project at the ANSTO Bragg Institute Neutron Beam Instrument to determine the proportions of amorphous, hexagonal and cubic ice that form on super-cooling from small water droplets.

Secondary Ion Mass Spectroscopy - SIMS: Isotopic analyses like the D/H-ratio, Oxygen and Carbon isotopic signatures are usually performed by mass spectroscopy. Depending on the required spatial and mass resolution different SIMS instruments including ToF-SIMS, Nano-SIMS and high mass resolution SIMS are available.

Sample Curation: The most crucial part in studying Solar System Ices in laboratories on Earth is the need to keep the samples at very low temperatures, safely store and securely send the samples for analyses, which will require a special cryo curation facility.

Conclusion: A comprehensive study of solar system Ices is fundamental for the understanding and reconstruction of processes which lead to the formation of our Solar System, its alteration history and finally the formation of habitable environments. Therefore, we predict that an ice sample return mission from either a comet or a moon will represent one of the main challenges within the next decades of solar system exploration

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THE TECHNOLOGY AND FUTURE OF IN-SITU RESOURCE UTILIZATION: A CAPSTONE SEMINAR THIS SPRING.
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Introduction: In Situ Resource Utilization (ISRU) is a suite of concepts and technologies that can enable safer and more cost-effective use of space by exploiting local resources rather than bringing everything from Earth. ISRU includes commercial applications, robotic planetary exploration, human exploration, and the establishment of outposts. This capstone graduate seminar explores the context of ISRU, its economics, the state of the art in ISRU technology, and a range of ISRU applications including fuel generation, lunar and asteroid mining, in-space manufacturing, habitat construction, infrastructure construction, farming, and recycling. The University of Central Florida (UCF), NASA's Solar System Exploration Research Virtual Institute (SSERVI), UCF's SSERVI node the Center for Lunar and Asteroid Surface Science (CLASS), and a number of other SSERVI nodes and Universities are teaming to produce a capstone graduate seminar on ISRU.

Our goal is to capture where ISRU technology is today and where it can go in the next 20 years to support an expanding and vigorous space economy, to reduce costs and risks of exploration missions, and to enable cost-effective exploration missions that would otherwise be prohibitive in future budget climates. The core content will be a series of topic-focused lectures given by leaders in the field that cover most of the major issues and applications for ISRU. The lectures will be accessible on-line through the SSERVI Adobe Connect system in real-time and will be recorded for online reference, accessible from the CLASS and SSERVI websites. The format provides an opportunity for direct participation through questions and discussion, not only for the local audience, but also for the larger online audience. The level of the seminar is aimed at the knowledgeable professional in planetary exploration and our goal is to capture how ISRU can impact the planning and architecture of future robotic and human exploration missions. For more detailed information please contact Dan Britt (britt@physics.ucf.edu).

Seminar Leaders and Topics:

- **Dan Britt (UCF): Why use space resources? What resources are available?**
- **Jerry Sanders (JSC): NASA's ISRU Programs**
- **Leslie Gertsch (MST): Mining and Beneficiation**
- **Paul van Susante (MTU): Conveying Technologies, Mining Cycles and Mining Requirements**
- **Tony Muscatello (KSC): Oxygen Extraction from Minerals**
- **Laurent Sibille (KSC): Extracting Metals**
- **Joel Sercel (TransAstra): Optical Mining**
- **Phil Metzger (UCF): Water Extraction and Cleanup**
- **Tony Muscatello (KSC): Atmospheric Capture on Mars**
- **Rob Mueller (KSC): Construction with Regolith**
- **Jason Dunn (MIS): We Can Make It In Space**
- **TBD: Farming in Space**
- **Barnard Kutter (ULA):Propellant Depots**
- **Rob Mueller (KSC): Overview of Lunar, Asteroid, and Martian ISRU Mining Camps**
- **Dan Britt (UCF): Toward a Space-Based Economy**

DETECTION AND QUANTIFICATION OF VOLATILES AT MARS USING A MULTISPECTRAL LIDAR.

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Introduction: We present a concept for using a polarization sensitive multispectral lidar such as the *ASPEN* instrument proposed in [1] to map the seasonal distribution and exchange of volatiles among the reservoirs of the Martian surface and atmosphere.

Concept: The *ASPEN* instrument will be a multi-wavelength, altitude-resolved, active near-infrared (NIR, with 10 bands around 1.6 microns) instrument to measure the reflected intensity and polarization of backscattered radiation from planetary surfaces and atmospheres. The proposed instrument would be ideally suited for a mission to Mars to comprehensively investigate the nature and seasonal distributions of volatiles and aerosols. The investigation would include the abundance of atmospheric dust and condensed volatiles, surface and cloud/aerosol grain sizes and shapes, ice and dust particle microphysics and also variations in atmospheric chemistry during multiple overflight local times throughout polar night and day.

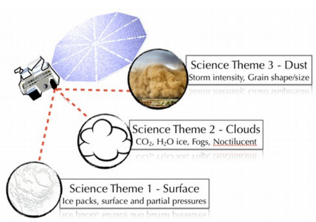

Figure 1 – Multispectral lidar concept in orbit around Mars, with science themes of Surface, Clouds and Dust

Cubesat opportunity: Although the full scale multispectral lidar requires a 1m receiver mirror that dictates space and weight of the instrument by today's technological standards, an opportunity exists to carry out a pathfinder mission with a cubesat footprint similar to that used on the Lunar Flashlight mission [2]. Lunar Flashlight utilizes a multi-band laser reflectometer to measure the surface reflectance, thereby demonstrating this multiband lidar concept on a small spacecraft in lunar orbit. If payload space becomes available in the coming decade for Martian cubesat class missions, for example as part of a SpaceX ridealong mission, we would like to exploit this for a trispectral lidar (at least 3 bands) and perform a proof of the concept of the *ASPEN* mission that provides some of the science discussed here (e.g. high altitude H_2O clouds and lower spatial resolution surface H_2O ice) for a reduced cost.

Previous work with passive hyperspectral instrument: As reported in [3], we have used observations from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) of the north polar cap during late summer for four Martian years, to monitor the summertime water cycle in order to place quantitative limits on the amount of water ice deposited and sublimed in summer. The most compelling result of this map is that we have identified regions and periods of 'net deposition' and 'net sublimation' on the summer north polar cap. Regions of the cap undergo a 'mode flip' from sublimation to deposition mode and the timing of ***mode flips*** is latitude dependent. This enables us to place firmer estimates on the dynamics by using the concept of depositional mode flips, a previously unknown observable that is also applicable to testing and verifying Martian Global Climate Models (GCMs).

H_2O index volatile tracking: Previous work has tracked the variations in the so called H_2O index [4-6] over the parts of the cap that received CRISM coverage throughout the summer period over four Mars Years. The index is based on the depth of the water ice 1.5μm absorption band. It is high when water ice is present, and grows with the water ice grain size. When deposition of fine grained ice occurs, the H_2O index decreases, because finer grained ice scatters light back to the observer more readily and in turn decreases the depth of the 1.5μm H_2O absorption band [7].

Applicability of a multispectral lidar: As described in detail in [1], a 10 band NIR multispectral lidar system can carry out the same measurements of atmospheric volatiles as CRISM in the polar regions, and is in fact more sensitive when the multispectral bands are chosen effectively. Not only will the lidar produce finer maps of the H_2O index (and a CO_2 index), but those indexes can be extended into the polar nighttime, thus extending our knowledge of the distribution of polar volatiles throughout the year. Finally, the lidar will provide time resolved measurements, allowing discrimination of clouds and fog, a task which is very difficult for CRISM and other passive instruments. As with the MOLA instrument, surface elevation can be measured to determine seasonal cap thicknesses and mass wasting processes on longer timescales.

Previous work on brightening of north polar cap: A long-standing problem of the Martian climate is the summer brightening of the north polar cap. This was first reported by Kieffer [8] using IRTM data, and subsequently observed with TES by Titus and Kieffer [9]. Bass and Paige [10] used IRTM and MAWD measurements to determine the peak of water vapor over the north polar cap. They found that the lowest visible albedo occurred during L_s=93-103° and water vapor was also released after L_s=103°; however they could not determine whether this was caused by changes in water ice grain size or dust deposition.

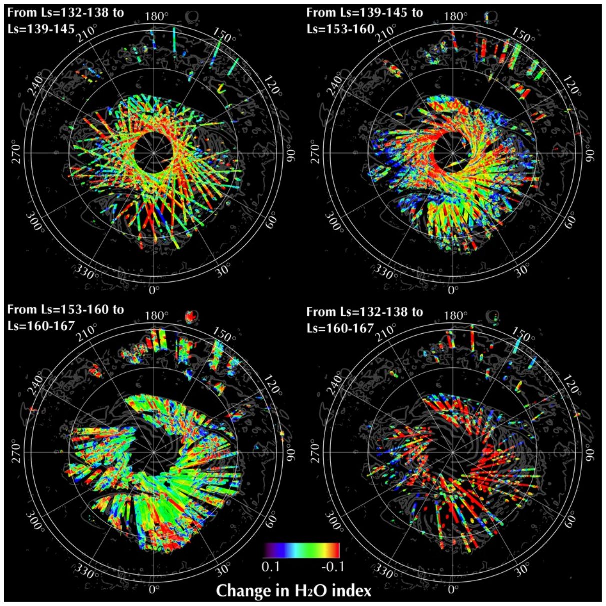

Figure 2 – Changes in H_2O index for MY28 showing net deposition in red colors and net sublimation in blue. The bottom right image is a summary of the whole period from L_s=132 to L_s=167.

'Mode flips': We used CRISM H_2O index maps (Fig. 2) to show that in a key region in the interior of the north polar cap, the absorption band depths grow until L_s=130°, as reported in [6], followed by a period when they begin to shrink, until they are obscured at the end of summer by the north polar hood (Figure 2). This behavior is transferable over the entire north polar cap, where in late summer regions 'flip' from being net sublimating into net condensation mode as the weather cools (Fig. 3). This 'mode flip' happens earlier for regions closer to the pole, and later for regions close to the periphery of the cap. For some parts of the periphery of the cap, there are regions where water ice absorption band depths have not been observed to decrease over the time we have observed them, suggesting that they may remain in net sublimation mode during the entire summer season and only go into condensation mode in winter.

Total deposition of water ice during summer. Under the assumption that the observed shrinking of grain sizes is entirely due to the deposition of fine grained water ice, we have approximated the total amount of water ice deposited on the cap each summer, which equates to 70 microns of deposition over the L_s=132-168° late summer period. This amount is considerably more than the ~6 microns of deposition of water ice on the south polar cap during the summer period as reported in [11].

Conclusions: A multispectral lidar could make fundamentally new observations of the Martian surface and atmosphere to quantify the deposition of volatiles throughout the entire Martian year at an unprecedented spatial resolution. We have briefly introduced the water absorption band maps made using CRISM for the entire north polar region as a function of space and time over late summer which identified 'net deposition' and 'net condensation' regions and periods. This provides a tantalizing glimpse into what a multispectral lidar in orbit around Mars would reveal that would be crucial to understanding the long term Martian volatile inventory and dynamics.

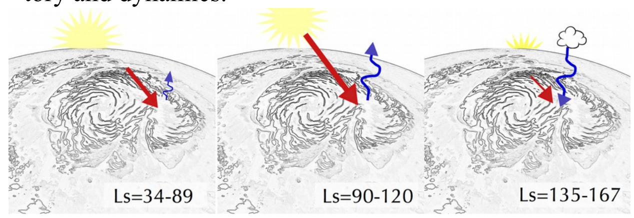

Figure 3 – Cartoon representation of deposition/sublimation 'mode flips'. Dates given are relevant for the Gemini Lingula region (where the arrows point in the right image).

Take home message: 1. Previous studies have identified regions and periods of net deposition and net sublimation on the Martian polar caps [3].

2. Studies such as [1, 4-6] have revealed the path forward for investigations into the transport of water in the Martian climate cycle. Using CRISM observations, we have now quantified the spring and summer water ice deposition for both poles. These measurements are crucial to our understanding of the construction and ongoing stability of the caps under today's climate. However, there is a ***clear and pressing*** need to understand the fall and winter 'dark side' of the Martian polar region that is impenetrable to passive instruments like CRISM and MARCI and instead requires multi-wavelength lidar instruments such as the *ASPEN* concept discussed here.

Acknowledgements: Part of this work was carried out at the Jet Propulsion Laboratory under a contract with NASA.

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The Many Ways to Invent Biology

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The next 35 years will see tremendous advances in defining how life can arise spontaneously, and these advances will guide missions to look for life beyond Earth. Multiple bodies in the Solar System are candidates for hosting extant recognizable life or for having hosted life in the past. These bodies represent enormously diverse physical, geological and chemical environments, each of which could potentially produce Life through different means. Recent advances have made it possible to engineer living organisms with ever greater precision, and there is growing expectation that we will soon (10-20 years) be able to generate very simple, fully-artificial living entities in the lab.

A major goal for 2050 should be to build artificial life not just once, but many different ways through diverse pathways, chemistries and constraints. To achieve that goal will require continued bottom-up and top-down advances related to the classic pursuits of pre-biotic chemistry, functional macromolecules and deep history of Earth life. However, it will also require a much greater exploration of systems-level considerations that bridge the properties of individual components with their abilities to display emergent properties within a given suite of geo/physico/bio/chemical settings. One example of this approach (among many) is to bridge the gap between the fruitful studies of individual catalytic RNA molecules (ribozymes) and the almost complete lack of studies of multi-step pathways or systems of reactions catalyzed by RNA or their impact on living organism. The field of Synthetic Biology offers rich opportunities for infusing these efforts with useful experimental, conceptual and computational tools. Furthermore, these efforts should be informed—but not strictly circumscribed—by the unfolding understanding of planetary (and cometary, etc) inventories and conditions, whether large-scale or niche, stable or transient, current or historical. Explicit emphasis on the multiplicity of mechanisms to make life under a variety of conditions will help define the robustness of the Origins process in general and the probability of Life beyond Earth.

LEVERAGING THE STRENGTH OF COMPARATIVE PLANETARY GEOLOGY IN THE COMING DECADES. Paul K. Byrne[1], [1]Planetary Research Group, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695, USA (paul.byrne@ncsu.edu).

Introduction: In 1984, thirty three years before the Planetary Science Vision 2050 workshop, humans had yet to fly spacecraft by the ice giants and their moons, no rover had successfully explored Mars, half of Mercury remained unseen, and no asteroid, comet, or dwarf planet had been visited. Our knowledge of the Solar System, although substantial even in 1984, has increased markedly in the years hence. What new discoveries await us in the next thirty three years?

A key tool for maximizing the scientific value of those discoveries is comparative planetology, by which the landforms, processes, and properties of other planetary bodies are assessed in the context of our understanding of similar phenomena on Earth. There has been no shortage of efforts to compare other worlds with Earth, or with each other, and numerous excellent compilations of these efforts exist for topics as diverse as planetary climate, ring systems, atmospheres, magnetospheres, interiors, and even habitability [e.g., 1–7]. Yet far more can be done to leverage the power of comparative planetology in the years to 2050.

Take geology, the field with which this author is more familiar: comparative planetary geology has been applied successfully in studies of the numerous Solar System bodies [e.g., 8–10]. Specific instances—of which there are a great many!—collectively define a wide range of topics that encompasses the assessment of extraterrestrial aeolian dunes with those on Earth [11], the characterization of how lacustrine and fluvial landforms on Titan parallel those on our own world [12], and the investigation of large-scale crustal shortening structures on Earth as analogues to tectonic landforms on other worlds [13].

Earth vs. Other Planetary Bodies: However, the field of planetary geology is small compared with the discipline of geology overall, the major focus of which is on Earth landforms and processes. (As a crude metric by which to illustrate this difference in size, Planetary Geology is but one of 18 Geological Society of America Divisions; at least eight other divisions overlap thematically with planetary geology. The European Geosciences Union is similarly structured: Planetary and Solar System Sciences is one of 22 divisions.)

Further, few students reading geology at post-secondary level are exposed much (if at all) to geological processes on other bodies. (The author writes from experience). As a result, students acquire a detailed training of the geology of a world with plate tectonics, even though that process is almost exclusive to Earth. Similarly, most solid-surface bodies in the Solar System are heavily cratered, many are dominantly volcanic in nature, and almost none interacts with a hydrosphere—so the geological processes and landforms to which most students are exposed are the exception, rather than the rule. On the other hand, the early histories of many Solar System bodies are recorded on their surfaces, providing insight into the conditions and processes likely present on the ancient Earth, for which little evidence now remains. As for any aspect of planetary science, then, the study of the geology of other worlds facilitates a better understanding of our own planet, and a thorough grounding of the geology of Earth allows for a more comprehensive view of our Solar System neighbors.

Opportunities: The pace of geological discoveries in this solar system is likely to increase even in the relative near-term [e.g., 14–16], and so there continues to be enormous scope for combining the expertise of researchers who focus on Earth-based geological topics with those who specialize in planetary geology.

Moreover, the greatest volume of new planetary science discoveries in the past couple of decades has come not from exploration of this solar system, but from astronomical characterization of extrasolar planets. Prior to the early 1990s we had no definitive evidence that planets existed in other star systems [17,18], but as of the time of submission of this abstract, 3,545 planets in 2,659 planetary systems are known [19]. With numerous missions currently working to characterize additional extrasolar planets, and yet more such missions planned [e.g., 20,21], it is likely that this field will continue to grow much faster than Solar System science in the next 33 years.

Finally, there exists the possibility—however remote—that extant or fossil life will be discovered on or within another planetary body in the next 33 years. Such a discovery would change planetary science fundamentally, with the biological sciences quickly playing a considerably larger role in planetary research than they do now, and planetary geology placing a greater focus on geobiology and paleontology.

A sustained and focused effort by planetary geologists to engage the global geological research community via thematic colloquia, interdisciplinary sessions at meetings, and topical special issues will foster comparative geological investigations. Working to integrate planetary geology topics into undergraduate (and even secondary and primary) education will ensure a steady supply of researchers cognizant of how our world resembles, and differs from, other Solar System bodies. These efforts will be augmented by partnering with the astronomical and biological disciplines as fully as possible, to apply comparative planetary geology to our growing understanding of extrasolar worlds, and to rise to the incredible challenge of helping to characterize how, where, and when extraterrestrial life arose, should the need arise. And above all, it will be crucial to these efforts to encourage policy makers and funding agencies to support comparative planetary geology through existing and new interdisciplinary programs.

Outlook for : It may be too lofty a goal to have dropped by 2050 the "planetary" in planetary geology, whereby the study and comparison of other bodies is as fundamental a part of the geological curriculum as petrology or stratigraphy—but the *spirit* of that goal should drive us over the next 33 years.

More broadly, we should continue to take every opportunity to more closely align planetary geology with the other disciplines that constitute planetary science, including (but by no means limited to) astronomy and biology. Advocacy for comparative planetary geology—and comparative planetology in general—must feature in the growth of our community going forward, for we will come to understand the workings of this and other solar systems most effectively only when we operate as more than the sum of our parts.

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Mars 2050: Air Vehicles and Extreme Environments. W. M. Calvin[1], [1]Department of Geological Sciences and Engineering, University of Nevada–Reno, wcalvin@unr.edu.

Synopsis: Mars Sample Return is the highest priority in the Planetary Sciences Decadal Survey and Humans to Mars continues to energize the public and underlies the long-range plans for the Journey to Mars NASA vision. Development of air vehicles for Mars and deep drilling or rover access to the Martian poles will enable pioneering exploration and science of the planet while also benefitting outer planet and ocean world missions.

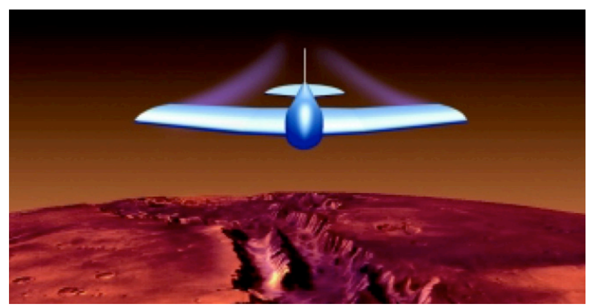
First, a look back: In 1986 I had just begun my graduate career at the University of Colorado in Boulder. I was working with Bruce Jakosky on a model of radar scattering from Mars, which ultimately became my first peer-reviewed paper (published in Icarus in 1988). Students in LASP were eagerly anticipating the launch of Galileo to Jupiter, until the Challenger Shuttle explosion grounded the shuttle fleet and delayed the planned launch. We were in the planning stages for Magellan's orbit of Venus, Mars was on hold following Viking, and my former boss at Ball Aersopace was planning participation in ESA's Giotto mission to encounter Halley's comet.

In the three decades since we have completed orbital or fly-by reconnaissance of every type of object in the solar system, including the major planets and their moons, asteroids, comets and dwarf planets. We (or our international space partners) have returned samples of the solar wind, comet dust, and asteroids. We have landed on Titan and roved on Mars, and sent projectiles hurtling into the Moon and comet Tempel 1. We have also had our share of failures.

Fast Forward to 2009: As the Vice-Chair of the Mars panel and a member of the Steering Group for the most recent decadal survey "Visions and Voyages" [1], the Mars panel Chair, Phil Christensen, and I worked to create a panel that encompassed the science of Mars from the core to the atmosphere, and I think we were successful at that. While Mars sample return emerged as the highest priority, both for the Mars community and the decadal report overall, there is obviously much to be done at Mars beyond sample return and understanding resources to support the eventual work of astronauts on the surface.

The Future: While numerous scenarios can be imagined there are two technologies that could enable break-through discoveries in Mars science. This includes development of air vehicles that operate in the extremely thin martian atmosphere, and electronics that can survive the extreme temperatures at the polar regions. These take advantage of the emerging field of autonomous air vehicles on Earth and a vast legacy of polar exploration that continues to inspire the public's imagination.

Air Vehicles. Although our landed vehicles have been tremendously successful at Mars, Opportunity has traveled only 40km over the span of nearly 13 years. While that may set a distance record for autonomous driving, it is paltry compared to what could be and has been imagined for unpowered and powered flight on Mars. The KittyHawk Discovery class mission concept [2] dropped gliders from orbit that were deployed in the atmosphere to traverse ~ 140km over rugged terrain that is inaccessible to landed and roving vehicles. The ARES powered aircraft [3] would have also deployed in the atmosphere and executed a pre-defined trajectory covering 500km within an hour. I have recently consulted with an engineering firm that has credible and exciting designs for vertical take-off and landing (VTOL) small aircraft that could be used as reconnaissance for up to 10km from a base station in hours rather than years.



All these advanced concepts would allow reconnaissance over larger distances in shorter periods of time than land-based vehicles. Science instruments on board could collect critical data on atmospheric winds and composition, surface and sub-surface resources and the planet's deep interior. Such technologies could also be envisioned to allow break-through science discoveries on Titan or Venus as well.

Extreme Environments. For the decadal I was also "science champion" for a rapid mission architecture study to consider mission concepts for crucial Mars climate observations [4]. Surface access at the poles via sampling or drilling has been widely proposed as the only way to constrain recent Martian climate history [5,6], understand the stratigraphic record preserved in the polar layered deposits [7], and search for potential biomarkers in buried ground ice - one of the most habitable places on Mars [8]. The success of the Phoenix lander notwithstanding, significant hurdles exist for long-lived missions that seek to access the ice-rich terrains at latitudes above 70º. Both landed and roving mission scenarios would benefit from using ASRGs as a power system instead of solar, and such systems might even survive a full martian year. This would enable direct observation of the polar environment throughout the spring, summer, and fall seasons during which the majority of the atmospheric interaction takes place. Technology development supporting deep drilling would allow unprecedented access to the subsurface of Mars. This technology could also enable innovative or pioneering explorations of icy satellites and ocean worlds.

The World's View: Planetary exploration is already encountering private sector influence (Google's Lunar X Prize) and increased international participation (India's MOM, China's Jade Rabbit lunar rover, UAE's planned Mars orbiter "Hope"). In the coming years, these developments are expected to continue to build, and will create a crowded playing field vying for the public's attention and continued Federal support. NASA's role and legacy should always be one of "firsts" lest we lose the 21st century space race. I propose "fly Mars" and being the first to touch the poles of Mars (celebrating and honoring the many terrestrial Arctic and Antarctic expeditions), are compelling ways to continue our long and storied history of exploration.

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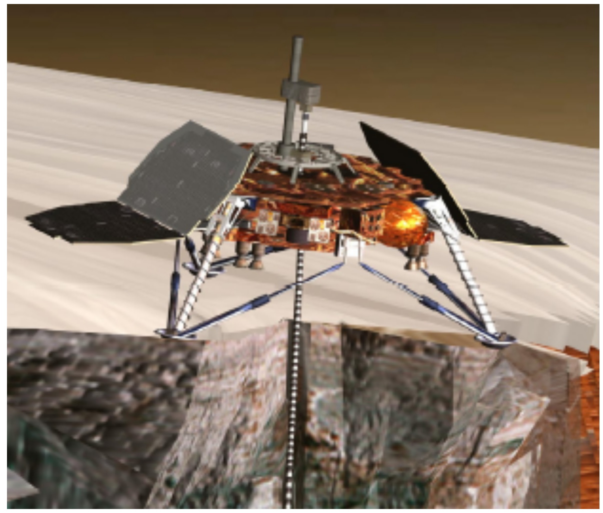

EXPLORING BELOW THE SURFACE AT HUMAN SCALES: ADDING A THIRD DIMENSION TO OUR KNOWLEDGE OF PLANETS.

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Introduction: Much of our exploration in the last decade has focused on surface imaging and compositional mapping. Near surface geophysics, the upper tens of meters to a couple hundred meters, provides information about the structure and composition of the subsurface. These techniques include ground penetrating radar, seismic studies, magnetics, electromagnetics methods like TEM (transient electromagnetism), high-resolution gravity and radar imaging of the subsurface at long wavelengths. These data products contribute a complimentary view of the evolution of planetary surfaces by measuring and mapping stratigraphy and compositional differences that are produced by processes such as regolith development, volcanism, aeolian deposition, cementation, impact cratering, and fluvial and lacustrine processes. These techniques penetrate through dust and regolith layers to reveal past environments and provide a more complete view of the evolution of local to regional scale surface regions.

The development of near surface geophysical techniques has been closely related to the field of exploration geophysics for the Earth, because these techniques produce data products that are of relevance to human resources. They can be used to find mineral resources underground, and to pave the way for safe construction and digging. These techniques produce data with a vertical scale (cm to tens of m) that is practical for human activities. As such, the development and deployment of packages of geophysical instrumentation to other planets will greatly reduce the risk associated with human exploration of the Moon and Mars.

There have been very few geophysical spacecraft instruments, and so the upper part of the subsurface remains a mystery in most cases. Many geophysical techniques common in terrestrial field work have never been used on the surface of other planets. In the next 30 years, advances in instrument technology, automation, and data downlink could provide the opportunity to fill in the gaps in our knowledge of the subsurface, and add a third dimension to planetary maps.

New Technologies: The high resolutions of many of these techniques, particularly radar surveys, produce large amounts of data that pose a challenge to return to Earth, especially when multiple instruments compete for downlink. Optical communications and a more robust data downlink infrastructure are very important for high data volume, multiple instrument surveys.

Dramatic improvements in onboard processing software will also significantly improve our ability to collect a diverse suite of data. For example, ground penetrating radar (GPR) systems benefit from multi-mode operation and an ability to adjust sounding depth and sampling depending on the characteristics of the subsurface [1]. Onboard data processing could also compare the data from multiple instruments to decide which measurements will be the best choice for any given terrain, depending, for example, on what has already been detected in the subsurface along the trace.

These onboard decision-making capabilities will require mobile platforms with greater autonomy and longer lifetimes than are possible today. Automation will enable the use of geophysical techniques as they are used on Earth – including large scale and multiple remote sensor systems surveys. Gridded GPR radar studies require the ability to choose traverses without constant intervention from humans, and seismic packages benefit from long lifetimes (e.g. [2]. The ability to rove on the surface or fly on a drone provide higher resolution and greater signal-to-noise than operating from orbit, and by 2030s such systems could be equipped with geophysics tools to create subsurface maps that integrate seamlessly with our surface images. This next generation of software and spacecraft infrastructure (communications and standard mobile platforms), is a key technology for regular collection of data of the near subsurface.

Significant improvements in instrument technologies are also needed. For radar systems, advancement

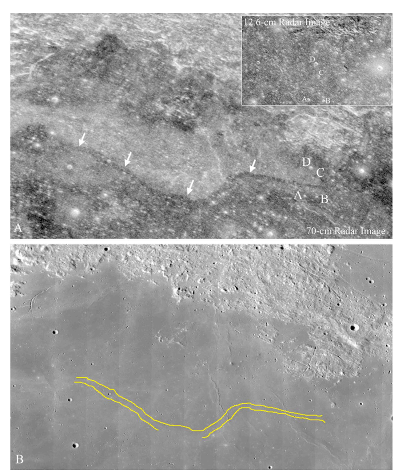

Fig 1: Radar images (70 cm wavelength) at ~ 200 m spatial resolution reveal buried lava flow structures in Mare Serenitatis, including possible lava tubes [3].

in digital components to accommodate high bandwidths and use less power, along with new antenna designs that enable beam steering from orbit and greater gain for ground penetrating radar systems would produce low power systems that can see deeper with better signal to noise and/or lower power than are used today. For all instruments, the ability to work in extreme environments (e.g. Venus surface, near active volcanoes, high radiation regions, very cold surfaces) will create opportunities for paradigm shifting science for Venus and the outer Solar System.

Finally, data processing on the ground also has the potential to revolutionize how geophysics is used in space. Advancement in inversion techniques and statistical methods will provide faster science results that also avoid the "non-uniqueness" problems that many geophysics techniques have today. The ability to simulate many surfaces, compare with multiple types of 3D remote sensing data, and calculate likelihood estimates will produce better quantitative science results and allow geophysics data to be used by non-specialists. Investments in these types of software should be made now, to ensure that new data will produce the best, fastest science results.

Example science advancements:

- **Venus:** In the next 30 years, Venus landers with geophysical instrumentation have the potential to significantly change our current understanding of the planet. For example, in order to understand the provenance of tesserae regions, geophysical remote sensing will almost certainty be needed to determine their density, internal structure, and relationship to the plains. A Venus seismic package would finally provide information about the nature of the crust. Rovers could provide radar profiles near regions of tesserae to investigate the boundary between the plains and highland crust.
- **Moon:** The Moon is an obvious choice for the near-term deployment of geophysics instruments because of the science relevance for understanding the Earth-Moon system, proximity of the Moon to Earth, potential for long duration science packages, and importance for human exploration. Orbital radars could be used to map buried lava flow features such as channels and possible lava tubes [3, Fig. 1]. Future human missions need safe shelter from radiation events, and geophysical techniques can be used to find buried caves that be used in case of emergencies.
- **Mars:** Rover-based ground penetrating radar can attain cm scale vertical resolution and see tens of meters under the surface (Fig. 2) to map stratigraphy at scales relevant to local studies of volcanism, aqueous deposition, and ice detection. Magnetic and gravity surveys would provide new information about volcanism and volcanic pluming systems. In the 2030s, multiple autonomous rover systems could use radar and other remote sensing techniques to regularly track subsurface stratigraphy and look for buried ice or brine deposits. Such systems would be able to operate at lower frequencies and autonomously decide on data collection strategies based on current collected data. Airplanes and helicopters could also carry science instruments to map wider areas, and regions where rovers would be slow due to very rugged terrain. High-resolution topography and advanced processing will allow a 3D model of the surface even in high-clutter situations [4].

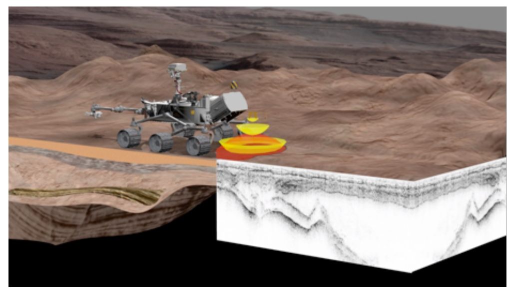

Fig 2: Ground penetrating radar, such as the RIMFAX radar on the Mars2020 mission, can map subsurface structure, discover buried features, and provide important context for surface exploration. Credit: FFI, [1]

- **Asteroids:** Geophysical remote sensing will also be key to exploring asteroids and comets [5,6]. Orbital GPR can be used to map the stratigraphy of the upper hundred meters of larger tens to hundreds of km-sized objects, something that we currently have no data for. Such observations could also be used to search for buried ice.
- **Outer Moons:** The discovery of likely subsurface oceans associated with many outer Moons has led to increased interest in a robust program to determine the extent and properties of liquid water in the subsurface [7]. The near surface structure of these objects is currently unknown but is critical to understanding the observed surface features, assessing the habitability of the different icy moons and providing information for future landers that may have drills or sampling systems.

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SMALL INSTRUMENTS FOR PLANETARY SCIENCE APPLICATIONS – STATUS AND WAY FORWARD. J. C. Castillo-Rogez, S. M. Feldman, J. D. Baker, G. Vane, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109.

Introduction: Nano-platforms, in the 1-10 kg range, are gaining maturity for deep space exploration thanks to increased investments from various space agencies into miniaturized subsystems and instruments. The last decade has seen the introduction of small platforms such as JAXA's Minerva hopper and the MASCOT (Mobile Asteroid Surface Scout) [1] developed by the German Space Agency (DLR), both of which are flying on the Hayabusa 2 mission. Rover missions to Mars developed by NASA (e.g., Pathfinder, Mars Exploration Rovers, Mars Science Laboratory) and ESA (e.g., Huygens, Rosetta's Philae, ExoMars) have fostered the development of small in situ instruments, some of which can be leveraged on future nano-spacecraft. NASA's recent focus on planetary Cubesats has led to the development of a reference 3U bus (INSPIRE, Interplanetary Nanospacecraft Pathfinder in Relevant Environment, [2]) and a 6U bus (MSFC NEAScout and JPL Lunar Flashlight missions [3]) developed under the sponsorship of NASA HEOMD. The growing interest across the science community for Cubesats and other nanosatellites for deep space exploration requires the availability of instruments that can be implemented on these platforms while providing sufficient performance capability.

We review the current state of the art in small instruments that may be applicable to future missions involving independent or deployable platforms in the 1-10 kg range. We first highlight instruments inherited from past missions and then address requirements and paths forward for the development of future small instruments. This abstract is relevant to all the themes of the *Planetary Visions 2050* Workshop in support of science applications that might leverage or be best addressed by small spacecraft (e.g., [4]).

Framework: Nano-spacecraft open a new dimension in planetary exploration with the introduction of new architectures that offer the potential to increase science return at low additional cost through networked constellations [4], complementary vantage points between mothership and daughterships, multiple atmospheric probes, and expandable assets for the exploration of high-risk areas (e.g., cometary plumes) [5]. An obvious trade to the low scale and cost of these platforms is a degradation in science data quality and quantity in comparison to the science return of larger missions, which the planetary science community is used to obtaining.

Mass and power are obvious limitations intrinsic to nano-spacecraft. Smaller detectors and apertures generally imply degraded spectral resolution and spatial resolution. These may be compensated for by flying the spacecraft closer to the target or by defining science objectives that can be achieved with reduced performance. Short lifetime and limited data rates require science to be returned shortly after acquisition. Operational complexity, associated for example with material sampling and processing, or calibration, may simply preclude the implementation of certain measurement techniques into small spacecraft. As the field of miniaturized instruments progresses, it will be important to consider new ways of implementing old techniques. This is expecially true for optical instruments which could benefit greatly from the most recent technological advances enabling miniaturization, for example computational methods, on-chip spectrometers, and new semiconductor-based devices.

State of the Art in Small Instruments: A review of instruments that have flown on past and current missions shows the availability of a spectrum of geophysical and fields and particles instruments (seismometers, penetrometers, thermal probes, particle detectors, etc.); only a few optical and spectrometer instruments are available in a small form factor, including visible cameras (e.g., NEAScout imaging system [3]), ultraviolet sensors [6], new generation of small IR-spectrometer such as the Lunar Flashlight point spectrometer [7], the LunarCubes' BIRCHES [8], as well as a submillimeter wave spectrometer currently in development at JPL. A few analytical chemistry instruments have already been demonstrated on small landers, including an alpha-particle X-ray spectrometer [9] and gas chromatograph-mass spectrometer [10]. More advanced spectrometers for chemical measurements, especially isotopes, typically require larger platforms, especially when solid material sampling and processing is required. However a new class of miniaturized mass spectrometers (e.g., JPL's quadrupole ion trap mass spectrometers [11]) will open up possibilities in atmospheric sampling with small probes [12]. Tunable laser spectrometers have seen a huge success in recent years, with the tunable laser spectrometer (TLS) on Curiosity, capable of measuring gas abundances and isotope ratios to extremely high precision [13]. The feasibility of miniaturizing to a ~2U form factor has already been established, and instruments targetting specific gases and isoptope ratios (e.g., D/H in H_2O) could be designed to fit on small platforms. These instruments could, for example, sample cometary plumes, or deploy mechanisms for surface heating and gas capture on icy bodies. Key technological gaps have been identified in the area of radar instruments, although novel approaches such as passive radio experiments could enable probing deep interiors with small spacecraft from orbit or even during flybys [14].

Many instruments required for addressing strategic knowledge gaps at Near Earth Asteroids and Mars' moons are already small enough to be deployed on small spacecraft as is illustrated by recent Cubesat concepts: NEAScout [3] and the Hedgehog platform currently developed under NASA's Space Technology Mission Directorate [15].

Emerging Technologies for the Next Generation of Small Instruments:

- Advanced detector technologies, e.g. the HOTBIRD (High Operating Temperature Barrier Infrared Detector [16]), enable instrument miniaturization without loss of performance.
- Increased aperture, for example in the context of Cubesat-based exoplanet search and characterization; origami-inspired deployable optics have been recently introduced as a promising approach [17].
- Increased on-board intelligence can help optimize science return when lifetime and downlink resources are tight and/or when observing opportunities are time constrained, e.g., in the case of a flyby or impacting experiment. Agile Science algorithms [18] can help optimize science return via on-board data processing, compression, and triage.
- Deployment mechanisms: low-cost nano-spacecraft should ideally avoid the number and complexity of internal mechanisms. However deployable booms have been recently introduced, for example for the INSPIRE magnetometer and RainCube Ka-band radar mission [19].
- Smart configuration of the lander may help optimize the shielding of electronics [20], as well as relax operational requirements, e.g., thermal control
- Low-temperature electronics would be suitable in order to relax requirements on thermal control.
- Smart packaging, for example foldable electronics, can help to significantly decrease instrument volume.
- The development of standard instrument interfaces will also be instrumental to the introduction of reference nano-spacecraft flight systems that may be considered for a variety of missions.

Environment-Specific Requirements: Significant customization of miniature instruments is likely to be required for high-radiation, extreme temperature, atmospheric, and/or in situ environments. This may conflict with the perception that nano-spacecraft, and especially Cubesats, may offer reference platforms for plug and play experiments. For example, instrument types for future small-class deployable platforms at Europa are currently limited to field and particle measurements. High-g investigations (penetrators) set requirements on instrument survivability that may be out of reach from the current generation of instruments, except for seismometers [21].

Acknowledgements: This study is being developed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA.

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ROADMAP FOR THE EXPLORATION OF DWARF PLANET CERES.
J. C. Castillo-Rogez[1], C. A. Raymond[1], C. T. Russell[2], A. S. Rivkin[3], M. Neveu[4], Ceres afficionados all over the world. [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA (Julie.C.Castillo@jpl.nasa.gov), [2] Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA. [3]Applied Physics Laboratory, John Hopkins University, Laurel, MD. [4]School of Earth and Space Exploration, Arizona State University, Tempe, AZ.

Introduction: Ceres, the largest asteroid, and only dwarf planet found in the inner solar system, offers a playground for testing hypotheses pertaining to the early Solar system evolution as well as the habitability potential of large volatile-rich bodies. The Dawn mission has revolutionized our undertanding of Ceres in a decade that has also seen major breakthroughs in solar system dynamical modeling, cosmochemistry, and the rise of ocean worlds. Probably the most significant finding from the Dawn mission is unambiguous evidence for oceanic material right on Ceres' surface associated at least in one place with a recent cryovolcanic feature. This goes above and beyond pre-Dawn predictions. This and other discoveries from the Dawn mission are raising new questions and setting the stage for future exploration, as described in this presentation.

Post-Dawn State of Knowledge of Ceres: Ceres is one of the best explored solar system bodies thanks to the extensive observation campaign achieved by the Dawn Mission. The combination of mineralogical, elemental, geological, and geophysical observations set standards for future missions. These led to key findings, including the confirmation that Ceres has been subjected to the hydrothermal processing of its materials at the global scale, likely fueled by short-lived radioiostope heat [1]; the discovery that that environment involved ammonia- and carbon-rich compounds, pointing to an origin of Ceres' materials from the outer solar system; a geology driven in part by volatile abundance in multiple forms, including ground ice, persistently shadowed regions, and icy regolith toward high latitudes [2, 3, 4]; the likely role of brines in driving cryovolcanism in the form of several outstanding features (Ahuna mons and Occator bright spots, as well as potential ancient features in the same vein) [5]; and the signature of volatile activity driven by solar wind [6].

Dawn's observations have been complemented over the past years by investigations with the Hubble Space Telescope leading to the finding of abundant carbon on Ceres' surface, as well as, potentially, sulfur rich species [7]. The discovery of water vapor by the Herschel Space Observatory [8] is consistent with the detection of many ice-rich sites, suggesting that ice is present below a thin regolith and regularly exposed via landslides and small impacts.

These pieces of information allow for a fresh assessment of Ceres' astrobiological significance, which was identified prior to Dawn's arrival [1] and have led Ceres to turn from a "*credible*" possible ocean world to a "*candidate*" ocean world [9]. Specifically, in the frame of the Roadmap for Ocean Worlds Goals, Dawn brought positive answers to the following questions: *Goal 1 (Identify Ocean Worlds), A.1 Is there remnant radiogenic heating? B.1 Do signatures of geologic activity indicate the possible presence of a subsurface ocean? B.7 Can the surface composition be linked with the presence of a sub-surface ocean?*

Dawn's discoveries at Ceres also introduced new evidence (or context) for addressing questions of broad interest. First, the presence of ammonia adds to the story of early Solar system migration although alternative scenarios are possible [10]. Also the nature of oceanic material on Ceres' surface, including sodium carbonate [11], a species found only on Earth and Enceladus' plumes [12], can help better understand the geochemical processes ongoing in other ice rich bodies. Indeed, per its size and water abundance, Ceres belongs to a class of objects that could host relatively alkaline conditions as was suggested for Europa [13] and inferred from Cassini observations of Enceladus [14]. It has been suggested that the deep oceanic material could be exposed via the removal of an ice shell via impact-induced sublimation [15]. This combined with clues for carbon suggests that the study of Ceres' surface directly addresses the ROW *Goal II B.3 "Characterize the ice-ocean interface"* and offers a playground for testing hypotheses aboud the chemical evolution and habitability potential of Ocean Worlds.

Key Open Questions: *Workings and Life*: The next step in the assessment of Ceres' astrobiology significance is to evaluate the extent of liquid in its interior. This is a difficult endeavor for bodies that are not subject to tidal deformation and sources of seismological activity. This question might be addressed by studying the interaction of Ceres with the solar wind although this remains to be quantified. Comparison between images returned by Dawn and a future mission could be used to search for the signature of a deep liquid layer in Ceres' rotation [16] and possibly also reveal telling changes in surface properties. Indeed the key to evaluating Ceres' internal structure might come from the long-term observation of the faculae (bright deposits) observed in the Occator crater. The exposure age of those deposits appears inconsistent with the ~100My age of the crater and may indicate that the reservoir involved in the formation of these features is not yet at thermal equilibrium.

If pursuing the exploration of Ceres in the context of the Roadmap for Ocean Worlds, a future mission to Ceres could address the following questions, e.g., *Goal II (Characterize the Ocean), A.1 What is the thickness, salinity, density and composition of the ocean? How do these properties vary spatially and /or temporally? Goal III. (Characterize the Habitability), A.1 What environments possess redox disequilibria, in what forms, in what magnitude, how rapidly dissipated by abiotic reactions, and how rapidly replenished by local processes? B.1 What is the inventory of organic compounds, what are their sources and sinks, and what is their stability with respect to the local environment? B.2 What is the abundance and chemical form of nitrogen, oxygen, phosphorus, sulfur, and inorganic carbon, what are their sources and sinks, and are there processes of irreversible loss or sequestration relative to the liquid environment?*

Origins: Despite the evidence for ammonia and carbon compounds the origin of Ceres remains uncertain; several competing theories can explain an origin of Ceres at its current location with supplies of solar system planetesimals [17] or even from ammonia-rich organics formed in the inner solar system [18] These various hypotheses may be addressed via isotopic chemistry of low-z elements, and especially hydrogen, oxygen, and nitrogen isotopes. However, the extensive hydrogeochemistry that modified Ceres' materials also likely altered their original isotopic signature. Hence answers to volatile migration might be better addressed at more primordial objects (e.g., comets, smaller C-type asteroids, main-belt comets).

A Roadmap for Ceres Exploration: The in situ investigation of outstanding landmarks is an obvious next step in the exploration of Ceres and might be accomplished within the constraints of the Discovery program. Key objectives could focus on assessing habitability (the natural next step in the ROW framework) by investigating the chemical fingerprints contained in bright deposits to infer constraints on the environment in which they formed. Geophysical measurements are required to assess the extent of a deep liquid layer including high-resolution gravity measurements to study the endogenic processes driving cryovolcanic features. A Dawn follow-on mission could also aim to clarify the nature of the dark material covering the surface and the mechanisms involved in its formation (hydrothermal, space weathering).

The answers to these questions would drive the third step in Ceres' exploration, with regard to better understanding "*how life might exist at each ocean world and search for life*" [ROW *Goal IV*]. Exploration strategies developed for Mars may be applicable there, in particular planetary protection technologies.

Finally, the exploration of Ceres and large icy satellites requires a theoretical framework and experimental progress to assess, e.g., the stability and thermophysical properties of salt-rich materials, the physics driving endogenic processes in a (relatively) small gravity body, exogenic processes altering its surface, and the development, thriving, and preservation of life and biosignatures in salt-rich environments.

Ceres as a Stepping Stone for the Exploration of Ocean Worlds: Ceres represents a critical data point for understanding the chemical evolution of volatile-rich worlds and especially their potential for forming and preserving organic compounds. With it low gravity and relative begnin environment, Ceres also offers easy surface access (in comparison to Mars or Europa) whereas the roundtrip light-time to/from Ceres requires the introduction of semi-autonomous techniques for advanced surface operations. Hence a long-term exploration program of Ceres is compelling, not just for the anticipated science return, but also because it will help us practice and hone new technologies of relevance to the future exploration of ocean worlds, such as surface operations, planetary protection, and end-to-end sample collection and return to Earth.

Acknowledgements: This work is being carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA.

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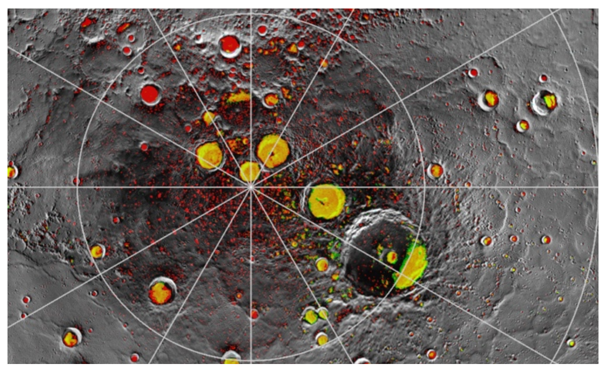
FUTURE MERCURY EXPLORATION: UNIQUE SCIENCE OPPORTUNITIES FROM OUR SOLAR SYSTEM'S INNERMOST PLANET. Nancy L. Chabot[1], Ralph L. McNutt, Jr.[1], David T. Blewett[1], Brett W. Denevi[1], Carolyn M. Ernst[1], Erwan Mazarico[2], Lauren M. Jozwiak[1] [1]Johns Hopkins Applied Physics Laboratory, Laurel MD 20723. (Nancy.Chabot@jhuapl.edu), [2]NASA Goddard Space Flight Center, Greenbelt, MD, 20771.

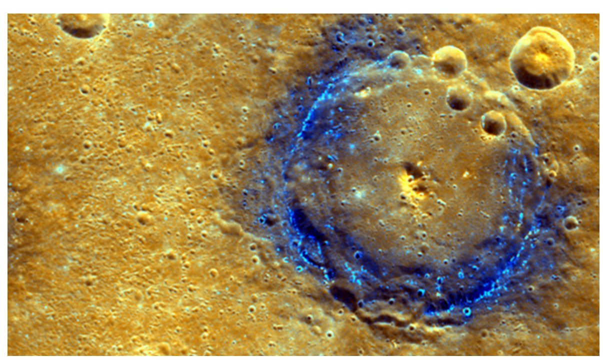
The Need: Mercury is one of only five terrestrial bodies (the four rocky planets and the Moon) in the inner Solar System, each of which is unique. Mercury represents an endmember of planetary formation: the planet closest to the Sun, with a highly reduced, but volatile-bearing surface, and an oversized metallic core in comparison to the other planets. A truly fundamental question in planetary science is: *What properties and processes make these terrestrial bodies form and evolve along different paths, resulting in the diverse bodies that we observe today?* The future scientific exploration of our Solar System must use all five bodies to make advances on this fundamental question. The implications are significant, not only for understanding our own Solar System but also for understanding Solar System formation and evolution in general and interpreting exoplanet systems. Any Planetary Science Vision must include Mercury exploration.

The Present: NASA's recently completed MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission was hugely successful, returning unprecedented data about Mercury [1]. The joint ESA-JAXA BepiColombo mission [2] is scheduled to launch shortly, carrying two orbiters to further advance knowledge of the space environment and surface science of the planet. Continued support for research investigations related to and motivated by these orbital datasets is critically important. With these orbital missions, the reconnaissance and initial exploration phases of investigating Mercury will have been completed [3], laying the foundation for the next phases of Mercury exploration.

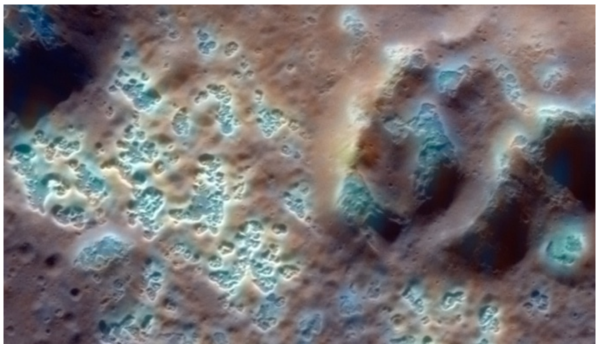
The Near Future – Landed Science: The next step in Mercury exploration is to conduct *in situ* investigations on the surface. Though Mercury's proximity to the Sun means the surface reaches temperatures as high as 700K in daylight and can plunge to 100K at night, even with current technology, short-lived landers and rovers to do focused science on the surface are possible. Varied mission designs, from a sunshade, to a nighttime or shadowed landing site, to a radioisotope power supply, for instance, can overcome the challenges of Mercury's thermal environment. Future technological advancements to operate landers or rovers at even higher temperatures than currently envisioned would also extend mission lifetime and the science achieved, enabling very accurate knowledge of Mercury's orbital and rotational dynamics through radio tracking. Technology to equip landers with seismic and heat flow instrumentation would provide crucial information about Mercury's internal structure, as would enhanced orbital gravity mapping. *In situ* age dating of any surface would establish key constraints on the chronology of Mercury's evolution. Launch vehicles larger than those of the Mariner 10 or MESSENGER missions could enable novel landed missions to Mercury, potentially even without the need for multiple gravity assists. Mercury is an evolved planet and consequently has a diversity of surface regions each with compelling science questions. Examples of high-science-return landed science locations, not in priority order, include:



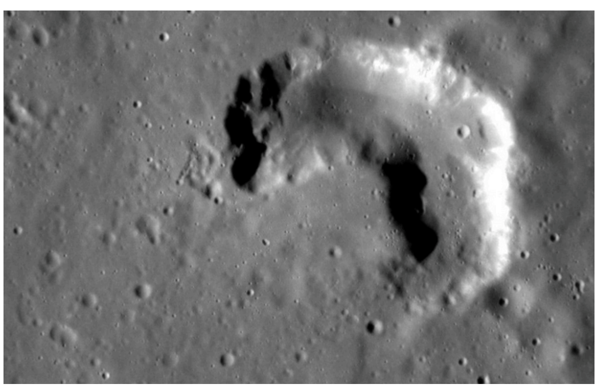
Polar Deposits. Extensive water-ice deposits are contained in the permanently shadowed regions near Mercury's poles, hypothesized to be covered by organic-rich volatiles. A landed science mission would determine the composition, distribution, and physical properties of these deposits, answering key questions about the delivery, evolution, and retention of water and organics to the terrestrial planets, with comparisons to lunar polar cold traps and potential implications for early Earth. [e.g., 4, 5]



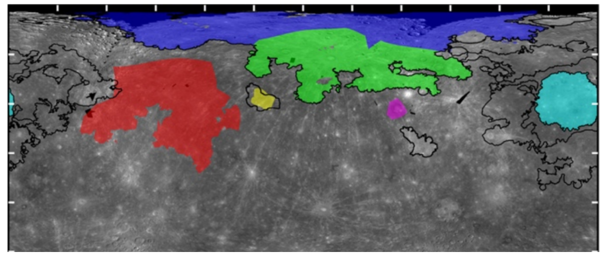
Low-Reflectance Material. Mercury's carbon-rich low-reflectance material appears to stem from Mercury's ancient crust, providing unique insight into the early stages of planetary evolution. A landed science mission would determine the mineralogical nature and elemental makeup of this material, testing models of early crust formation on Mercury and the processes of early crustal formation in general, which are not preserved on Venus and Earth. [e.g., 6]



Hollows. Discovered by MESSENGER, hollows are enigmatic landforms that appear to be extremely young and unique to Mercury, potentially forming in the present day. A landed mission would determine crucial information on the composition, physical properties, and the processes that formed hollows. This information would provide insight into the roles played by volatile elements in Mercury's crust and the relative importance of solar heating, micrometeoroid impact, and ion bombardment in the extreme form of space weathering that occurs on Mercury. [e.g., 7, 8]



Volcanic Features. Mercury's surface has been heavily shaped by volcanism, with extensive smooth volcanic plains and explosive volcanic vents distributed across the surface. A landed mission would determine the elemental and mineralogical composition of these volcanic features, providing new insight into the nature of Mercury's magma source regions and key constraints for thermal models of the interior and the timing of volcanism in relation to Mercury's global contraction. [e.g., 9, 10]



Geochemical Terranes. Mercury's surface shows evidence for distinct geochemical terranes, each with unique elemental compositions. A landed mission to a given terrane would determine the distinct mineralogical and chemical characteristics of the terrane, enabling a new understanding of how the terranes relate to each other and the extent to which mantle chemical heterogeneities or large impact events shaped the formation and evolution of the terranes. [e.g., 11]

The Distant Future – Multiple Landed Missions and Sample Return: From the preceding section, it is clear that a single lander or rover, equipped with *in situ* measurement capabilities, to any of these locations would address compelling science on its own, and is the next logical step in Mercury exploration. However, as at Mars, a single lander or rover cannot answer all of Mercury's highest level science questions. Technologies to support multiple landed missions, to multiple diverse surface locations, would be a game-changing advancement for Mercury exploration. Networked small landers or rovers communicating with a larger orbiter that would collect and relay the data back to Earth would enable the *in situ* exploration of multiple surface locations on Mercury.

Ultimately, sample return is key. The advanced analytical techniques in Earth-based laboratories always have, and will, surpass capabilities of *in situ* landed measurements. Advances in sample return capabilities, such as the technologies and architectures being developed for Mars, would enable samples returned from any Solar System body, including Mercury. High-performance launch vehicles could, with appropriate investment, enable Mercury sample return by 2050.

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SCIENCE POSSIBILITIES ENABLED BY THE MARS BASE CAMP HUMAN EXPLORATION ARCHITECTURE. T. Cichan, D. W. Murrow, S. D. Jolly, E. B. Bierhaus, and B. Clark, Lockheed Martin Space Systems Company (P.O. Box 179, MS H3005, Denver, Colorado, 80201)

Introduction: Orion, the Multi-Purpose Crew Vehicle, is a key piece of the NASA human exploration architecture for beyond earth orbit (BEO). Lockheed Martin was awarded the contracts for the design, development, test, and production for Orion up through the Exploration Mission 2 (EM-2). Lockheed Martin is also working on defining the cislunar Proving Ground mission architecture, in partnership with NASA. In addition, Lockheed Martin is exploring the definition of Mars missions as the horizon goal to provide input to the plans for human exploration of the solar system. A human mission to one of the two moons of Mars has been suggested as an easier precursor before a mission to land humans on Mars itself.

Here we describe the Mars Base Camp architecture, which includes human exploration of both Martian moons and provides an opportunity for the crew to interact with pre-staged robotic assets on Mars for the first mission to the Martian system [1] [2]. For later missions, the architecture includes a re-usable human lander for crewed sortie missions to the surface. This study is a high-level assessment to identify architecture drivers and science opportunities.

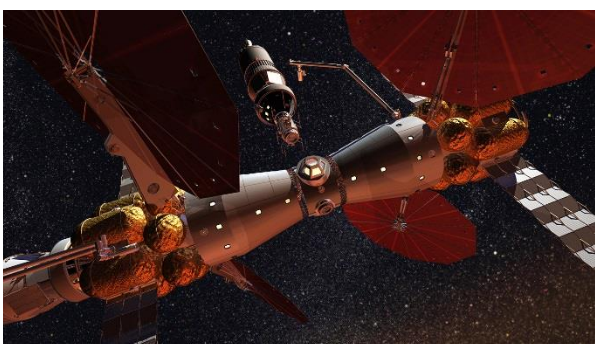

Fig 1. Phobos Sortie Mission Returning to Mars Base Camp in Martian Orbit.

ey Tenets: There are some key tenets for this architecture, including the assumptions that system redundancy and a self-rescue capability is required. Also, the number of system developments is minimized, and the use of the already developed systems like the Space Launch System and Orion is maximized. To avoid single events that could lead to the loss of crew, the architecture does not require rendezvous and docking at Mars of pre-staged elements. To maximize science return, we assume that the astronauts are trained scientists.

Mission Design: A key feature of this architecture is the comprehensive exploration of Mars from the 'high ground' of orbit and with sortie missions prior to selection of a location for long-term human presence. The crew spends about a year in orbit at Mars. The ability to tele-operate robotic assets such as rovers and UAVs will allow selection of the optimum site, balancing resource availability, safety, local science, and accessibility. Additionally, sortie missions allow Mars samples to be analyzed in the Mars Base Camp orbiting laboratory, in order to select the best samples for more detailed future exploration.

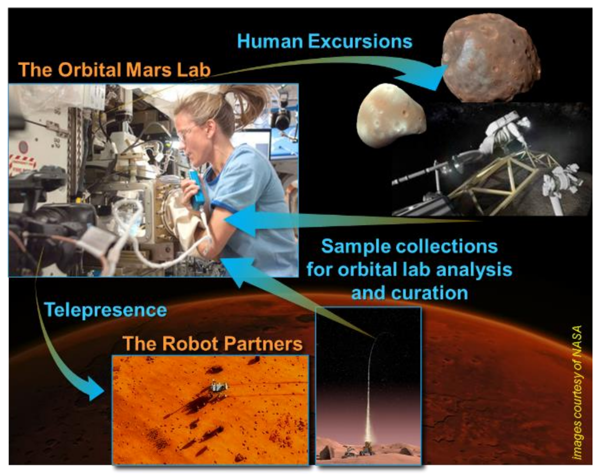

Fig . Mars Base Camp Orbital Mission Science Elements.

The initial mission's 1-sol orbit was chosen to allow surface synchronized telerobotic operations while optimizing the ΔV split between the large transit configuration, the smaller Phobos and Deimos sortie systems, and the robotic Mars ascent vehicle that delivers samples to Mars orbit for recovery by the Phobos sortie crew in the vicinity of Phobos. The selection of the possible Mars orbits for follow-on missions will be discussed, including how that affects the different missions that can be performed.

Laboratory E uipment: On the Mars Base Camp itself a preliminary allocation of 7.0 metric tons of science equipment is dedicated to the Laboratory Module, along with 40 kW of electrical power. These allocations are intended to be a starting point for the discussions of science objectives, measurement types, instruments and support equipment, sample curation, external robotic elements, interfaces, operational concepts, and the identification of driving functional and performance requirements.

Robotic Elements: Operated from orbit with low latency, surface rovers and perhaps aerial drones will be able to scout potential exploration zones for desirability. Orbital measurements indicating subsurface water, for instance, can be verified in-situ with a rover. This reconnaissance of potential landing sites, at ultra-high resolution, can provide detailed site survey information to validate sortie landing safety and eventual settlement suitability.

Cislunar Proving Ground: Since this architecture will be demonstrated in cislunar orbit before departure for Mars, there are opportunities to perform similar objectives from lunar orbit. The progression of Stepping Stones missions in cislunar space provides opportunities to develop and validate sample return and low gravity body mission elements, systems and protocols prior to their use at Mars.

Conclusion: The results of this architecture study will reveal possibilities enabled by a crewed orbital base camp, and that collaborative human and robotic missions should be part of the vision for Mars exploration by 2050.

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THE IMPORTANCE OF UV/VISIBLE SPACE-BASED TELESCOPIC OBSERVATIONS FOR PLANETARY SCIENCE. J. T Clarke[1], [1]Boston University (Center for Space Physics, 725 Commonwealth Ave, Boston MA 02215; jclarke@bu.edu).

Introduction: First rate science has repeatedly been accomplished with Hubble Space Telescope observations of solar system objects. In addition to unique discovery science, like the images of Jupiter during the impacts of the fragments of Comet Shoemaker/Levy 9, a large number of HST observing programs has been conducted over the years in coordination with various planetary missions of NASA and ESA. Planetary auroral observations were coordinated with Galileo (Jupiter) and Cassini (Jupiter and Saturn), airglow/coronal observations of Mars and Venus were coordinated with the MEX, VEX, and MAVEN missions, and there are many other examples. This presentation will give an overview of the science goals and outcomes of some of these programs to illustrate the importance of combined telescopic and in situ measurements.

Short History of HST Planetary Science: The scientific contributions from HST to solar system science comprise a list far too long to include in this abstract or to mention in the talk. The wide variety of scientific topics can be seen at the press release site (http://hubblesite.org/newscenter/archive/releases/solar-system/). Scientific observations have included every planet but Mercury (too close to the Sun for HST to observe), comets, asteroids, the Kuiper belt, and exoplanets. A few inspiring examples will be shown in the presentation, but the reader is encouraged to click on the link above and scan over the wide range of topics, it is impressive.

Importance of Space-Based UV/Visible Observations for the Future: In the post-HST era there will be IR observations using JWST with a lifetime of 5-10 years, but *there is no currently planned capability for UV/visible high resolution observations*. As long as there are missions to the other planets, coordinated high resolution observations from Earth orbit will greatly enhance the science return, and in fact will be needed to reap the full scientific benefits of planetary missions. This is largely due to the ability of telescopes like HST to obtain the "big picture" from a large distance, while the *in situ* planetary spacecraft measure the local environment. The synergy is extremely important to obtain the full scientific benefits of each mission.

An excellent example from recent missions is the coordination between JUNO charged particle and UV/IR spectral observations of Jupiter's magnetosphere and upper atmosphere near closest approach, coordinated with HISAKI/EXCEED data on the Io plasma torus and overall auroral power, and a large HST program to image the auroral regions at high resolution. The changes with time in the Io plasma torus, in the aurora, and in magnetospheric charged particle motions range from minutes to weeks. With the combination of spacecraft data it has been established that the aurora drive the plasma torus, which is the opposite of what had been expected, and the plasma motions responsible for this control have been identified. Without the HST high resolution auroral imaging it would not have been possible to identify the regions in the magnetosphere where the action was taking place.

HST has become a workhorse for planetary science, including its growing extension to exo-solar systems. One key advantage to HST observations that is often under-appreciated is the stability of response in space. As one example, having a highly stable and repeatable point spread function makes it possible to establish the size of small objects, like dwarf planets in the Kuiper belt, much more accurately than with much large ground-based telescope with adaptive optics and potentially higher angular resolution. The stability of sensitivity similarly makes possible cross calibration of planetary missions. As one example, the UV instrument on MAVEN is being calibrated in comparison with HST data to establish the D/H ratio in the upper atmosphere of Mars with a high accuracy.

Finally, it should be emphasized that HST solar system science has not consisted *solely* of one-off observations that have answered important scientific questions (although there have been those discoveries). HST science has addressed new scientific targets that were unknown when the mission was launched (i.e exoplanets), it has supported space missions that were not planned when HST was launched (i.e. JUNO), and it will be used in the future in ways that no one has imagined today (i.e. we have no idea what we will miss in the future). It is a facility for key science, and represents a capability that will be needed for decades to come. It is very important for the solar system community to find a way to maintain this capability at a reasonable cost level for the long-term future, and we should discuss how to make this happen.

Universal Mass Spectrometry-Based Life Detection. H. J. Cleaves[1,2,3,4] and C. Giri[5], [1]*Earth-Life Science Institute, Tokyo Institute of Technology, 2-12-IE-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan (Henderson.cleaves@gmai.com)l,*[2]*Institute for Advanced Study, Princeton, NJ 08540,* [3]*Blue Marble Space Institute of Science, 1515 Gallatin St. NW, Washington, DC 20011,*[4]*Center for Chemical Evolution, Georgia Institute of Technology, Atlanta, GA 30332,* [5]ELSI Origins Network, *Earth-Life Science Institute, Tokyo Institute of Technology, 2-12-IE-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan (chaitanya.giri@elsi.jp).*

Introduction:

The search for evidence of extraterrestrial life in the solar system will remain one of the most important goals of solar system exploration in the 21st century. Recognizable biological systems will almost certainly be based on organic compounds.

However, several facts complicate this search. First, terrestrial biological contamination may be difficult to eliminate completely from spacecraft, and this is likely to become more problematic as detection methods become more sensitive. Second, we now know that many environments in the solar system are replete with organic compounds, either those left over from the early formation of the solar system (*e.g.*, those present in comets (1), asteroids (2), cosmic dust and interplanetary dust (3)), which continuously become implanted on planetary surface environments, and those which are continuously generated in planetary environments (*e.g.*, in Titan's atmosphere (4)). Third, an independent biology might be based on organic compounds wholly or partially distinct from those used by terrestrial biochemistry (5, 6). Fourth, all organics, regardless of their provenance, may degrade and/or alter over time due to various types of thermal, shock and radiational processing (*e.g.*, (7), rendering their initial composition difficult to discern.

High-resolution mass spectrometry offers a relatively comprehensive and rapid way of "chemotyping" environmental samples (8). Using modern instruments large numbers of unique mass organic compounds (to which molecular formulas can be assigned) can be identified in a single measurement, and these can be further identified using multiple dimensions of fragmentation and mass spectrometry. It seems likely in the coming decades such instruments will become smaller and more efficient, and thus more appropriate for inclusion in planetary probes.

In order to use this type of instrumentation effectively in planetary environments in the coming decades, it will be essential to have a "catalogue" of abiotic and terrestrial biological samples which can be referred to in this search. Ideally this catalogue would contain examples guiding the classification of samples as terrestrial or extraterrestrial, biological or non-biological, and degraded or pristine.

We detail here the preparation of such a catalogue, and the types of molecular signals that can be obtained from it to allow for the classification of systems as described.

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GEOCHRONOLOGY AS A FRAMEWORK FOR PLANETARY HISTORY THROUGH 2050. B. A. Cohen[1], R. Arevalo Jr.[2], W. F. Bottke, Jr.[3], P. G. Conrad[2], K. A. Farley[4], C. I. Fassett[1], B. L. Jolliff[5], S. J. Lawrence[6], P. R. Mahaffy[2], C. Malespin[2], T. D. Swindle[7], M. Wadhwa[8], [1]NASA MSFC (Barbara.A.Cohen@nasa.gov), [2]NASA GSFC, [3]Southwest Research Institute, [4]California Institute of Technology, [5]Washington University, [6]NASA JSC, [7]University of Arizona, [8]Arizona State University.

Introduction: In the decades of planetary exploration since the 1970's, the science community has made great progress characterizing the contemporary state and relative geologic histories of the terrestrial and outer planets, satellites, and primitive bodies. In parallel, we have significantly advanced the state-of-the-art in laboratory-based absolute geochronology techniques and exposure age determinations applied to planetary samples. Despite this progress, little headway has been made improving our knowledge of absolute ages for common events, such as the Late Heavy Bombardment, planetary volcanism, and the establishment of astrobiologically-relevant environments. In the next 40 years, we advocate constructing a common framework of geologic time across our solar system, linking individual planetary evolution to solar system history. Accomplishing this theme requires the integration of geochronology with in situ investigations, targeted sample return missions, and continued advancements in laboratory analysis and modeling.

Absolute Geochronology: Our knowledge of absolute surface ages on other bodies, including Mars, Mercury, asteroids, and outer planet satellites, relies primarily on the crater calibration record for the Moon. While lunar cratering history is bounded between ~1 and ~4 Ga by isotopic ages of the Copernicus and Imbrium impacts and multiple volcanic units, the impact rates before 4 Ga and after 1 Ga are more poorly constrained [1]. Absolute ages of Martian surface units can be uncertain by a factor of two on older (Hesperian) surfaces, and by an order of magnitude on younger, lightly-cratered surfaces [2, 3]. This uncertainty encompasses major events on the terrestrial planets, including thermal evolution, impact bombardment, and climate change.

Planetary Origin: Chemical evolution of planetary bodies, ranging from asteroids to the large rocky planets, is thought to begin with differentiation through solidification of magma oceans. Rocks from the crust and mantle date the processes of silicate (and metal) segregation of planetary formation and magmatic evolution – yet ancient lunar crustal rocks have ages that range to much younger than magma-ocean models would predict [4, 5]. The most ancient Martian meteorite, ALH84001, crystallized much later than predictions of crustal formation on Mars [6]. Some worlds, such as Europa and Venus, have evidence of extremely recent activity, indicating long-lived heat sources driving crustal processes. Identifying the most ancient crust across the solar system and obtaining more precise ages of the oldest and youngest magmatic products will provide a way to understand the dynamics of magma oceans and crust formation, and the longevity and evolution of interior heat engines and distinct mantle/crustal source regions.

Bombardment History: Determining the flux of impactors on all bodies, and whether it was constant across the inner and outer solar system, is a primary goal of the planetary science community. The energetic nature of impact cratering can have wide-ranging consequences extending to a planet's subsurface and atmosphere, perhaps destroying life or creating transient abodes for it. One of the biggest questions is whether there was a lunar cataclysm, or late heavy bombardment, defined as the creation of multiple lunar nearside basins within a short period [7, 8]. This event potentially relates the impact bombardment history of the inner solar system to the time when life began on Earth [9]. Yet, the crater-based age estimates of the Rheasilvia basin on Vesta range from 1 Ga to 3.5 Ga [10, 11] and the epoch of large-basin formation on Mercury and Mars is uncertain by hundreds of Myr [12]. It is crucial to determine the time interval for the creation of large basins on the terrestrial planets and establish how the flux delivered to inner and outer planets reflects the dynamical evolution of the solar system [13].

Astrobiology: An incomplete knowledge of absolute Martian geochronology limits our understanding of the timing of the planet's evolutionary milestones – for example, whether the Noachian-Hesperian boundary occurred before, after or concurrent with the late heavy bombardment on the Moon [2], or when Mars' surface environment transitioned from wetter and more chemically neutral conditions to volcanically dominated, acidic, oxidizing, and dry surface conditions [14]. Absolute dating also will be required to relate habitability markers to the timescale of evolution of life on Earth [15]. Moreover, measurements of exposure ages are proxies of biosignature preservation potential, enabling the prioritization of samples to be returned to Earth and/or analyzed by life-detecting techniques in situ.

Strategies through 2050: Through the next several decades, a sustained effort will be required to create a framework that relates planetary geologic events to each other. In this decade, investment is needed to increase the technology readiness levels to TRL 6 for in situ geochronology instruments using complementary radiogenic isotopic systems. Sample collection and handling systems are required to ingest samples for all in situ dating methods; these systems need to be matured, along with operating scenario for their use, such that the operational burden for sample collection and analysis is reduced. Further improvements to spacecraft mobility and dexterity will enable more geologic units to be interrogated during each mission. In the 2020's, these technologies will be ready to be included in developing missions to key stratigraphic targets on terrestrial planets, alongside planning sample-return efforts for the Moon and Mars. In the 2030's, an in situ geochronology component should be considered as an augmentation to human exploration of the Moon and Mars and for robotic missions to targets beyond our current capabilities for sample return in the inner and outer solar system (including Mercury, Venus, Europa, and Io). By the 2040's, we should expect in situ geochronology to be a standard capability on planetary landers. In parallel with these developments, Earth-based laboratory capabilities for returned samples must continue to advance in sensitivity, accuracy and precision, as well as efficiency in the handling and processing of diverse samples.

In situ Dating: The capability of flight instruments to conduct in situ geochronology is specified in the NASA Planetary Science Decadal Survey and the NASA Technology Roadmap [16, 17] as needing development to serve the community's needs. Radiometric dating on Mars is now a validated technique, although the Curiosity method is not purpose-built for dating and requires many assumptions that degrade its precision [18]. To achieve more precise and meaningful ages, multiple groups are developing dedicated in situ dating instruments [19-23]. These instruments are on track to demonstrate TRL 6 readiness by 2020 and will need to be selected in the 2020's and 2030's for competed and directed flight missions to relevant destinations where in situ precision (±100 Myr) can provide meaningful constraints on geologic history.

Sample Return: High-precision geochronological investigations of samples returned from selected locations on the Moon, including the New Frontiers target South Pole-Aitken Basin, would significantly advance our understanding of lunar chronology and solar-system processes. Such investigations will allow us to distinguish events closely spaced in time, and better evaluate samples having complex chronologic histories. In particular, both the old and young ends of the crater flux curve and lunar magmatic history require additional constraints [24, 25]. Though Mars sample return (MSR) efforts are driven by the search for astrobiologically relevant materials, a crucial objective for MSR is to establish an absolute geochronological anchor for the impact history of Mars. Samples suitable for these efforts [26, 27] are not always considered high-priority in landing site and architecture discussions. We urge the community to make a geochronology anchor sample a critical sample in MSR, or to consider groundbreaking MSR to a suitable surface for this purpose. Such a sample would be able to be studied using multiple geochronological systems in state-of-the-art laboratories on Earth, as well as other techniques (such as isotopic and trace element analysis) that provide additional constraints on understanding the history of the planet.

Laboratory Facilities: Missions such as Genesis and Stardust drove the advancement of laboratory capabilities for the analysis of smaller and smaller samples [28] and the streamlining of analytical protocols (e.g., beginning with non-destructive techniques). For sample geochronology, the primary instruments are high precision mass spectrometers, equipped with thermal or plasma ionization sources, secondary ion and noble gas mass spectrometers, and accelerator mass spectrometers. Sustained investment in laboratory upgrades and advancements, as well as in training future generations of research analysts, will be needed to extract maximum scientific return from geochronological investigations of existing and future samples from planetary targets.

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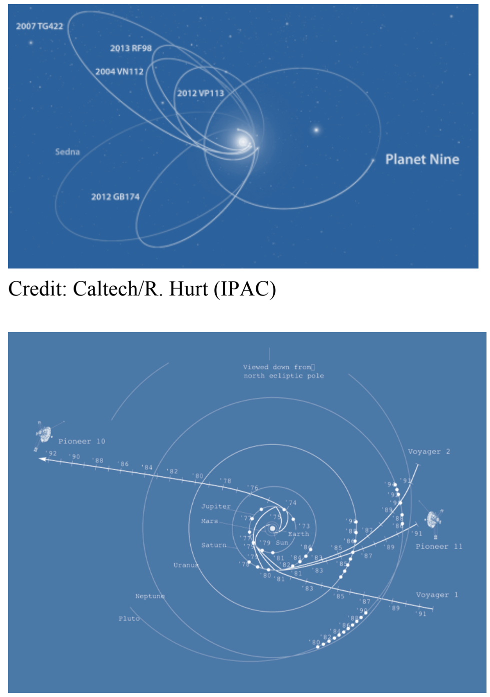
THE ROLE OF EARTH-BASED OBSERVATORIES FOR SOLAR SYSTEM SCIENCE IN 2050. A. R. Conrad[1], [1]LBTO, U. of Arizona, Tucson, AZ 85721 (aconrad@lbto.org)

Introduction: In 34 years the current class of 8 to 20 meter ground-based telescopes will be in their twilight, the three extremely large telescopes will seem only modestly large, and several 50+ meter ground-based telescopes (or wider baseline interferometers) will be racing toward first light. The situation in near-Earth space will be similar. JWST will be past its expected lifetime, but one or more 10+ meter class telescopes (or wider baseline interferometers) will be available in near-Earth space or on Earth's moon. Will the majority of these new telescopes be filled-aperture, or will interferometers dominate the landscape?

What will all this mean for planetary science? We explore possible scenarios for each of three cases: Outer solar system, planetary defense, and the Galilean Satellites. For each of these, we consider how the giant telescopes available in 2050 will change: (a) how planetary scientists conduct their research, (b) how Earth-based astronomy will compliment spacecraft missions, and (c) the role of interferometry, versus filled aperture, in Earth-based systems.

Outer Solar System: Today much of what we know of the outer solar system comes to us from observations carried out with telescopes that are Earth-based.[1] Space probes (e.g., Voyager and New Horizons) have provided exquisite results on a small population [1] [2], however, for studies that require statistics from a larger population (e.g., a potential 9th planet! [3]) we must rely on Earth-based observations (see Fig. 1). This situation is likely to continue up to, and well beyond, 2050. As we discover more objects in Sedna-like orbits, and with the increasing importance for obtaining astrometry of ever more distant bodies,[2] the importance of small population studies enabled by spacecraft that require decades to arrive at the outer solar system will remain low and could possibly decline.



Credit: Caltech/R. Hurt (IPAC)

Credit: NASA

Figure 1. Earth-based observations, like those needed for the discovery and orbit determination of the objects that lead to the 9th planet result (upper panel), versus the exquisite close-up observations given by spacecraft (bottom panel), will continue to compliment one another in the decades to come. But will one of these become the more dominant method for exploring the outer solar system?

Or, in another scenario, the opposite will occur. Interest in deep space exploration will spur research into propulsion systems that send spacecraft outward at a velocity that is higher than what is possible today. This combined with a *cubesat* style of sending multiple probes in a single package could favor spacecraft for the study of large populations in the outer solar system.

We will estimate the relative cost versus scientific output of these two extremes.

Planetary Defense: For fast-moving NEA, the role of Earth-based observatories will likely continue to be the primary technology to be applied. We will also see improved synergy between optical/infrared observations with active radar Doppler imaging [4]. But for fast moving objects, the giant telescopes of 2050 will only be effective if non-sidereal tracking and guiding is built-in at first light and not retrofit ad hoc. History has shown, for the current class of 8-10 meter telescopes, this is often not the case. [5]

[1] Here, and throughout this discussion, in addition to ground-base telescopes like Gemini, LBT, IRTF, and Keck, we include near-Earth ***space-based*** observatories like IRAS, HST, and JWST.

[2] In addition to orbits in the ecliptic, we now know that it is important to see bodies at high inclination (e.g., many of the Centaurs) when they are more distant (i.e., not just when they visit the neighborhood of Jupiter).

Galilean Satellites: Unlike the outer solar system, at significant distance for spacecraft visits; or near earth asteroids with a large population, the Galilean Satellites stand as scientific targets that likely favor spacecraft visits over Earth-based observations as the field moves forward in the next decades. In this category, more than the others, the ability of Earth-based telescopes to keep pace with spacecraft probes will be determined by the success of Earth-based interferometry. Today, for example, we have the first planetary science result published for the Large Binocular Telescope (LBT) interferometer, using Fizeau imaging with a 23-meter aperture, to measure emission at Loki Patera (see figure 2).[3] [6]

We will further investigate the potential of interferometry to compliment spacecraft visits to the Galilean Satellites.

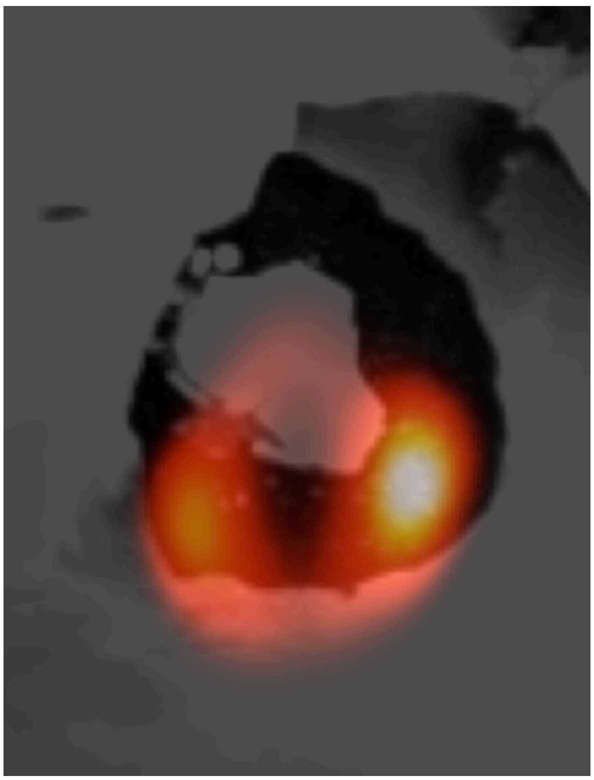


Figure 2. M-band emission within the lava lake at Loki Patera as measured with the LBT interferometer. [6]

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[3] It may be possible in future to apply this technique more widely with the next generation interferometer at LBT. [7]

AEOLUS: A MISSION TO OBSERVE THE THERMAL AND WIND ENVIRONMENT OF MARS

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Introduction: Aeolus is a mission concept to observe the thermal and wind environment of Mars, by measuring surface temperatures and Doppler shifts in atmospheric spectral lines. To date, direct measurements of Martian wind speeds have only been possible at the surface, only during daylight hours, and over small areas limited by rover traverse capabilities. From orbit, thermal measurements as well as still images of dust storms and dune migration have provided inputs to derive the latest datasets in Mars climate modeling. However, recent models (*Figure 1*) generated by Co-I Kahre of the Mars Climate Modeling Center at NASA Ames Research Center (ARC), demonstrate ***that model wind speeds derived from these indirect measurements may be in error by 50 to 100%***. For this reason, direct wind velocity measurements have been deemed "High Priority" by the Mars Exploration Program Analysis Group (MEPAG); measuring wind speeds and corresponding thermal data is vital to understanding the climate of Mars.

Aeolus will carry four miniaturized Spatial Heterodyne Spectrometers (SHS), coupled to two orthogonal viewing telescopes. These high-resolution near-infrared spectrometers will measure CO_2 (daytime absorption) and O_2 (day and night emission) lines in the Martian atmosphere. Doppler shifts in these lines can be measured during Martian day and night, resolving wind speeds with ~5 m/s precision. Orthogonal views allow the spectrometers to capture wind vectors (as opposed to only line of sight measurements) over all observation locations. Aeolus will also carry a high-heritage Mini Thermal Emission Spectrometer (Mini-TES) to measure surface temperatures and CO_2, H_2O, and dust column abundances in nadir views. Finally, the Surface Radiometric Sensor Package (SuRSeP) will measure the surface for total reflected solar radiance, and low surface temperatures down to ~140K. These combined spectral and thermal measurements will provide a new understanding of the global energy balance, dust transport processes, and climate cycles in the Martian atmosphere. The Aeolus mission concept consists of a single satellite in a near-polar orbit, allowing it to pass over all local times, with the baseline mission observing all seasons of an entire Martian year (two Earth years).

The Aeolus mission concept is led by PI Anthony Colaprete and Deputy PI Amanda Cook, from Ames Research Center. The Aeolus Science Team is also based at ARC, where the Mars Climate Modeling Center supports a team of veteran Mars climate scientists, research staff, and students.

Science Objectives: The overarching goal of the mission is to provide empirical data for refining current climate models[1]-[5] and for contributing to the understanding of Mars atmospheric phenomena that are not yet clearly understood. The first objective is to **(1) produce a vertically resolved global wind speed map of Mars**. Winds on Mars have never been direct-

(a) (b) (c)

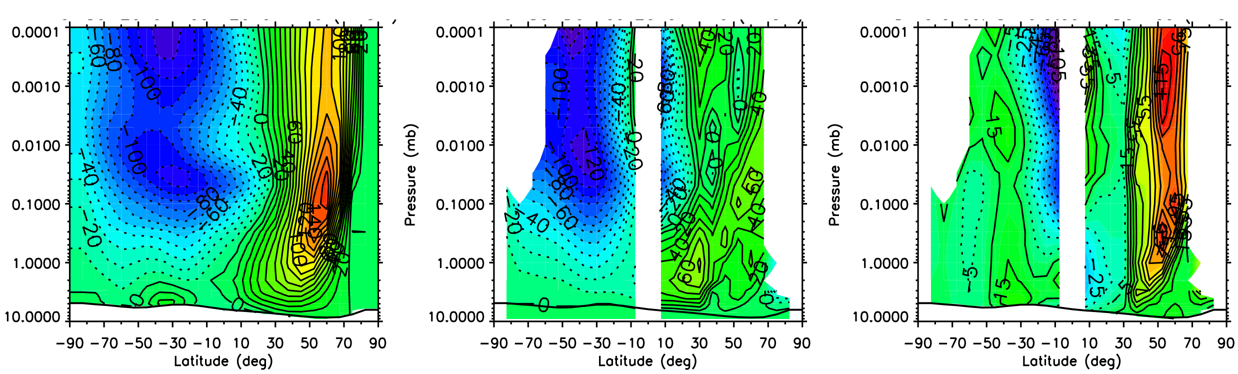

Figure 1. Wind speeds derived from thermal measurements can be in error by up to 100%. Contours show wind speeds in m/s. Solid lines are westerly winds, and dotted lines are easterly winds. (a) Global Climate Model simulated wind speeds. (b) wind speeds derived from thermal balance; (c) Difference between panels (a) and (b) shows that winds are not in balance with the thermal fields. Similarly, the actual winds on Mars are expected to be different from those derived from observed thermal fields. Source: Aeolus Co-I, M. Kahre.

ly measured, except for Viking[6], Pathfinder[7], and Phoenix[8] surface point measurements All other wind speeds have been derived from *indirect* thermal measurements or compositional variations in the atmosphere, and orbital imagery. Creating a global wind map would provide essential ground truth and corrections for the current Mars climate models. The last two objectives are to **(2)** ***Determine the global energy balance at Mars*****,** and **(3)** ***Correlate wind speeds and surface temperatures with H_2O, CO_2, and dust (aerosol) column densities***. To determine the thermal balance in the Martian atmosphere, the wind velocities will be correlated with surface temperatures, and dust, H_2O, and CO_2 column abundances. This combination of measurements enables Aeolus to provide an essential dataset within the context of the three most influential factors determining Mars climate variability: temperatures, wind speeds, and atmospheric composition.

To measure wind speeds, Aeolus will measure Doppler line shifts for the O_2 and CO_2 lines detectable from the Mars atmosphere. O_2 primarily resides in the Martian troposphere (near 50-km altitude), while CO_2 exists at all altitudes. Measuring CO_2 absorption lines allows for more continuous altitude coverage for daytime measurements. Likewise, it is essential to include O_2 airglow emission measurements to capture wind speeds *at night*, since CO_2 is not observable in the night atmosphere. It is worth noting that no past or current orbiter missions have measured the Martian atmosphere at night. Thermal infrared and aerosol measurements of the surface will allow the Aeolus science team to correlate temperature gradients with wind speeds, and to assess the overall thermal balance in the Martian atmosphere.

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CENTENARIAN RETROSPECTIVE ON SPACE ENVIRONMENT INTERACTIONS AND PROCESSES OF THE SATURN RING AND MOON SYSTEM.

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Introduction: One hundred years ago in the year of my birth, 1950, we were still seven years away from the first artificial satellite, Sputnik, and had twenty-nine years remaining before Pioneer 11 first explored the Saturn system and I then entered into the exciting field of planetary science. As a surviving centenarian of this present year, 2050, I look back on the remarkable progress made in understanding the interactions between Saturn's ring system, plasma magnetosphere, neutral atmosphere, and energetic particle radiation belts.

Although my personal memories of the events contributing to this progress have long begun to fade, I am aided in recollections by my earlier account [1] and many by others and myself since then. For the 2017 account I am eternally grateful to my co-authors of that time (Peter Kollmann, Edward C. Sittler, Jr., Robert E. Johnson, Elias Roussos), and looking forward to seeing them again soon at the Solar System Geophysics Union (SSGU) Meeting at Shackleton Base on the Moon.

I have for these many years reflected on fond memories of the late Professor John A. Simpson, my "doctor father" at the University of Chicago for the Saturn work, and one of the four energetic particle instrument investigators on Pioneer 11. I also fondly recall being initiated into the "Cosmic Ray Albedo Neutron Decay (CRAND) Fraternity" by the late Professor James A. Van Allen, who discovered the Earth's radiation belts and later made key measurements and models of such belts at Saturn along with Simpson and others. He and another Pioneer 11 investigator, Walker Fillius, led the first modeling efforts from their measurements to understand the impact of neutrons from galactic cosmic ray (GCR) interactions on population of Saturn's inner radiation belts via decay of the neutrons into protons and electrons. It was by their efforts, and later by many others including myself, that we learned about this unique relationship of the Saturn system to the cosmos.

The Last 1 Years at Saturn: At largest scale in space and time this system of planet, rings, moons, and and magnetosphere is driven by four major space environment inputs. (1) Solar ultraviolet radiation sputters oxygen and other molecules off the ring and moon surfaces. (2) GCRs bombard these surfaces (mainly the A-B-C rings) to produce secondary radiation including neutrons, gamma rays, and charged particles. (3) interplanetary solar wind magnetic field and plasma interactions perturb the global magnetosphere and drive the radial transport and energization of radiation belt particles that subsequently interact with surfaces. (4) High-velocity meteroids impact the rings and moons, vaporizing surface materials and ejecting sprays of icy grains at nanometer to millimeter sizes into Saturn's space environment. Over the centenarian time scale the first three inputs have varied with the nine solar cycles of activity since 1950. During tthis time there have been seven seasonal equinoxes, when the Sun crossed the ring plane, and seven solstices at each pole of Saturn.

Our greatest challenge and success has been in understanding how all these time-modulated inputs act to drive the physical and chemical evolution of the space environment in the Saturn system and to drive the interactions between the moon and ring elements of that system. Most challenging of all was that we could only make measurements during the occasional flyby and orbital missions at Saturn. Like for the Jupiter system, it was recognized that all spacecraft visitor and permanent residents at Saturn *must* make environmental measurements to follow the long-term and short-term trends of variation. It was, for example, the 2004 – 2017 orbiter mission at Saturn that first revealed the seasonal variation of the magnetospheric ion densities and the solar cycle variation of the low-energy and high-energy proton radiation belts from CRAND.

Without the many following ancillary measurements of space environment parameters from Saturn Probe, Saturn Ring Observer, and what followed, it would have been difficult if not impossible to disentangle cyclic contributions from differently modulated inputs. Among many such measurements it may have been the discovery of the previously undetectable cloud of nanometer dust that most changed our perception of radiation belt source, transport, and loss processes, providing the necessary missing link between the plasma and energetic trapped ion populations and the meteoroid impact source in the main rings. Addition of neutron and gamma-ray imaging spectrometers to the post-Cassini missions provided direct data on internal composition and structure of the rings, thereby allowing *very suprising* conclusions to be drawn on the ring origin and evolution. These results were key to motivation to the ring sample return mission, which has just now concluded with delivery to lunar laboratories.

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IN-SITU SAMPLE PREPARATION DEVELOPMENT FOR EXTRATERRESTRIAL LIFE DETECTION AND CHARACTERIZATION. K. L. Craft[1], C. Bradburne[1], J. Tiffany[1], M. Hagedon[1], C. Hibbitts[1], J. Vandegriff[1], S. Horst[2], [1]Johns Hopkins University Applied Physics Laboratory (11100 Johns Hopkins Rd., Laurel, MD 20723, Kate.Craft@jhuapl.edu), [2]The Johns Hopkins University, Baltimore, MD 21218.

Introduction: Detection and characterization of life outside Earth would be an incredible discovery, revolutionizing our perception of life and providing insight into how life develops and persists in various environments. Looking to the future of the search for life, our understanding of the habitable zone has evolved and there are many outer planets' moons that we know harbor liquid oceans, planets that harbor possibly habitable atmospheres and exoplanets that may yet indicate habitable environments. Future in-situ life detection techniques must have the capability to function in multiple environments with large temperature swings, high radiation and be automated to function far from the control of a human being. They must be able to prepare samples for analyses in such as way as to remove inhibitors while retaining sufficient material to provide adequate concentrations. Such sample preparation techniques need further development in the coming years to enable the exciting life detections we seek and confidence in the findings.

The most robust strategy for searching for life in extraterrestrial environments would be to employ several techniques on a mission to corroborate the detections/non-detections. Possible techniques include: chirality ratios, electron-transfer/redox gradients/disequilibrium, long chained polymer detections, physical morphology characterizations, and organic detections. Each measurement, on its own, would lack confidence for a true extraterrestrial detection as contamination may be the detection source and/or measurement values may not be significant enough to be conclusive. What each technique requires is sample preparation processing that will best handle, clean, concentrate and deliver the sample to the instrument. Certain areas of sample preparation can be generalized for several techniques and others are more specific to the process to be applied. Those techniques searching for amino acids (such as Gas Chromotography Mass Spectrometry (GCMS)) and long-chained polymers (such as the MinION nanopore sequencer (Oxford Nanopore Technologies)) require removal of salts and other potential contaminants. Many life detection techniques will also require concentration of the sample since collection techniques and inherent low biomass levels present will only allow collection of extremely small amounts. These preparation needs can be addressed currently in laboratories, however only limited flight applications have been developed to date.

Another important consideration in the search for life is understanding how terrestrial organisms change and evolve within different environmental conditions. Increasing our understanding of biological mutations and adaptations to micro-g, radiation, vacuum and various pressures, extreme temperature swings, etc. would provide insight into life that may have evolved on various bodies in our solar system. The investigations would also provide a means to address planetary protection concerns in understanding how organisms may mutate that are accidentally sent along on a planetary mission.

Areas in need of development: Certain areas should be focused on leading up to 2050 to enable improved detection and characterization of extraterrestrial life.

Experiments and analog studies on evolution in alternate environments. Simulations of various planetary and small body environments should be simulated on small satellite and space station platforms while biology is allowed to grow and evolve. These experiments would then feed forward to the life detection techniques tweaked for each special environment and the sample preparation needs. Additionally, further studies and tests of preparation techniques in analog environments on Earth or the Moon would provide improved understanding of organisms and how they adapt to survive there as well as factors inherent in their detection by the technology.

Sample separation and inhibitor removal. Flight qualified techniques to enable separation of the sample from its environmental matrix (soil, ice, water, methane, etc.) are necessary to enable most all life detection techniques. Sonication and bead-beating vibrational techniques are often employed in the laboratory and act to open any spores present and detach the material of interest from the background matrix. These techniques should be developed to function on a spacecraft lander or probe such that low power and mass are required along with the ability to intake a sample from a high- to zero-pressure outside environment. Additionally, the separation process would need to take care not to damage the material of interest and retain the maximum amount possible. These techniques work in the laboratory currently but would greatly benefit sample preparation for planetary in-situ analyses through miniaturization and a certain amount of automation such that the process could detect when enough of the separation process was performed to move on to the next sample preparation step.

Once a material of biological interest is separated from its host matrix, removal of salts and other inhibitors would need to be performed. Salts and other potiential chemical inhibitors can confound downstream analyses and prevent biosignature detections. High levels of salts are expected in many planetary environments believed to be habitable including in the ice and water of the the ocean worlds of the outer solar system as well as the soils of Mars. Characterization of how sensitive analyses are to salts and to what salt types and sensitivities to other potential inhibitors including ammonia, sulfates, sulfuric acid, and irradiated materials needs to be performed and techniques for removal developed into small size weight and power flight ready packages.

Biological material concentration. The amount of biological material that will exist in a planetary environment is unknown and detection techniques must be able to detect very low amounts. A strategy of concentrating samples would assist with this issue and should also be developed as certain cases will only allow the collection of small amounts of sample (e.g. Enceladus plume fly-throughs). Concentration techniques would be automated and retain only the material of interest, while disposing of extraneous materials.

Fluidic Transport. Microelectromechanical and microfluidic systems are used for a variety of applications throughout industry and would be an ideal technique for application to fluidic processing in space flight sample preparation and transport. A process of sample intake to a microfluidics channel, application of the sample preparation processing, and delivery to several life detection instruments would be ideal. Automation of quantification and qualificiation checks on the biomass/material of interest should be developed and integrated into the fluidic system.

Characterization algorithms. Recent work has improved the error inherent in the terrestrial sequencing using the nanopore MinION to close to <10% and better [1]. Software should continue to be developed for this life detection technique as well as for other techniques that will require processing of data to decifer detections vs. contamination or background noise. Artificial intelligence should also be developed and employed to do initial data analyses to automate the decisions on sampling again in a location or moving to another location for another try at acquiring the material of interest. This could enable higher yield sampling if on a time-restricted mission and also enable missions with restricted communication windows with Earth.

Data return. For many of the life detection techniques, the data volumes generated are so large they represent a special challenge to complete return delivery. The raw data from molecular sequencers like MinION (and any conceivable successor) is orders of magnitude beyond what can be currently sent back to Earth. Computing constraints on planetary probes will require specialized, intelligent data exploration agents to be developed that can efficiently sift through raw data and downselect the best for actual on-board analysis or downlink. Because the data processing and throughput constraints are unique to planetary exploration, the needed techniques are not likely to be developed for terrestrial applications. Therefore, it is important for the planetary community to commit resources to developing the needed data reduction and selection algorithms for emerging and future life detection techniques. Additionally, as pointed out in the 2013-2022 Planetary Decadal Survey [2], uplink and down-link capabilities in S-, X- and Ka-bands should be developed where necessary for transmission through atmospheres (e.g. Venus and Titan) and long range missions.

Techniques for "weird" life searches. As we begin to explore places with vastly different environments from Earth, for example the moon Titan that has a methane based cycle, the search for life there likely needs different instrument detection ranges, possibly different fluid bases for analyses and modified materials and packaging designed for handling the fluids. Experiments on organism evolution and subsequent polymer extractions from methane and other expected fluid bases should be performed now to educate the community on the biosignatures expected and to enable designs and tests of the proper instrumentation required for detections and characterization.

Summary: Many life-detection techniques for insitu exploration of planetary environments require particular sample preparation processes and these techniques require further development for application on flight missions. Areas of particular development over the next few decades include miniaturization and fluidic techniques for sample preparation, handling, and delivery to instruments as well as experiments and analog studies on life developing in alternate environments. Improvement and automation in data downlink and processing will also enable life searches in remote and communication- or time-challenged locations. Focusing on these aspects of detection techniques will greatly enhance the robustness of any extraterrestrial find and enable discoveries in environments we have yet to explore.

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Exploring Outer Planet Magnetospheres with Small Focused Missions. F. Crary[1], F. Bagenal[1], G. Clark[2], P.A. Delamere[3], R. Ebert[4], A. M. Rymer[2], M. Vogt[5], and 26 other planetary magnetospheres scientists. [1]CU-LASP, Boulder CO, [2]JHU-APL , Laurel MD, [3]UAF, Fairbanks AK, [4]SWRI, San Antonio TX, [5]BU, Boston MA

Studies of magnetic and electric fields, charged particles and their interactions with planetary surfaces, atmospheres and conducting interiors all play important roles in our understanding of solar system bodies. To exploit the major contributions of magnetospheric studies we need to develop a program for the development of small, low-cost spacecraft for planetary exploration.

The Trend Towards Focused Missions: The past decades have seen a trend from broadly-focused missions to those with focused goals. This is a necessity for Discovery class missions, but also applies to larger New Frontiers and flagship missions. Spacecraft like *Galileo* and *Cassini* explored almost all aspects of the jovian and saturnian systems, from the core of the planet to the magnetotail. In contrast, *Juno* is focused on three aspects of the jovian system (the deep interior and the composition of the planet and the polar/auroral magnetosphere) and the planned Europa Multiple Flyby missions will study Europa and its subsurface ocean. While this focus has many benefits, it also creates the risk of neglecting other important aspects of planetary science.

Opportunities for New Frontiers and flagship missions are rare, and the list of important, planetary science goals is lengthy. Addressing these goals with smaller missions would be a great advantage. In the case of planetary magnetospheres, we know from terrestrial experience that small spacecraft are capable of making major discoveries. In many ways, small spacecraft can make these measurements more efficiently than they could be made on a large, multi-purpose mission. In discussing and illustrating these points, we will focus on studies of the jovian magnetosphere but the concept might be applied across the solar system.

Science Goals: *Galileo* studied and *Juno* is studying the jovian environment. While *Galileo* made key discoveries on the satellite-moon interactions and the Io plasma torus, the results were limited by the loss of the spacecraft's high gain antenna and the resulting very low data rate. Our knowledge of moon-magnetosphere interactions remains preliminary and the dynamics of the system beyond the Io torus is poorly sampled. *Juno* is making great advances in our knowledge of the aurora and polar magnetosphere but the mission does not include any satellite encounters.

Mass flow though the system. Jupiter's magnetosphere contains a huge internal source of plasma, originating from the volcanoes and atmosphere of Io. An estimated 1000 kg s^{-1} of heavy ions flow through the system. Roughly half are believed to charge exchange and leave the system as energetic (300-1000 eV) neutral atoms. The rest are transported outward and eventually flow down the magnetotail. The transport processes within the Io torus have been modeled and, to some extent, observed. Farther from the planet, the process is both poorly observed and poorly understood.

Solar wind control. Although Jupiter's magnetosphere is largely driven by the internal plasma source at Io, there is evidence that the solar wind also plays a role. Aurora and planetary radio emissions have been associated with solar wind transients. But the relative role of the solar wind is unknown. Is it 10% or 40%? This cannot be determined without systematic, simultaneous and long-term monitoring of the variable upstream solar wind.

Satellite-magnetosphere interactions. The discoveries of the *Galileo* and *Cassini* missions have shown the limits of the earlier flyby missions. In the case of magnetospheres, simply flying past a planet a few times does not provide nearly enough data to understand a structurally complex and dynamic system. The same is true of our current knowledge of the interactions between outer solar system moons and their plasma environment. The best-studied moon, Titan, proved to be in such a dynamic plasma environment, and so inherently complex, that over 100 *Cassini* encounters were inadequate.

Lessons From Earth: Studies of the Earth's magnetosphere provide a roadmap to studies of other planet's magnetospheres. In the past decades, advances have been made by employing proven instruments on small and simple spacecraft, by advances in electric field measurements and energetic neutral atom imaging, and by using multiple spacecraft to make multipoint measurements. The latter is enabled by the ability to observe from small and simple spacecraft.

Magnetospheric spacecraft can be small. Compared to many outer planets missions, highly successful magnetospheric missions have employed small and operationally simple spacecraft. For example, the FAST spacecraft had a mass of 191 kg, the THEMIS spacecraft, 77 kg, and even the Swedish Astrid 2 at 30kg made valuable measurements. While significantly larger than a CubeSat, this is very small compared to a major planetary mission. The particles and fields instrumentation on FAST and THEMIS was comparable to the equivalent instruments on *Cassini* or *Juno.* All of these spacecraft were spinning, with few turns or maneuvers, and all employed a simple operational process of continuously collecting data in one of a small number of modes.

Multi-spacecraft measurements. Single-spacecraft magnetospheric measurements are plagued by an ambiguity between temporal and spatial variability. As studies of the Earth's magnetosphere have shown, the resolution to this problem is simultaneous, multi-spacecraft measurements. Even at Earth, this is only practical due to the potential simplicity and small size of each spacecraft. In some cases, these multi-spacecraft observations have been from independent spacecraft whose missions overlapped, either by design or a fortuitously long extended mission. In some cases, the spacecraft were part of the same mission and the coverage was coordinated. The THEMIS mission used five, identical spacecraft and arranged for frequent "conjunctions", when they were all distributed in a line extending down the magnetotail. This definitively determined how substorms and other events propagate through the magnetosphere.

Separate Magnetospheric Spacecraft: In many ways, achieving magnetospheric goals is more efficient when preformed on a separate spacecraft. Obtaining the necessary measurements from a larger mission, with diverse goals, is more difficult, limits the quality of the data, requires more resources and adds complexity to the larger spacecraft.

Spinning spacecraft. The three-axis stabilized platform preferred for remote sensing presents major challenges for many magnetospheric instruments, especially particle and plasma instruments, which need full sky coverage. On a three-axis spacecraft, they must rely on multiple sensor heads, mechanical actuation, or simply accept lower quality data from partial coverage. On a spinning spacecraft, simpler versions of these instruments can view the entire sky once per spacecraft rotation. Electric field sensors, which have proven critical to terrestrial magnetospheric missions, require long (tens of meters) antennas. These can only be deployed in the spin plane of a spinning spacecraft and, as a result, have never been flown on a planetary mission.

Electromagnetic Cleanliness. To avoid compromising magnetospheric measurements, great care is required to avoid interference from the spacecraft itself. These requirements are, in general, an annoyance for the other (e.g. remote sensing) instruments and increase the cost and complexity of a multi-purpose mission. The use of small, specialized spacecraft, with focused goals, will confine this requirement to the missions and observations which necessitate it.

Avoiding radiation exposure. For spacecraft operating in a planet's radiation belts, especially at Jupiter, radiation exposure drives spacecraft resources and limits lifetime. Not all planetary science goals require orbiting through a planet's radiation belts. For example, many of the outstanding questions about Jupiter's magnetosphere require measurements in the middle or outer magnetosphere or in the magnetotail. A mission focued on these goals need never enter the intense radiation environment of the inner magnetosphere and, therefore, these questions can be answered without the costs of severe radiation hardening or shielding.

Possible Planetary Magnetosphere Missions:

Solar wind control of dynamics. Perhaps the easiest and simplest small mission to study Jupiter's magnetosphere would be a solar wind monitor. Simply monitoring the solar wind requires very simple instruments with very low data rates (five minute averages from a magnetometer and Faraday cup would suffice.) If transported to Jupiter by another, larger mission, it could place itself in a high eccentric orbit upstream of Jupiter. Such a mission would need to operate in parallel with other observations of Jupiter, either in orbit or Earth based monitoring of radio emissions and aurora. A more capable spacecraft, but still below the 180-kg limit of ESPA-class secondary spacecraft, could monitor the jovian system on its own.

Multi-spacecraft studies of the Jovian magnetotail. The role of mass transport through Jupiter's magnetosphere, the structure of the magnetotail and its dynamics can all be studied by copying the very successful, terrestrial THEMIS mission. Multiple spacecraft would be placed on eccentric orbits with apoapsides at various distances down the magnetotail. Enhancing the THEMIS observatories for the power and communications needs of a jovian mission would increase their mass to 150-200 kg, and three/four spacecraft could be sent together to Jupiter within the scope of a Discovery mission.

Satellite-magnetosphere interactions. By 2050 we expect there to be major missions orbiting outer solar system moons. The moon-magnetosphere interaction is best-studied by small sub-spacecraft. A precedent for this is the *Apollo 15* and *16* missions, which left magnetospheric sub-spacecraft (PFS-1, -2) in lunar orbit, without distracting from the primary mission goals or adding impractical requirements on spacecraft cleanliness. Ideally, an outer planet moon orbiter would release two sub-spacecraft, one to observe the upstream plasma and a second to observe the interaction close to the moon.

Planetary Magnetospheric Exploration in 2050: The exploration of planetary magnetospheres can be accomplished using small, focused missions. These missions, often secondary payloads of larger missions, will provide an efficient and flexible framework for magnetospheric science in the outer solar system.

SPACE LAUNCH SYSTEM PAYLOAD TRANSPORTATION BEYOND LEO. S. D. Creech[1], J. D. Baker[2], A. L. Jackman[3] and G. Vane[4], [1]NASA/MSFC Huntsville, AL 35812, steve.creech@nasa.gov, [2]Jet Propulsion Laboratory, Pasadena, CA 91109, john.d.baker@jpl.nasa.gov, [3]NASA/MSFC Huntsville, AL 35812, angie.jackman@nasa.gov, and [4]Jet Propulsion Laboratory, Pasadena, CA 91109, gregg.vane@jpl.nasa.gov

Introduction: NASA has successfully completed the Critical Design Review (CDR) of the heavy lift Space Launch System (SLS) and is working towards the first flight of the vehicle in 2018. SLS will begin flying crewed missions with an Orion capsule to the lunar vicinity every year after the first 2 flights starting in the early 2020's. As early as 2021, in addition to delivering an Orion capsule to a cislunar destination, SLS will also deliver ancillary payload, termed “Co-manifested Payload (CPL)”, with a mass of at least 5.5 mT and volume up to 280 m^3 simultaneously to that same destination. Later SLS flights have a goal of delivering as much as 10 mT of CPL to cislunar destinations.

In addition to cislunar destinations, SLS flights may deliver non-crewed, science-driven missions with Primary Payload (PPL) to more distant destinations. SLS PPL missions will utilize a unique payload fairing offering payload volume (ranging from 320 m^3 to 540 m^3) that greatly exceeds the largest existing Expendable Launch Vehicle (ELV) fairing available. The Characteristic Energy (C3) offered by the SLS system will generate opportunities to deliver up to 40 mT to cislunar space, and deliver double PPL mass or decrease flight time by half for some outer planet destinations when compared to existing capabilities. For example, SLS flights may deliver the Europa Clipper to a Jovian destination in under 3 years by the mid 2020’s, compared to the 7+ years cruise time required for current launch capabilities.

This presentation will describe ground and flight accommodations, interfaces, resources, and performance planned to be made available to potential CPL and PPL science users of SLS. In addition, this presentation should promote a dialogue between vehicle developers, potential payload users, and funding sources in order to most efficiently evolve required SLS capabilities to meet diverse payload needs as they are identified over the next 35 years and beyond.

Ocean Worlds Explorer. J. Crouch[1,] J. H. Waite[1], K. Reh[2], S. Bolton[1], R. D. Lorenz[3], K.P. Hand[2], C. Glein[1] and C.R. German[4], [1]Southwest Research Institute,, [2]NASA Jet Propulsion Laboratory (JPL), [3]Johns Hopkins APL, [4]Woods Hole Oceanographic Institution (WHOI)

Introduction: These are the themes of the conference that this abstract focuses on:

ORIGINS — understanding the formation of icy satellites within the Saturn system from what appears to be rather pristine ices [1] and determining the origin of the materials forming the Galilean satellites.

WORKINGS — understanding the thermal evolution of the interior of Enceladus and the subsequent coupled geophysical and geochemical modification that ensued to produce an interior ocean.

LIFE — understanding of the origin and evolution of life; sequence the microbes if you find them; are they similar to Earth microbes or completely different?

Ocean Worlds have been recently identified by NASA as an important destination in looking for life in the outer solar system. NASA's Europa project is underway to send a reconnaissance spacecraft to fly by Europa over forty times in search of information regarding its habitability [2]. Titan and Enceladus have recently been added to the New Frontiers list of candidate targets due to their unique ocean characteristics – methane oceans at Titan [3] and an abundance of organics [4] and a global subsurface ocean at Enceladus [5], [6] complete with hydrothermal systems linked to the interior [7] and again an abundance of organics [1]. To date we know more about the ocean of Eneladus than any ocean outside of Earth due to the gas and ice grains that pour forth in abundance from the south polar "Tiger Stripes" (*Science special volume 311*, 2006). From this material we can deduce the pH [8] and look for basic volatiles that might provide chemical energy sources for life, such as H_2. However, our search for life will remain limited until such time as we can deploy a submersible spacecraft to investigate those oceans' interior – a lesson we have learned from Earth in the exploration for seafloor fluid flow and Ocean World-relevant chemosynthetic systems [9-11]. Our earth experience has already given us some preliminary direction on what instrumentation will be needed. Maturing these instrumentation ideas is a parallel task that is being actively pursued in Earth's ocean with NSF funding. This presentation will explore how this type of Submersible Explorer (SE) can be extrapolated to provide direct sampling of the basic chemistry, habitability, and potential life in the oceans of the outer solar system.

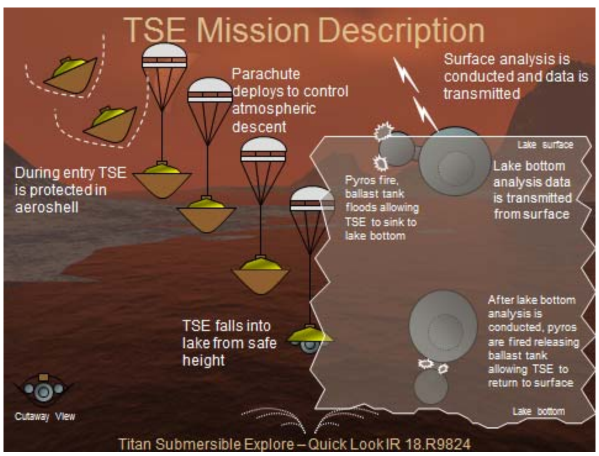
Motivation for a Submersible Probe: Southwest Research Institute (SwRI) has been designing, fabricating, and testing custom submersibles for more than five decades. These unique vehicles were often designed and built out of non-standard materials or were intended to be used in relatively severe environments. In the 50's, SwRI provided the preliminary design for an aluminum submarine (Aluminaut) to demonstrate the capabilities of aluminum in harsh conditions. In the 70's we designed and built an experimental vehicle out of acrylic for the US Navy (NEMO) to demonstrate the ability to form and operate a spherical pressure hull using a transparent material. In the 80's we built the US Navy's largest autonomous vehicle, a ¼-scale SEAWOLF SSN21, out of high yield steel (LSV 1 "Kokanee"). And, in the last 10 years, SwRI has designed, fabricated, tested and delivered the US Navy's one-of-a-kind pressurized submarine rescue vehicle out of a high yield steel (Falcon) and their deepest diving titanium submersible sphere (Alvin) capable of diving in >80 % of the earth's oceans.

In 2008, to determine the feasibility of an SE concept, SwRI performed the Titan Submersible Exploration (TSE) concept study. This TSE study was conducted as an internal research and development (IR&D) project. Preliminary results were presented to JPL and APL. The concept was also presented to the European Space Research and Technology Center (ESTEC) at an event that was held in Noordwijk, the Netherlands on the 21st and 22nd of July, 2008. Follow submersible design work was carried out during the Decadal study with Team X personnel from JPL The value of and interest in missions of this sort has been underscored by a recent NASA Innovative Advanced Concepts (NIAC) study on a Titan Submarine [12].

Research conducted in these studies demonstrated that a SE concept is indeed feasible. In order to insure the highest probability of success, an SE concept would enable utilization of multiple proven technologies and a low risk overall design approach. The low risk, high reward, nature of a SE mission should ensure consideration as a viable mission element for any future Ocean World mission.

This presentation uses the findings of the TSE, the JPL Team-X, and the NIAC studies and previous work on scientific exploration of the Earth's oceans to outline the utility of a SE for exploration of Ocean Worlds. The Titan Submersible Explorer (TSE) is a simple concept that, when implemented, would enable scientists to investigate the depths of one of Titan's lakes. Similar to the Huygens probe, the TSE would be targeted by a Saturn Orbiter, released to enter Titan's atmosphere, and descend into one of the larger lakes. Once in the lake, the battery (or nuclear) powered TSE would accomplish two primary tasks: 1) evaluate chemistry at the surface of the lake, and 2) evaluate chemistry at the bottom of the lake. Evaluating chemistry at the lake's bottom is important due to potential interaction from material from an interior water ocean.

This venting could provide an environment that supports formation of organic compounds. Once the TSE has completed bottom analysis it will release its buoyancy control module and return to the surface of the lake. On the surface it will transmit its data back to the orbiter.



The challenges are great on Titan, but our study found that they are manageable. The temperature extremes, requisite data transfer, energy requirements, and the sequenced pyrotechnics envisioned have all been faced before. These difficulties, however, would be added to on Europa, Enceladus, or other icy worlds. 1) The challenge of penetrating a deep layer of ice to access a liquid ocean adds complexity to a mission like this. 2) The need to maintain a communication channel while operating below the ice layer would require additional solutions. 3) Of critical importance and a prime candidate for development is a very high level of autonomy that would allow the vehicle to operate independently for long periods without the need for telepresence or telecommunication. Such an approach is already being investigated, in its infancy, in a cooperation between WHOI and JPL [http://web.whoi.edu/oases-for-life/] and is recognized as a pre-requisite for the outer solar system where light times are prohibitively long.

We will present the science rationale for the submersible approach based on Earth experience. The simple TSE concept will be presented and expanded upon [12]. The presentation will also show how this simple concept can be generalized to other ocean world environments at Europa and Enceladus. Finally we will focus on near long term developments that are needed to make this technology viable by 2050: drilling through the ice core and autonomous systems.

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VENUS EXPLORATION TO : J. A. Cutts[1], R.E. Grimm[2], M. Gilmore[3], and members of VEXAG, [1]Jet Propulsion Laboratory, California Institute of Technology, MS 321-550, 4800 Oak Grove Drive, Pasadena, CA 91109, James.A.Cutts@jpl.nasa.gov, [2]Southwest Research Institute, Boulder, CO, [3]Wesleyan University, Middletown, CT.

Venus should be an Earth-like planet due to its similar size and adjacent position in the solar system, but its dense atmosphere, high surface temperature, lack of water, and unique geology indicate it developed very differently. Venus is effectively a controlled experiment in the atmospheric and geological evolution of terrestrial planets. With the recent explosion of findings on extra-solar planets, Venus figures prominently in assessing the likelihood that Earth-sized means Earth-like elsewhere in the galaxy.

The Venus Exploration Analysis Group (VEXAG) has formulated a series of reports that describe the scientific goals [1], technology plan [2], and exploration roadmap [3] that will advance knowledge of Venus in the coming decades. Here we review how these documents frame Venus exploration and we extrapolate to 2050. We also draw on other recent work describing new measurement techniques and instrument development.

Science. VEXAG's current science planning [1] centers on three unprioritized goals: (I) Understand atmospheric formation, evolution, and climate history, (II) Determine the evolution of the surface and interior, and (III) Understand the nature of interior-surface-atmosphere interactions over time, including whether liquid water was ever present. Subsidiary, prioritized objectives and investigations pose specific questions, including: What controls the superrotation and the greenhouse? How do clouds influence energy balance and climate? Is the cloud zone habitable? How does Venus release heat from its interior and how is this related to resurfacing and outgassing through time? How chemically evolved is the crust? The technology and roadmap documents, described below, present capabilities that could substantially resolve these questions.

Technology. The dense atmosphere and high surface temperature of Venus affect both orbital remote sensing and spacecraft entry and in situ operations. In particular, >40 years after the first lander deployed to Venus, these vehicles can survive for no more than a few hours. Technologies required for the next few decades of Venus exploration [2] are, in priority order, (1) new thermal protection systems (TPS) for atmospheric entry, (2) high-temperature subsystems and components for long-duration (months) surface operations, (3) aerial platforms for similar long-duration operations in the atmosphere, (4) in situ instruments for landed missions, (5) deep space optical communications, (6) advanced power and cooling technology for long-duration surface operations, (7) advanced descent and landing. Related technology requirements include aerocapture, deployable heat shields, pinpoint landing and hazard avoidance, surface or near-surface mobility platforms, directed movement of all platforms, sample-return technology (including ascent vehicle), thermal control, and data storage.

Roadmap. The roadmap combines science and technology into specific mission recommendations. Near, mid-, and far-term time frames were assumed to represent 2014-2019, 2020-2024, and 2025 and beyond, respectively [3].

Near-term missions are improved orbital remote sensing (radar imaging, infrared emissivity, gravity, topography), sustained aerial platform, deep probe, short-duration lander, multiple probes/dropsondes, and flyby opportunities. The last was studied by the Venus Gravity Assist Science Opportunity (VeGASO) report [4], which describes how the Bepi-Colombo, Solar Probe Plus, and Solar Orbiter missions (initially) could provide useful measurements during Venus fly-bys. ESA's completed Venus Express and JAXA's ongoing Akatsuki will serve as cornerstones for atmospheric science.

All of the remaining missions, or mixtures thereof, have been studied or proposed for flight. VERITAS and DAVINCI, currently in Phase A, address the orbital and deep-probe missions, respectively. ESA's EnVision (under review) would similarly make improved orbital measurements, whereas the EVE balloon (proposed earlier) satisfies the aerial platform and dropsondes. The Venus Climate Mission (VCM, ref. 5) studied by the 2011 Planetary Science Decadal Survey (PSDS), would deploy a balloon, a deep probe, and dropsondes. The 2009 Venus Design Reference Mission (VDRM: ref. 6) included an orbiter, two balloons, and two landers. This high-end flagship concept could itself have addressed all of the near-term mission requirements.

Mid-term missions are multiple deep probes, short-duration tessera lander, and a long-lived geophysical lander. The tessera lander was studied [7] as part of the 2011 PSDS. Recent progress on high-temperature electronics has brought forth new concepts for long-lived (months or more) geophysical landers [e.g., 8], but there is still no appropriate data storage. Live-streaming would then require extensive orbital assets for continuous data capture. The Russian Venera-D mission [9] in principle includes an element with 24-hr survival, but this is insufficient for geophysical monitoring and is conceptually in the short-term framework. Ongoing science definition [10] may reorient the mission.

<u>Far-term missions</u> are surface (or near-surface) platform with regional mobility, long-lived seismic network, and sample return. The Venus Mobile Explorer flagship (VME, ref. 11) studied by the 2011 PSDS may have been ahead of its time, but derivatives of the metallic bellows float technology could enable regional traverses to search for evidence of an ancient ocean on Venus. Rovers could exploit innovative mechanical designs and wind-powered propulsion [12].

A seismic network is a necessary extension of a pathfinding long-lived lander in order to move from crude estimates of seismicity to imaging of the interior and mapping quake mechanisms and locations.

Finally, surface sample return represents NASA's desired (temporary) end state for exploration of all solar-system bodies. For Venus, this has long been considered to be enabled by balloon loft of the ascent rocket [13]. An intermediate mission concept (VISE) advocated by the 2003 PSDS [14] was to perform sample analysis in a buoyant station at the clement balloon-float altitude. Continuing advances in and miniaturization of mineralogical and chemical instrumentation (e.g., age dating) imply improving cost-effectiveness of in situ analysis. On the other hand, cloud sample return motivated by a search for extant life could be an important stepping stone to surface sample return

Revised Roadmap to . As currently framed, the science objectives for Venus will require multiple missions to achieve. With a horizon to 2050, however, we do not know what the next questions will be, i.e., what are the “unknown unknowns.” With regard to technology, substantial progress is being made on 1, 2, 4, and 5; but much more needs to be done for our strategy for 2035-2050 to be fully unconstrained by and exploitive of the Venus environment.

Given the lack of any Venus missions before 2020, the likelihood of a few Venus missions at most before 2030, and the time to implement technology, we conservatively stretch the roadmap time frames to 2030, 2040, and 2050, respectively. The revised roadmap would then implement orbiter, probe/sonde, and short-term lander in the 2020s, aerial platforms and pathfinding long-lived landers in the 2030s, and (near) surface mobility, geophysical network, and sample return in the 2040s.

New Visions for . New elements can be added to the VEXAG roadmap using ongoing developments in geophysics, small satellites, aerial platforms, and temporal monitoring.

Due to strong mechanical coupling between the atmosphere and ground, seismic waves are launched into the atmosphere, where they may be detected by infrasound on a balloon or infrared or ultraviolet signatures from orbit [15]. This could effectively shift the far-term seismic network into the mid-term with aerial platforms or near-term with orbiters.

NASA wishes to enhance science return by manifesting cubesats or smallsats as secondary payloads on every planetary launch. Many Venus orbital remote-sensing observations could be carried out in small, single-instrument spacecraft, particularly in constellations. A communications relay infrastructure is another obvious application.

Aerial platforms will be essential to regional-to-global study of the Venus atmosphere and surface. VDRM and VCM planned to use balloons, essentially upscaled versions of the 1986 VEGA mission. While the basic science objectives can be achieved this way, horizontal control such as provided by the VAMP concept [16], would provide control in latitude and allow specific targets to be investigated. Vertical mobility would enable sampling of different levels of the atmosphere.

Finally, as the basic mechanisms of the atmosphere, surface, and interior are understood, 4D (space + time) monitoring will become important. This will involve updated reflights of earlier missions, possibly in constellations, to look for tectonic, volcanic, or mass-wasting surface change and continuous atmospheric study.

Conclusion. The VEXAG science objectives, technology plan, and roadmap are a robust outline for Venus exploration for the next several decades. Science responses to new mission findings will occur no earlier than the mid-2020s, with any changes to the mission set implemented in the 2030s. As we move toward 2050, new capabilities in global monitoring, beyond the existing roadmap, can be added. Significant and sustained technology investments throughout the next decades are necessary to realize this vision. The road to our closest neighbor is clear, but remains long.

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Future Role of Aerial Platforms at Venus: J. A. Cutts[1], M.Pauken[1], J. L. Hall[1], K. H. Baines[1,] R. Grimm[2] [1]Jet Propulsion Laboratory, California Institute of Technology, MS 321-550, 4800 Oak Grove Drive, Pasadena, CA 91109, James.A.Cutts@jpl.nasa.gov, [2]Southwest Research Institute, Boulder, CO

The dense atmosphere of Venus and the high temperatures in the lower atmosphere and surface have presented impediments to the deployment of exploration techniques that work on airless bodies and planets with thin atmospheres such as Mars. However, they also create opportunities for the use of aerial platforms to explore Venus in many different ways. This paper reviews the brief experience with deploying aerial platforms at Venus, the various mission concepts that have been proposed over the last three decades and a vision for their application through 2050.

VEGA BALLOON MISSION

It is more than 30 years since the first and only aerial platforms were deployed at Venus, or indeed at any planet, by the Soviet Union in 1985. Two VEGA aerostats implemented as 3.5m superpressure balloons were successfully deployed at Venus and were each tracked from Earth as planned for about two earth days as they drifted halfway around the planet in the super-rotating atmospheric flow at an altitude of about 55 km. Although the total payloads suspended beneath each aerostat was only 6.9 kg, including sensors, batteries and communications equipment, VEGA remains an important proof of concept paving the way for more ambitious missions.

MISSION CONCEPTS

There has been no aerial platform mission to Venus since VEGA and currently none are under development. However, in this period there have been several proposals in both the US and Europe to fly more capable aerostats at Venus. There have also been some important technology developments and the option space for the use of aerial platforms at Venus has been extensively explored.

VEGA Type aerostats with larger payloads: One direction of research has been to develop an aerostat with a much larger payload capability than VEGA. JPL has been developing superpressure balloons tolerant of both the sulfuric acid environment on Venus and capable of accommodating the diurnal stresses induced on the balloon. A 5.5-m balloon with a payload capability of 45 kg is now at TRL 5 [1] and a 7.0-m balloon with a payload of 110 kg is now under development. Demonstrations have also been conducted of aerial inflation of superpressure balloons.

Several proposals have been made to apply this technology to a NASA or ESA mission. The VALOR Venus Aerostatic-Lift Observatories for in-situ Research) proposal was typical of these which focused on the atmosphere [2]. The European Venus Explorer (EVE) conceived at about the same time, also focused primarily on the atmosphere. Other more ambitious concepts involved the deployment of sondes from the aerostat. In this case, the aerostat serves as both a platform for precise deployment of the sondes and also as a communications relay. The proximity of the balloon to the short lived sondes enables greater data return than would have been possible for sondes communicating with an orbiting or flyby spacecraft.,

The 2011 Planetary Science Decadal Survey recommended a Venus Climate Mission (VCM) as a small Flagship mission, comprising an aerostat, deep probe, and two sondes. The objectives for the aerostat align with previous atmospheric goals. The deep probe would be released during initial descent and provide atmospheric and chemical data into the deep atmosphere, whereas the sondes could be released any time. Recent work suggests valuable geoscience studies can be performed from the aerostat itself. Infrasound signatures of earthquakes can be detected in the atmosphere [3] and natural-source electromagnetic sounding can probe the upper mantle [4]. Together, these techniques can constrain the geodynamics of Venus without ever touching the surface.

Venus Geoscience Aerobot: More ambitious concepts for the use of aerostats at Venus have also been formulated. The Venus Geoscience Aerobot (VEGAS) concept [5] has a buoyant platform capable of making repeated short visits to the surface of Venus, and extracting power from the thermal gradient in the atmosphere in the process of conducting these maneuvers. VEGAS would exploit the properties of water ammonia mixtures for buoyancy and altitude control.

Aerostats and Sample Return: Venus Surface Sample Return (VSSR) has long been considered to be enabled by balloon loft of the ascent rocket [6]. An intermediate mission concept – Venus In Situ Explorer (VISE) advocated by the 2003 PSDS [7] was to perform sample analysis in a buoyant station at the clement balloon-float altitude. A number of concepts for implementing VSSR and VISE have been considered including an innovative dual balloon concept. One spin off of this effort was a concept for a near surface balloon system called the Venus Mobile Explorer (VME) first identified in the NASA Solar System Roadmap of 2006 [8].

Altitude Control: In 2011, motivated by enduring questions about the nature of the mysterious time variable ultraviolet haze in the Venus upper atmosphere, upper atmosphere, JPL began an investigation of approaches to altitude cycling in the 55 to 70 km range.. Initially concepts using either ambient gas ballast (AGB) or Lift Gas Compression (LGC) were explored by the group at Smith College [9]. Subsequently, a concept for involving mechanical compressions by changing the volume of the envelope was developed by Red Line Aerospace using their Ultra High Pressure Vessel (UHPV) technology [10] offering potential simplifications in fabrication and deployment of the aerostat.

Aerial Platforms with hori ontal control Aerostats at a float altitude of 55 km will circumnavigate the planet in about five earth days as a result of the superrotating flow and are expected to gradually drift towards the nearest pole. The rate is believed to be small a few meters per second but quite uncertain. Concepts for controlling this motion have been studied in recent years.

A solar powered Venus aircraft can fly high in the clouds where there is sufficient energy. However, according to Landis [11] in order to stay aloft it must "station keep" on the sun side of the planet by flying in the opposite direction to the flow.

The Venus Atmospheric Maneuverable Platform (VAMP) concept developed by Northrop-Grumman [12]is a semi-buoyant, maneuverable, solar powered air vehicle conceived for flight in the Venus' atmosphere on both the night and dayside.

FUTURE ROLE OF AERIAL EXPLORATION

Aerial platform technology must play a vital role in the future exploration of Venus. We envisage a phased approach beginning with proven technologies that operate in the upper reaches of the Venus atmosphere where temperatures are near Earth surface ambient. In subsequent decades, aerial platforms would penetrate deeper in the atmosphere in step with advances in the technology for operating in those environments. Opportunities should be taken to demonstrate these technologies in advance of a major commitment of science payloads.

the focus should be on formulating missions such as Venus Climate Mission, endorsed by the 2011 Planetary Science Decadal Survey and Venera D, a mission under study by a joint NASA-IKI SDT which includes an aerial platform option. These platforms would be based on mature technologies for light gas superpressure aerostats that operate near 55 km altitude. In addition, to the atmospheric science these platforms can also address geophysical objectives through the use of infrasound generated by Venus quakes, electromagnetic sounding using Schumann resonances, and searching for remnant magnetism.

This should also be a period for intensive technology investment in more capable systems that can make excursions in altitude both to 65 or 70 km near the top of the cloud layer and downward to 40 km near the base of the cloud layer. Other objectives would include systems capable of control in latitude including heavier than air and hybrid technologies. There should be a focus on systems capable of miniaturization enabling low cost missions with rapid turnaround

Mid Term to : In this time frame, it should be possible to deploy aerial platforms with altitude control in the range of 40 km to 70 km. For the lower altitude range, these can use high temperature electronics technologies that are maturing today. Given the new science that will be enabled by the ability to repetitively profile in altitude, scientifically productive missions should be possible with modest payloads. The science would include investigations of a broad habitable zone within the cloud layers

Technology work in this time frame should focus on systems for the lower 40 km of the atmosphere including the near surface environment. Success in this phase will hinge on contemporaneous progress in high temperature electronics. This phase could include tech demos of mobile systems with limited scientific measurement capabilities in the near surface environment.

Long Term : Aerial mobile exploration would be extended to the surface with sophisticated in situ measurement capabilities. The technology would now also be ready to implement VISE the mission that the Decadal Survey originally conceived in 2003 – an aerial platform that would raise surface samples to 55 km for prolonged analysis under benign conditions.

Technology work should focus on the aerial platform requirements for surface sample return Several architectural concepts have been identified and the focus would be on the enabling technologies for the mission.

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MODELING NEEDS FOR ADVANCING SOLAR SYSTEM EXPLORATION: MAGNETOSPHERE-IONOSPHERE-ATMOSPHERE-SURFACE-INTERIOR INTERACTIONS. L. K. S. Daldorff[1], A. Glocer[2] and O. Cohen[3] , [1]John Hopkins University, Applied Physics Laboratory (11100 John Hopkins Road, Laurel MD 20723, Lars.Daldorff@jhuapl.edu), [2]NASA Goddard Space Flight Center (8800 Greenbelt Road, Greenbelt MD 20771, Alex-Glocer-1@nasa.gov). [3] UMASS Lowell (600 Suffolk St., Lowell, MA 01854, ofer_cohen@uml.edu)

Introduction: Models of planetary and exoplanetary systems are key to understanding how these environments evolve and what the implications are for the origin and evolution of life on these planets. To do this, we need models that couple every aspect of the system from the solar/stellar energy inputs, to the planetary atmosphere, all the way to the interior. Such modeling capabilities are vital to future mission planning and understanding new planetary data. We will discuss specific examples of modeling needs in this area and the importance of including model development and improvements in the roadmap of future planetary exploration needs.

Solar wind interaction with mantel: When simulating a planetary bodies interaction with the solar wind we see the importance of understanding the composition of the planet itself. As the semi-conducting outer mantel can give rise to induction currents opposing strong perturbations in the solar wind, stopping the solar wind from directly hitting the planet's surface [1], Mercury is a prime example of this issue. Its small magnetosphere does not fully shield the planetary interior from the Interplanetary Magnetic Field (IMF) and the interaction with the conducting interior must be included. Figure 1. Similar problems exist for non-magnetized objects, as solar wind magnetic field diffuses through the outer layer and wraps around a conducting core, as in the case of Venus. This leads to magnetic reconnection and energized particles hitting the neutral atmosphere.

Models capable of handing the interactions between the solar wind and the entire planetary system, from interior to the magnetopause, is a major area of need. By having models that describe the composition and structure of the planet we can better predict the actual interaction of the solar wind with the planets surface and atmosphere, and how it has changed over time. An additional factor to include is the formation of dusty plasma layer and sputtering to better handle the near body plasma and outflow into the solar wind.

Atmospheric loss for magnetized compared to nonmangeticed planets: A central question in origin of life is understanding how a planetary atmosphere is generated and kept stable with time. One central question here is the role of a planet's magnetic field, the magnetosphere. Are the planetary fields shielding the atmosphere from interacting with the solar wind and reducing atmospheric loss? Or is it increasing the planet's cross section with the solar wind's and channeling energy into the atmosphere to enhance loss. This leads to energized particles, plasma flows and current systems heating up the upper atmosphere and increasing the mass outflow from the polar region. Atmospheric evolution is critical not only to planets in our own solar system, but to understanding if planets in so-called "habitable zones" around other stars are able to support an atmosphere.

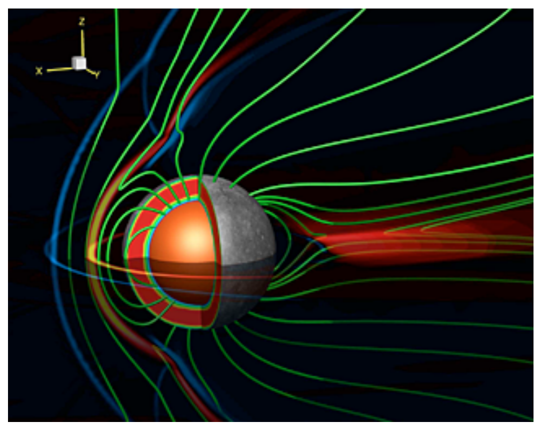

Figure 1 By including a simple model of the outer planetary mantel semi conductive layer we can capture the induction process counteracting the variation in the solar wind condition for Mercury[1].The green lines show examples of magnetic field lines with red, yellow and blue contours indicate the current system. X direction points toward the Sun.

Improved models of atmospheric loss that include magnetized plasma effects as well as other loss mechanisms are critical. To determine if the dominant atmospheric loss mechanism, be it hydrodynamic escape, photochemical escape, sputtering, or ionospheric outflow, we need models capable of treating all of these processes. Today, no such model exists to treat all of these effects simultaneously. Moreover, even in the context of ionospheric outflow, we do not yet capture fully how energy is transported from the reconnecting magnetic field in the tail to particles and transported to the ionosphere and upper atmosphere as auroras.

The extreme space weather environments of exoplanets: The area that is pushing hardest for integrated modeling efforts to search and understand the possibility for exoplanetary system to harbor life. Many exoplanets in habitable zones, however, are detected very close in around K and M type stars. These close in distances subject planets to extreme space weather environments with high levels of XUV emission, strong stellar winds, and elevated radiation flux levels. The impact of these extreme conditions on the exoplanetary atmosphere and conditions for life must be considered, and models need to be capable of assessing this scenario. Indeed, some simulations suggest that the atmospheres of close-in, M-dwarf planets in the habitable zone may loose their atmospheres at a very high rate[2][3].

The main drawback of the previous studies of exoplanetary atmospheres is that each particular study has isolated a subset of the global problem in a rather simplified way. For example, some models are one dimensional and neglect the day-night energy transfer, some models neglect the dynamic pressure applied by the stellar wind at the top of the model, some do account for the stellar wind, but in a simplified manner, and some models assume that the energy associated with stellar radiation is the only source for driving hydrodynamic escape, where in reality other processes may be involved. In order to fully understand the interaction of exoplanetary atmospheres with their space environment and the sustainability of exoplanetary atmospheres, one needs to use a coherent tool that covers as much of the physical system as possible.

In the next coming years we will see an increased integration of modeling domains and processes. For example, global magnetospheric models starting to couple their ionospheric models to global atmospheric models in recognition of the importance of the interplay between neutral and charged particles. We will also likely see an increased push to model the space weather environment of close in exoplanets and examination of the consequences for atmospheric evolution and conditions for life.

In the next couple of decades, we will see a shift away from a mostly fluid description of solar/stellar wind interaction with planetary bodies, to approaches that include kinetic and non-thermal physics. This will have to be paired with improved computational techniques and resources to allow the inclusion of new and improved (but computationally intensive) physics.

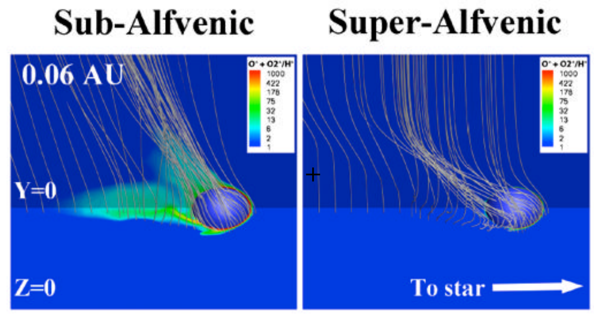

Figure 2 The solutions for all the cases shown on the y = 0 and z = 0 planes. The view is from the side where the stellar wind is coming from the right (the direction to the star). The left column shows the sub-alfvénic cases and the right column shows the super-alfvénic cases. Color contours are the ratio of the oxygen ion density ($O^+ + O_2^+$) to the H density. Selected magnetic field lines are shown as white lines[2].

Conclusion: Today we already have specific models for most areas of high scientific value. The problem is that most models only include a simplified interaction with other regions of the environment thereby limiting their use for the scientific community. To understanding how the processes in our solar system operate, interact, and evolve the community need the best models for each area of planetary research connected and working together. Indeed, many questions of atmospheric evolution and habitability can only be answer, at present, with modeling and simulation tools. It is moreover critical to recognize that the development of future missions to make progress on these fundamental questions rely heavily on model predictions for both planning and interpretation of data. It is therefore essential that the continued development and improvement of modeling capabilities be a key part of any roadmap to support future planetary science objectives.

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EXPLORING THE LARGEST MASS FRACTION OF THE SOLAR SYSTEM: THE CASE FOR PLANETARY INTERIORS. L. R. Danielson[1] , D. Draper[2], K. Righter[2], F. McCubbin[2], and J. Boyce[2], [1]Jacobs JETS (2101 NASA Pkwy., Houston TX, 77058, lisa.r.danielson@nasa.gov), [2]NASA JSC.

Why explore planetary interiors: The typical image that comes to mind for planetary science is that of a planet surface. And while surface data drive our exploration of evolved geologic processes, it is the interiors of planets that hold the key to planetary origins via accretionary and early differentiation processes. It is that initial setting of the bulk planet composition that sets the stage for all geologic processes that follow. But nearly all of the mass of planets is inaccessible to direct examination, making experimentation an absolute necessity for full planetary exploration.

Facility in development: Our vision is to establish a 5000 ton press open user facility that will serve the planetary science community as well as the greater scientific community as a whole. The Community Extreme Tonnage User Service (CETUS) will be responsive to current user needs, and adapt to carry out missions that benefit the greater research community. Instrument time and facility resources will be specifically dedicated for innovation and pilot studies. Projects that are community driven, such as the establishment of a standard synthesis library for distribution will be an ongoing priority for CETUS.

Current challenges in high pressure experimental petrology: Larger sample volumes will allow better control of the sample environment and complex mixtures of starting materials to be studied in greater detail, expanding the types of conductivity, diffusivity, and phase equilibria studies possible. This larger volume relative to the capsule interior area reduces or eliminates concerns about surface interactions between the sample and capsule, which can swamp experiments at the highest pressures in a capsule of <1mm^3 volume (compare to 1 cm^3 of a large press at the same pressure conditions). Controlling the oxidation state of the sample by adding solid media buffers would be feasible up to higher pressures.

Potential benefits to exploration community: The large press will allow experimenters to reach higher pressures (above 30 GPa) and larger sample volumes than is currently achievable with existing presses. Pressures corresponding to the central pressure of Mars (fig. 1) and deeper into planetary mantles will be attainable. The large press could also contribute to a greater understanding of physical properties of planetary interiors (e.g., thermal conductivity), rheology, paleomagnetism, all of which are linked by complex early planetary dynamics. This new capability even opens experimental opportunities for studies of the evolution and mantle-core compositions of exoplanets such as super-earths.

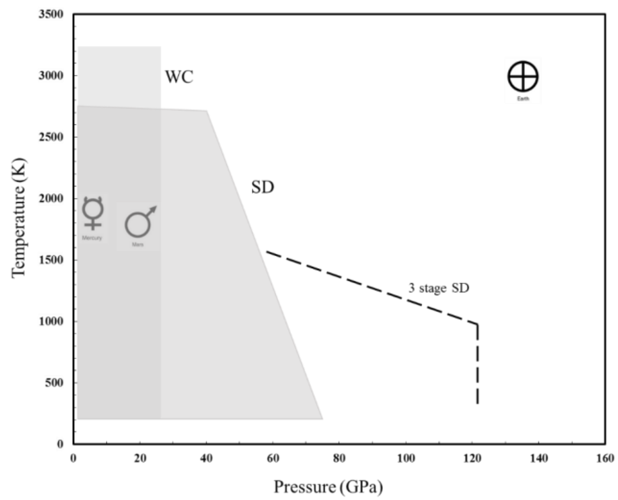

Figure 1. Schematic of achievable pressure-temperature space of multi anvil experiments with various second anvils, modified after [1]. Shaded block labeled "WC" (tungsten carbide) is the current pressure temperature regime of multi-anvil apparatuses in the United States. "SD" is sintered diamonds, which require modifications to the pressure module normally used for WC anvils. Even higher pressures have been achieved by use of a 3 stage assembly with additional nano-polycrystalline diamonds, [2]. Symbols for Mercury, Earth, and Mars approximate the core-mantle boundary conditions.

The potential for studies of volatiles in planetary evolution would be enhanced, with the expanded experimental assembly volume able to contain comparatively sizeable amounts of volatile-rich material within noble metal capsules. This ability opens up more direct simulations of the interiors of the outer planets.

As we continue to expand and extend our human exploration of the solar system, new materials and technologies will be needed. Ultrahard materials may be useful for shielding and durable tools, for example, and optically transparent ultrahard materials may have additional applications in instrumentation and space vehicles (fig. 2).

Figure 2. High-quality polycrystalline garnet synthesized at 15 GPa and at 1,400 °C, with a diameter of ~4 mm and thickness of ~2 mm; grossular with 2 mol% $Ca_3Cr_2Si_3O_{12}$ uvarovite (green), pure grossular (colorless, hardness of ~14Hk) and $Mg_3Al_2Si_3O_{12}$ pyrope with 5 mol% knorringite $Mg_3Cr_2Si_3O_{12}$ (purple). After [3].

Milestones and direction: A number of milestones have already been reached in 2016 for implementing the CETUS facility:

1) A Planetary Major Equipment proposal was submitted to the NASA Emerging Worlds solicitation for the full cost of the press and partial FTE for development team members. (6/3/16)

2) A full sub-award proposal was submitted to COMPRES for 2 FTE research and technical staff to run the CETUS facility. (8/15/16)

3) A sub-award was submitted to COMPRES for experimental cell assembly development. (8/15/16)

4) One development team member attended the European High Pressure Research Group International Meeting on High Pressure Science and Technology, Bayreuth, Germany, 9/5/16-9/9/16, and conducted a site visits to Bayreuth Geoinstitut and the Voggenreiter factory (fig. 3), which is the preferred vendor for the 5000 ton press.

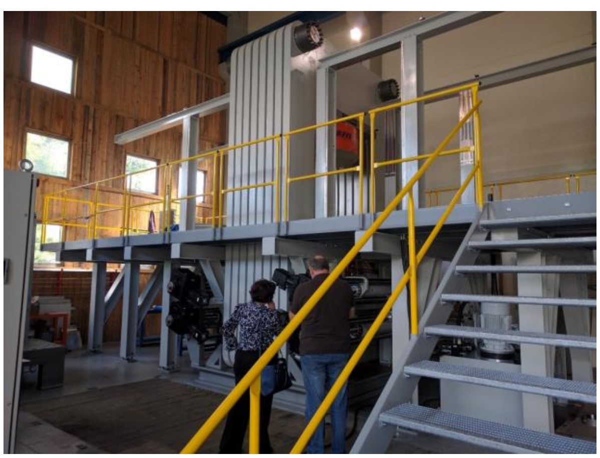

Figure 3. The two module frame of the 5000 ton press at the Voggenreiter factory in Mainleus, Germany. Lisa Danielson and Michael Petri, Head of Development in foreground.

5) A development working group meeting that will address a number of programmatic issues and outline a plan of action for CETUS development for 2017 was funded by COMPRES, and will be hosted by the Lunar and Planetary Institute January 23-24, 2017.

Our current timeline goal is to open CETUS for general use in 2021. The useful lifetime of CETUS should extend to 2050 and potentially beyond with our dedication to constantly evolving technology.

Team members of Experiments in Extreme Environments Laboratories, spring 2016, from center-front clockwise: Lisa Danielson[1]; Kellye Pando[1]; Loan Le[1]; Roland Montes[1]; Jenny Rapp[1]; Mark Cintala[2]; Dave Draper[2]; Frank Cardenas[1]; Frances McCubbin[2]; Poorna Srinivasan[3]; Kathleen Van der Kaaden[3]; Mya Habermann[1,3]; Kevin Righter[2]; Ian Szumila[1,3]. [1]JETS Contract; [2]NASA civil servant; [3]graduate student. Not shown: Fred Horz[1], emeritus; John Jones[2], Etienne Medard, visiting scientist, LPI; Asmaa Boujibar, NPP postdoc.

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Dual Mode Green Propulsion for Revolutionary Performance Gains with Minimal Recurring Investments. J. W. Dankanich[1] and P. C. Lozano[2], [1]NASA Marshall Space Flight Center, ZP30, MSFC, AL, 35812, john.dankanich@nasa.gov [2]Massachusetts Institute of Technology, 77 Massachusetts Avenue, Room 37-401, Cambridge, MA, 02139, plozano@mit.edu.

Introduction: The aerospace propulsion community has been making significant investments in both green propulsion combustion engine technology and micro electrospray propulsion (MEP). Combustion thruster technology will be matured to TRL 9 and demonstrated in flight on the NASA Green Propellant Infusion Mission (GPIM) [1]. The propellant selected for the green propellant infusion mission is The Air Force Research Laboratory (AFRL) developed AF-M315E, an ionic liquid based propellant. This propellant can also be used as propellant for scalable electrospray propulsion systems with high performance and efficiency. If scalability and lifetimes are achieved, a new architecture for spacecraft propulsion is possible, enabling significant mission performance increases with minimal recurring investments. By 2050, there is reasonable expectation that both green propulsion systems and electrospray propulsion system will be flight proven scalable options.

State of the Art: The state of the art (SOA) propulsion systems include a wide range of options such as monopropellant and bipropellant combustion engines, cold gas thrusters, Hall thrusters, gridded ion thrusters, pulsed plasma thrusters, arcjets, resistojets, etc. Chemical systems are typically hydrazine based, a toxic but reliable solution with established processes and procedures. Electric propulsion systems are typically xenon based or hydrazine based. The high performance electric propulsion systems are typically xenon, but rely on disparate propulsion systems for high thruster and therefore increased system complexity if high accelerations are required.

The propellant tank is the highest volume element of a propulsion system. Spacecraft have significant benefits of high thrust during orbit transfer to high value orbits and orbit insertion, while higher performance propulsion is desired during station keeping, formation flying and/or drag make-up. The existing options for bimodal systems have significant challenges. However, even those systems have received significant investments in recent years due to the exceptional need for this capability. The alternatives to the proposed concept include two independent propulsion systems or a lower performance integrated option.

Independent Systems: The state of the art option for two independent systems is commonly found on a number of large spacecraft. Larger spacecraft have sufficient volume to allow for independent propellant tanks. For these spacecraft, the high thrust propulsion capability is provided by hydrazine based propulsion. The hydrazine based systems, whether mono-prop or bi-prop, have limitations and costs associated with complex propellant system and hazardous propellant handling. The low thrust propulsion capability is often provided by a xenon based electric propulsion option (Hall thrusters or gridded-ion thrusters). The complexity of two independent propulsion systems increases total mission risk and increases cost. This is evidenced by the recent failure of the AEHF spacecraft where the chemical thruster failed and the xenon system was required to perform orbit insertion over months instead of hours and by the transition by Boeing to an all low-thrust option using only xenon. The all-electric option has a market due to the overall lower cost, but does not have full market capture due to the lost revenue and functionality without the possibility for high accelerations.

Low Performance Integrated Options: A single propellant tank option does exist for hydrazine as well. Unfortunately, the hydrazine options are limited for higher performance (i.e. higher specific impulse operation). Propulsion systems have been fielded that operate off a common hydrazine propellant reservoir for the combustion engine and to feed an electrothermal (e.g. arcjet) thruster. The limitation of this option is the significant performance ceiling for electrothermal thrusters versus electrostatic alternatives. As example, the MR-510 Aerojet arcjet has an average specific impulse < 600s at 45% efficiency. While this is 3x the combustion thruster I_{SP}, this is far less than the 2000 – 3000s performance and 70% efficiency goals of the MEP electrostatic option. However, the hydrazine option existence gives market proof of a dual mode propulsion expectation to supplant the SOA if the promise of AF-M315E comes to fruition.

Green Propulsion Alone: Significant investments have been made and continue for green propulsion solutions because of its merit over SOA. AF-M315E has 50% great density specific impulse, comparable combustion efficiency and offers a low-toxicity alternative with anticipated cost and safety advantages.

MEP Alone: It should be noted that a fully scalable electrospray propulsion option is enabling on its own merit. Any mission that would otherwise benefit from any SOA electric propulsion system, would likely be outperformed by a scaled electrospray system. The electrospray system produces ions without the ionization cost and therefore will always yield a higher system performance [2]. Only is rare cases of areal thrust densities would an alternative propulsion system have an advantage.

Propulsion End-Game: It is unlikely to achieve higher performance (system level efficiencies at specific impulses of interest) than electrospray systems. While there are significant technical challenges to achieve these high efficiencies, with long life reliability, and at power levels of interest, no fundamental limitations have been identified. When proven, scalable MEP will likely supplant all SOA electric propulsion alternatives. This would include xenon, krypton, bismuth, iodine, etc. Hall and gridded ion systems with a single device using a single propellant. Rather than investments of Hall thrusters at 200W, 600W, 1.5kW, 4.5kW, 12.5kW, 20kW, etc. as done today, and a different thruster if xenon or bismuth or iodine, and gridded ion thrusters and 4.5kW and 7kW, etc., a single thruster array with a single propellant outperforms all alternatives.

Also, that same propellant can be used for a high thrust combustion engine that can be packaged efficiently and leverage the same propellant tank without a priori limitations on the ratio of high thrust to low thrust application; therefore common to a wide range of missions. A dual mode green propulsion solution could save $100M in propulsion technology developments of disparate systems, each with a niche application.

Mission Performance Analyses: Preliminary mission analyses indicates potential for doubling science payloads for electric propulsion missions such as Dawn, increasing the number of targets for a Trojan asteroid tour, and potentially enabling missions such as Ceres Sample Return and Kuiper Belt Object rendezvous. Mission results and system level advantages are to be presented.

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THE FUTURE OF PLANETARY CLIMATE MODELING AND WEATHER PREDICTION.
A. D. Del Genio[1], S. D. Domagal-Goldman[2], N. Y. Kiang[1], R. K. Kopparapu[2], G. A. Schmidt[1], L. E. Sohl[3], [1]NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025 (anthony.d.delgenio@nasa.gov), [2]NASA Goddard Space Flight Center, Greenbelt, MD 20771, [3]Columbia University, New York, NY 10027.

Introduction: Modeling of planetary climate and weather has followed the development of tools for studying Earth, with lags of a few years. Early Earth climate studies were performed with 1-dimensional radiative-convective models, which were soon followed by similar models for the climates of Mars and Venus and eventually by similar models for exoplanets. 3-dimensional general circulation models (GCMs) became common in Earth science soon after and within several years were applied to the meteorology of Mars, but it was several decades before a GCM was used to simulate extrasolar planets. Recent trends in Earth weather and and climate modeling serve as a useful guide to how modeling of Solar System and exoplanet weather and climate will evolve in the coming decade.

The Next Decade: GCMs are now central to studies of the dynamics and climate of Mars, Venus, Titan, and jovian planet atmospheres. Most of these use atmosphere-only GCMs (AGCMs). For the ancient climates of Solar System terrestrial planets and exoplanets, though, many first-order science questions involve the potential for habitability and thus require GCMs that take surface liquid water into account, usually by coupling the AGCM to an ocean model.

Many previous studies assume a simple, computationally efficient thermodynamic ocean mixed layer whose temperature is determined by surface radiative and turbulent energy exchanges with the overlying atmosphere ([1], [2]). However ocean heat transport is important for planetary habitability and is not fully compensated by atmospheric transport when sea ice is present. Thus, planetary GCMs that couple atmosphere and dynamic ocean models (AOGCMs) have begun to appear ([3], [4]). We expect such models to proliferate in the next decade. This will require increased computational resources, since AOGCMs often take centuries rather than decades of simulated time to equilibrate, depending on the depth of ocean assumed. It will also require fundamental research into the spatial scale of ocean eddies, whose mixing effects are unresolved and thus parameterized for the rapidly rotating Earth but may be resolved for slowly rotating planets. Likewise, many planetary GCM studies have used simplified representations of moist convection that do not account for advances in understanding that are now being implemented in Earth GCMs, nor do they account for subgrid fractional cloud cover that is the primary contributor to cloud feedback in simulations of 21st Century climate change [5].

Over the past two decades, Earth science has increasingly synthesized more diverse Earth system processes into coupled AOGCMs to produce more complex "Earth System Models" (ESMs) that simulate not only the standard climate variables, but also their interaction with atmospheric (and possibly ocean) chemistry and aerosols, with dynamic land ice, and with land and ocean ecosystems. ESMs are much more computationally intensive than climate-only models, but the ability to predict rather than arbitrarily specify atmospheric composition is central to a fundamental understanding of planetary climate and habitability, as demonstrated by 1-D planetary model studies ([6], [7], [8]). We expect 3-D planetary GCMs to increasingly include interactive chemistry going forward. One such model already exists [9]. There has also been one exoplanet GCM study that utilized dynamic land ice [3].

As computational power increases, ESM groups are confronted with the question of how to partition computing resources among finer model resolution, more complex parameterizations, more ESM components, the ability to simulate longer time intervals, and the ability to conduct a larger number of simulations. Similar choices will confront the planetary modeling community in the coming decade. From the parameterization standpoint, three major questions loom:

(1) How accurately must radiative transfer be parameterized? For climates similar to modern Earth's, efficient parameterizations that treat atmospheric absorption and the stellar spectrum within a limited number of spectral intervals with acceptable accuracy are available. These parameterizations degrade, however, when applied to climates much warmer than Earth's and to stars much cooler than the Sun [10]. Even the line-by-line models that are the standard for evaluating the accuracy of a radiative transfer model disagree with each other in treatments of poorly understood features such as the water vapor continuum. For more exotic planets such as hot Jupiters, and even for some features of Solar System atmospheres, laboratory work is needed to more accurately define absorption coefficients of gases not found on Earth or for which the properties have not been measured over an adequate range of temperatures and pressures [11].

(2) Earth GCMs have sophisticated treatments of chemistry for modern Earth's oxidizing atmosphere.

For more reducing environments (Archean Earth, Titan, large planets with H_2 envelopes), choices must be made about things such as the number of hydrocarbon species and reactions that are accounted for. Chemistry modules that take into account a full range of redox states will need to be developed in the future. Likewise, there is a need for laboratory work to provide a greater understanding of the variety of organic aerosols that can form and their radiative properties [12].

(3) What impacts of life on climate and atmospheric chemistry can be explored with confidence with relevance to the search for life on other planets? While GCMs simulate fairly well the impact of ecosystems on surface albedo and conductance, biogeochemical interactions such as the carbon and nitrogen cycles are crudely captured due to limited understanding of how the diversity of life varies in these processes adapted to different environmental niches. Progress in identifying conserved relations between critical biophysical parameters [13] will advance GCM-coupled ecosystem models, whiel discoveries of wider biological diversity (metagenomics [14], biogenic gases [15]) will offer exotic possibilities for exoplanet models.

Looking further ahead: It is now possible for an Earth AGCM to be run at resolutions approaching the scales of individual clouds [16], producing dramatic visual portrayals of weather systems (Fig. 1) for limited periods of time. In 30 years, such “global cloud resolving models” might be run routinely for other planets, the advantage being that such models reduce the number of processes that must be parameterized.

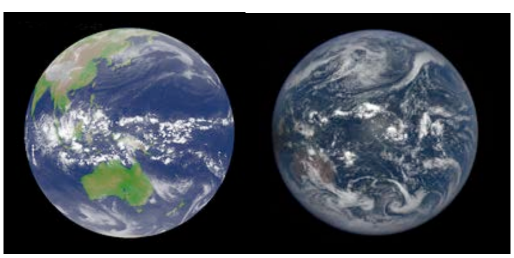

Fig. 1. Which is the satellite image and which is the model? A snapshot of Earth’s weather from the NICAM 870 m grid mesh GCM (left) vs. a DSCOVR satellite image of Earth (right).

Uncertainty in GCM parameterizations can be addressed by performing large “perturbed parameter” ensembles (PPEs) of simulations with various combinations of choices of uncertain parameters [17]. One might use the PPE approach to vary external planet parameters over the wide range of conditions that may exist on exoplanets to produce a library of reference simulations for interpreting transmission or direct imaging spectra from future missions. A future challenge is to couple such models to heliospheric magnetohydrodynamics models to capture atmospheric escape processes and their feedback on chemistry and climate.

Weather forecasting on Earth has been revolutionized by data assimilation techniques that incorporate many *in situ* and satellite observations to produce accurate forecasts, as well as global long-term climatologies of atmospheric circulation and thermodynamic structure known as reanalyses. Data assimilation is already performed for Mars GCMs using e.g. TES satellite data [18]. For Earth, even with nothing more than the assimilation of surface pressure from weather stations, it is possible to usefully simulate documented weather events back to the 19th Century with a few hundred such surface meteorology stations [19]. Might Mars be monitored by a similar network of weather stations spanning the planet in 30 years, producing short-term forecasts for visitors or colonists?

Finally, there is a great need for other planets to be observed using new approaches to remote sensing that have been applied to Earth (and vice-versa – techniques such as polarimetry and altimetry were first used to study other planets). Passive microwave remote sensing is now the standard for measuring water vapor on Earth. This is being attempted for the first time on another planet by Juno. For clouds, precipitation, and aerosols, the gold standard is active remote sensing (lidar and radar), which together provide the most sensitive detections and most accurate vertical locations of particulates. Might scanning lidars and radars routinely monitor other planets in 30 years?

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ENABLING RICH AND ROBUST SCIENCE DATA SETS ACROSS THE SOLAR SYSTEM VIA DEEP SPACE COMMUNICATIONS. L. J. Deutsch[1] and T. J. W. Lazio[1] and S. A. Townes[1], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA 91109.

Introduction: A common element of many concepts for the 2050 Vision is likely to be the development of larger and richer data sets. Science instruments will become more capable, more nations are likely to launch missions, and the development of interplanetary small spacecraft will open new mission possibilities. Further, human spaceflight is likely to expand beyond low Earth orbit and public engagement will necessitate higher definition images, videos, and other data products (Figure 1).

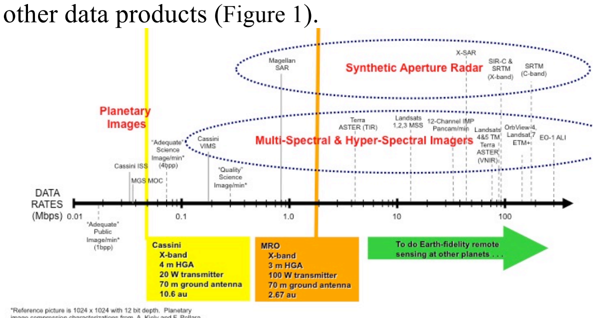

Figure 1. Motivation for higher data rates from spacecraft. The axis shows data rate, with a subset of planetary missions indicated; data rates from selected terrestrial remote sensing missions are shown as well. Across potential destinations, a common element is likely to be increased capability of science instruments and a closer approach to measurements akin to those obtained at the Earth. Further, multiple small spacecraft may generate aggregate data rates approaching those of larger missions, even if each spacecraft carries only a simple instrument. This figure focuses on science instruments, but public engagement and human spaceflight are likely to drive similar demands.

We sketch a roadmap for ensuring that the science community obtains the data from the science instruments and missions to be flown over the next three decades [1]. This roadmap is driven in part by historical trends, but it can be influenced by and respond to the 2050 Vision itself.

Higher Data Rates and Volumes: Over the past 50 years, the capability to deliver science data from spacecraft has increased by a factor of 10^{13} (Figure 2). This increase has both been driven by the demands of missions and been enabling for more complex missions. Recent growth in the downlink capability has slowed due to a natural maturation of radio communications technology, but also due to a focus on reducing operations costs.

As a measure of data delivery capability, we use the Mars Reconnaissance Orbiter (MRO), as it represents the state of the art in deep-space communications [2]. At maximum Mars-Earth separation, the link between MRO and the Deep Space Network (DSN) supports 0.5 Mbps. (For comparison, home wireless routers may provide 300 Mbps or higher.)

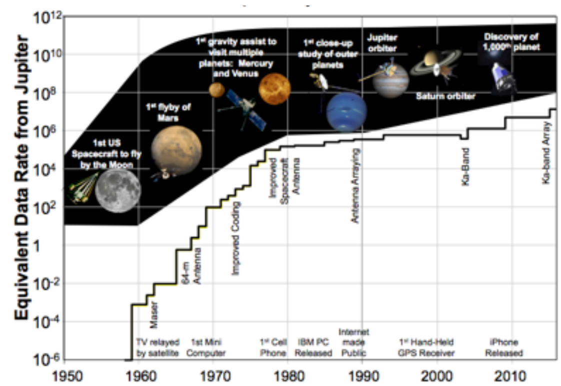

Figure 2. Improvement in planetary science data return over the past 50 years. Enabling new missions across the solar system will demand continued improvements, some of which are well understood and could be implemented in the near term.

Looking toward 2050, and without attempting to identify specific missions or destinations, it is nonetheless possible to predict a need for enhanced data rates and volumes. Different indicators suggest that data rates and volumes will *increase by a factor of 10 per decade*: (i) The DSN routinely models the set of missions to be flown by NASA and other space agencies. These models account for various paths that NASA mission selections may take. Even with different assumptions about the number and type of missions, a robust conclusion is a factor of 10 increase in data requirements over at least the next two decades. (ii) Since the advent of computer-to-computer communications on Earth (e.g., Internet), data rates have grown by a steady rate of almost a factor of 20 per decade.

The First Decade: Achieving the first factor of 10 improvement—equivalent to 5 Mbps from Mars at its maximum separation—is well within current technologies. The approaches are varied, but include the following: (i) There are new flight communications systems becoming available, such as the Universal Space Transponder, that is designed to enable data rates up to 300 Mbps. (ii) The deployment of multiple 34 m antennas at the various DSN complexes around the world allow for antenna arraying and flexible scheduling. Antenna arraying has been used historically for missions such as Voyager and *Galileo*, but, rather than being restricted to mission critical events, an increasing number of antennas around the world could enable this mode to become routine. (ii) Missions could switch to using Ka band (32 GHz) for downlink. As compared to X band (8 GHz), Ka band naturally provides for a higher data rate, and various misisons have already proven out Ka band.

The Second Decade: Achieving a factor of 100 improvement—equivalent to 50 Mbps from Mars at its maximum separation—will likely depend upon the routine use of laser communications. The Lunar Laser Communication Demonstration (LLCD) has demonstrated the capability to transmit up to 620 Mbps from cis-lunar space. The Deep Space Optical Communications (DSOC) is being developed as a potential technology demonstration option for the next NASA Discovery mission. The DSOC is capable of transmitting up to 264 Mbps, and it will be at a technology readiness level (TRL) of 6 by the end of 2017. One of the key considerations for achieving these higher data rates is the existence of sufficient ground stations, and the 2050 Vision roadmap could have an important role in affirming the need for science instruments and missions that demand these data rates.

The 2050 Vision could influence future technology developments for DSOC, if substantial data rates from the outer solar system are scientifically valuable. The DSOC is being designed assuming that the primary use will be in the inner solar system. In part, this design choice is driven by human spaceflight requirements. Missions to the outer planets or beyond may require additional technology investments for future DSOC versions for the outer solar system.

The Third Decade: There are multiple routes to achieving a factor of 1000 improvement—equivalent to 0.5 Gbps from Mars at its maximum separation. A number of technologies individually could provide factors of 2 to 5 improvement in the performance of laser communication systems. These improvements include increased laser efficiency, improved packaging of systems, and improved communication protocols (akin to what is used in terrestrial fiber optic systems). Collectively, these performance improvements could obtain a factor of 10 increase in data rates.

Sensor Networks and Constellations: Planetary science investigations have followed a trajectory of increasing coverage of a target body—flybys followed an orbiter, landers at fixed locations followed by a rover. Observations of the Earth itself have progressed from individual sensors to networks and constellations (seismic networks, the "A Train" constellation, the Constellation Observing System for Meteorology, Ionosphere, and Climate [COSMIC]). We envision a similar future for planetary science, noting that sensor networks have been described previously (e.g., the Lunar Geophysical Network) and that initial steps have been taken. For the Moon, the lunar laser ranging retroreflectors provide an initial sensor network for studying its interior; the *Galileo* orbiter-probe and *Cassini-Huygens* represent simple examples of relay networks; and the set of Mars orbiters provides a network critical for obtaining data from the Mars rovers.

The science return from sensor networks and constellations is significant and has been considered in many previous concepts. Examples of the science questions that can be addressed include

- Interior structure of terrestrial bodies, small bodies, and icy moons with seismic networks;
- Exploration of caves on terrestrial bodies and icy moons using relay networks; and
- Global weather measurements and climate modeling of neutral and ionized components of an atmosphere by visible, infrared, and radio wavelength sensors.

Further, while our focus is on the potential science return from sensor networks and constellations, there may be synergies with human spaceflight. Questions that can be addressed by sensor networks may address strategic knowledge gaps or planetary defense (e.g., determining the interior properties of small bodies) and some sensors could be emplaced by future explorers (e.g., the retroreflectors carried by *Apollo* astronauts).

Current experience in deep space communications will be essential to realizing sensor networks and constellations. Indeed, significant progress on many technological fronts has been made over the past decade, enabling more robust and lower cost sensor networks and constellations to be realized. Examples of recent innovations include

- Internet-like networks via Disruption Tolerant Networking, enabling data access in a variety of circumstances; and
- Improved small spacecraft communication technologies (deployable antennas, radios) that enable high data rates either to relay spacecraft or to the Earth.

Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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Prospects for the study of comets with surface sample return spacecraft

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Introduction: Comets are small bodies composed of molecular ices and dust that spent most of their lifetime in the outer regions of the Solar System. Their nuclei contain pristine material that have not evolved very much since the time of their formation in the early solar nebula. Therefore, characterizing the chemical composition of the coma can help to constrain the distribution of molecular material during the epoch of planet formation. In addition, studying the role of the volatile ice composition in the sublimation of material from the surface is important in the understanding of nucleus activity. Remote-sensing observations of cometary atmospheres at various wavelengths are an efficient tool for investigating the physical and chemical diversity of comets, and substantial efforts have been made in the last decades to develop a chemical classification of comets that displays a great compositional diversity (A'Hearn et al. 1995; Biver et al. 2002; Bockelée-Morvan et al. 2004; Mumma & Charnley 2011). However, close-up detailed measurements on the nucleus and inner coma of this comet can only be provided by in-situ observations such as a flyby, orbiting mission or a sample collection robotic probe.

In-situ observations: The results from flyby, orbiting and in-situ exploration from spacecraft in the past decades have revealed critical information about the composition of the material in the comet nuclei, such as the Deep Impact mission in 2005 and the Rosetta spacecraft first successful landing on of the Philae lander on comet 67P/ChuryumovGerasimenko in 2014. These latter mission has carried out a great variety of measurements including isotopic ratios, dust and organic compounds by analysing the gas in the coma and nucleus material, thus providing a comprehensive view of the comet. In addition, The comparison of spacecraft measurements with Earth-based observations gives a unique opportunity to test observing techniques currently used for comets. The measurements from Rosetta indicate that the D/H isotopic ratio in water vapour in comet 67P/ChuryumovGerasimenko is significantly larger from the value in Earth's oceans. Characterization of the nucleus density by the Rosetta instruments suggests that it is formed by a loose accumulation with higher porosity than previously thought. Therefore extracting a sample off the surface of the nucleus for laboratory analysis on Earth, a goal that was recognized as a priority in NASA's Solar System Exploration Roadmap, is the next step for a cometary mission.

Comet surface sample return mission: A mission to collect material from the surface of a comet nucleus to be returned to Earth for laboratory analysis has been studied by the National Academy of Science's Decadal Survey. Several sample return missions have been proposed since this study was recommended to NASA to develop a medium-class mission (e.g., Smith et al. 2007; Weissman et al. 2010; Chu et al. 2014). Laboratory analysis of the composition of a cometary sample on Earth using state-of-the-art techniques will provide crucial information about the composition of the nucleus and the evolution of the Solar System. In this poster we describe mission designs to extract the sample within a capsule and deliver the sealed sample back to Earth.

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Paradigm shifts towards understanding the full story of Mars a possible future. Serina Diniega[1] and Richard Zurek[2], [1]Jet Propulsion Laboratory (JPL), California Institute of Technology, 4800 Oak Grove Dr., M/S 321-630, Pasadena, CA (serina.diniega@jpl.nasa.gov), [2]JPL (richard.w.zurek@jpl.nasa.gov).

The conte t: We envision that it is 2050 and a new phase of Mars exploration and Planetary Science investigations has opened – similar to the way in which our understanding of the Earth changed between the 1960s and 2017. As with the realization of Plate Tectonics or climate cycles such as El Nino, enough data has been collected for Mars to be seen through a much more holistic lens. Individual datasets and models now fit together within a larger "story," one that encompasses the variety of compositions and structures found around Mars and finds them all to be generally consistent within a common set of interacting processes and global history.

This has had a profound impact in how we understand Mars as:

- an individual planet with complex processes, systems that transport materials over a range of scales, and an evolution history;
- a place where we can consider analog or completely-different-end-member comparisons with regards to climate, environment, and life within our Earth systems;
- and a well-studied member of the solar system, where the planetary bodies continually surprise us with their variety and activity yet all formed within the same "story" of solar-system environment conditions/states and processes.

Here, we explore a possible path for achieving this new understanding.

Early e ploration: As with most new exploration programs, early Mars investigations involved large-scale surveys. Efforts were focused on just seeing what was there, and some basic interpretations. For example, at first, geologic climate variations were recognized within coarse-resolution images, and were hypothesized to occur on Epoch timescales and within very-large scale terrains – the Noachian appeared to have been very wet (and possibly even Earth-like in environment, leading to questions about habitability), there was a decrease in wetness through the Hesperian, and then into the dry Amazonian.

As the "survey" data collection yielded variations within those Epochs/large-scale terrains, however, this simple model was shown to not be sufficient. Observations yielded signs that the early Mars climate may have been cold and icy with only transient periods of warm and wet. Obliquity cycles were also discovered, providing a reason for Mars' regional climates to vary on million-year timescales (with e.g., the extent of "polar" ice), not just over billion-year timescales; and explaining some of the geologic records that implied recent variation and even cycling.

Furthermore, higher-resolution orbital data was coupled with in situ measurements by rovers, allowing for piecemeal, deep investigations of specific locations. As more data was collected and correlated, the investigations of Mars moved away from the large-scale sweeping categorizations and interpretations into exploration of the nuances. High priority science questions were phrased within a recognition that variation and evolution happens, rather than reflecting assumption of an overly simple story.

Since 1 : Two types of observations have been instrumental in enabling Mars science investigations to move into yet more integrated analyses:

(1) Systemic, long-term coverage with ever improving spatial resolution across all wavelengths has allowed us to monitor and characterize the changes occurring over the modern-day planet, and

(2) Observations from networks (both landed and orbital) have allowed for concurrent observation of a range of locations and over all times of day.

These two types of observations allow us to see the full story of what is happening and what has happened on Mars. Within that context, we are better able to spatially and temporally correlate different datasets at a range of scales. We are more able to see how martian materials are transported and how environmental conditions shift, generating the variation in structure and composition seen at all scales within the atmosphere, surface, and sub-surface. We are also able to decouple local-scale perturbations (in space and time) from seasonal cycles and interannual changes, which allows for accurate refinement of state-of-the-art modeling tools, developed for earth and scaled/modified for use on Mars. For example, in 2050, these now provide routine weather forecasting which enables improved planning for exploration by humans and robots.

The development of satellite networks also allowed for the use of numerous small-satellites and spacecraft in the investigations, as now a "ride" and telecommunications could be covered by the primary mission. This technological shift in capability thus enabled an increase in the amount of data collected and investigations that could be addressed, that outpaced the number of primary missions flown. Additionally, the use of numerous, smaller payloads added to the overall access to Mars, enabling a much wider survey and collection of data, and thus feeding back into the studies that rely upon concurrent measurements from a range of locales. (Furthermore, this and a range of citizen science efforts have allowed a larger population to engage with and contribute towards Mars exploration.)

Improved *in situ measurements*, including drilling within both rock and polar ice samples, have allowed for critical and unprecedented groundtruth checks for orbital datasets. Additionally, the timing of important environmental changes has been determined by in situ dating of both icy and rocky materials. Samples returned to Earth laboratories have also allowed for state-of-the-art analyses for composition and dating measurements. In situ analyses also took a leap forward with extended stays by humans on the martian surface, aided by their operation of remote robots.

All of these advancements – *in measurement coverage, resolution and type; in technology and access; and in model/context development* -- have allowed us to greatly advance and quicken how we test hypotheses about how the components of the planet's system interact with each other. These have enabled a much better of idea of how to fit both old and new datasets together and extrapolate between and from them. In particular, major advancements have occurred in our understanding of the polar atmosphere and ice systems (which has led to improved interpretation of landforms and identification of resources for human exploration – such as accessible lower-latitude ice reservoirs), interior science (which was a neglected "boundary" within our study of the full martian system), and atmosphere cycles and transport (which also was a neglected "boundary," and which has been vital for enabling weather forecasting). These all have also been important for understanding how Mars has changed through its history – over epochs and over shorter time periods. For example, these advancements in measurements and models have improved our interpretations of the climate record within the martian polar layered deposits (as global atmospheric processes strongly influence how much dust and ice is available for deposition to form the layers, and the polar atmosphere and surface conditions and processes have influence over how the dust and ice is deposited and if that deposit is retained within the record), with historic changes dated and traced through the rest of Mars' record.

Frequent and strategic access to the planet has enabled our knowledge of Mars to develop to a maturity beyond that achieved elsewhere in the solar system (other than at our home planet). Additionally, the studies that have made this progress possible have come from a *broad and diverse community of researchers*. From this: our understanding of the larger "story" of Mars has greatly advanced our knowledge about how environments and climates on a planetary body can change and be represented within geologic records; models of physical processes active on the Earth, Mars, and other rocky bodies; and the formation and evolution of the terrestrial planets.

Getting humans to Mars a possible future. S. Diniega[1], D. Beaty[1], D. Bass[1], L. Hays[1], C. Whetsel[1], R. Whitley[2], R. Zurek[1], [1]Mars Program Office, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91001 USA (serina.diniega@jpl.nasa.gov), [2]NASA Johnson Space Center, Houston, TX 77058.

The conte t: We envision that it is 2050 and humans are exploring the Martian surface in situ. They survive on Mars for over a year at a time, with crews rotating through. Over a series of missions, a habitat and several support building have been constructed. Within the latter, crops are grown and resources like fuel are generated, decreasing the amount of basic supplies brought in from Earth and opening missions' "delivery" volumes to more interesting tools and more complicated resources. Although water sufficient for current needs is being sourced from the local region, a second habitat is being planned at higher latitudes where subsurface ice is more easily accessible – at least during the warm seasons. Support staff monitors conditions at the surface and within the atmosphere 24-7 (via visible imagery, atmospheric profiles, and regular communications with the Mars surface crew), allowing for weather forecasts and early storm warning systems, which is especially important during the dust storm season. Repeat high resolution imaging, coupled with spectral imaging and radar data, allows for careful geologic mapping of portions of Mars likely to contain resources and/or hazards. And detailed laboratory experiments, conducted on the martian surface and with martian samples delivered to Earth laboratories, have been and are answering key questions about biological potential and geologic history of surface materials – which feed into high-priority science as well as decisions about ISRU design and Planetary Protection (PP) protocols.

Datasets needed to enable this e ploration [1-3]**:**
*1. Orbital Infrastructure, Observations, and Telecommunications.* To support the humans and their necessary infrastructure (which includes picking the landing sites), a *systemic collection of high-resolution images and measurements* were needed. Such imagery has been collected over decades as the high-resolution images have small footprints and in many cases repeat images are needed – to monitor changes, to construct digital terrain models (DTMs) from stereo image pairs, and to understand the landscape under different lighting and seasonal conditions. For comparison, the HiRISE camera on MRO collected images covering ~2% of Mars over a decade; with advances in downlink capabilities and onboard storage, the rate of image acquisition was increased by a factor of at least 3 with the following orbiter. However, a substantial increase in image acquisition didn't occur until construction of the communications and reconnaissance network of satellites was begun, allowing for uninterrupted imaging of the surface, monitoring of the atmosphere, and telecommunications with the surface crew. (This increase in monitoring capability also yielded important science results in development of surface and atmospheric processes and transport models, as measurements and imaging were concurrently acquired over a range of locations and times-of-day. Numerous, small payloads also got to Mars, riding with the primary missions.)

These images were paired with *high resolution spectral maps of the surface and near-surface radar scans* (<10m and 10s-m planform resolution, respectively) – allowing for careful matching between the high-resolution (sub-meter resolution) images/DTMs and maps of subsurface structure and surface composition (which also feed into *2. Bio. & Geochem. Recon.*). Although these datasets have larger footprints than the high-resolution imagers and don't require overlapping acquisition, it still took decades to build up the desired coverage at the sufficient resolution for resource mapping and development of mining/processing plans (which, again, is needed for picking the landing site). Additionally, as only a handful of locations have been sampled in situ and those only to a shallow depth (10s of centimeters), decades of work were needed (and continues to be needed) for the creation and refinement of 3D geologic maps from orbital data, as well as development of surface/near-surface process models that feed into identification, mapping, and characterization of resource reservoirs (e.g., accessible water ice, hydrated minerals and/or propellant reactants within a sufficiently extensive, near-surface geologic unit). These resources are varied in type and sometimes are co-located with hazardous materials (avoidance of which requires at least detection).

Atmospheric measurement and monitoring has also been continued via a few orbital missions over the last few decades, extending the timeline begun with the MCS and MARCI in 2006. Near-continuous monitoring with coarse resolution, global images (showing e.g., cloud cover and dust storm development) and atmospheric profiles of volatiles, dust/aerosol content, and temperature over this long temporal baseline has allowed for atmosphere models to be developed and refined to the level used within terrestrial climate modeling – which is a crucial input for creating the context for weather forecasting and for enabling more precise and larger-mass entry, descent, and landing (EDL) technology. During the last decade, network reconnaissance satellites were also able to measure near-surface winds, which coupled with proxy measurements of upper-atmosphere wind flow (e.g., cloud movement) allows for important refinement of the martian climate and weather models and improved interpretation of geologic climate records.

2. Biological and Geochemical Reconnaissance. A high-priority piece of information for both science and human exploration advancement was whether or not Mars has extant life, and if so it is everywhere (including in the airborned dust) or if it is restricted to refugia. This needed to be known in order to design the PP aspects of the human landed mission. In particular, we'd needed to know if Mars has extant life as that is an important influence on how humans will begin interacting with that life and its habitat. One critical enabling data set of this was the *mapping of "Special Regions"* [4] (see *1. Orbital Infrastr., Obs., & Telecom.*), which allowed these potential habitable regions to be planned around and carefully investigated via orbital and landed robotic missions. A second critical enabling data set was the *study of samples of martian regolith that were returned to Earth*. Additionally, from the returned sample studies, as well as in situ measurements, it was determined whether the regolith and/or airfall dust contained potentially hazardous concentrations of certain "poisonous" compounds (such as CrVI) so as to engineer around them.

3. ISRU Exploration. As we intended to set up a base that was revisited, it was necessary to invest in the exploration for water deposits. This began with orbital recon (see *1. Orbital Infrastr., Obs., & Telecom.* and *2. Bio. & Geochem. Recon.*), but that alone was not enough. At least one exploration mission to the martian surface was also required to define what on Earth are called "reserves": deposits for which all of the essential attributes have been defined, such that a known mining/processing system can interact with it with predictible results [5].

4. ISRU Engineering. A critical antecedent to large-scale ISRU development was the MOXIE experiment on the M-2020 rover [6]. This was designed to be a sub-scale demonstration that martian atmospheric CO2 could be collected and processed so as to produce oxygen gas, which was a critically important technical pathway for long-term human presence on Mars. Also important was the *development of the engineering systems* needed to mine and extract the water from one or more categories of martian water deposits (either ice or minerals).

"Collateral" Science: All of these datasets together have also greatly advanced the development, testing, and refinement of models of martian surface processes – including aeolian and polar. While these studies have not directly fed into human exploration plans, the resultant improvements in the understanding of the present-day martian surface conditions and history of the evolution of these materials has provided a fuller set of contextual information to planners of mining/processing, construction, and operations processes.

Missions needed to generate these datasets in this possible future [1-3]**:**

- Several Mars orbiters have been needed over the years, first to replenish *imaging* capabilities (MRO, the Next Mars Orbiter [7], and those that followed – at least one per decade), then within the telecommunications satellite network that incorporated necessary visible and spectral imaging capabilities, greatly increasing coverage and allowing for concurrent monitoring over multiple locales. Also incorporated within these orbiters were atmosphere and radar instruments that allowed for the needed *atmospheric reconnaissance* (e.g., wind, temperature, and aerosol profiles) and *biological and geochemical reconnaissance* for the identification and characterization of sub-surface resource reservoirs and for PP assessments.
- Mars Sample Return (MSR) enabled careful measurement of *surface material properties and composition*, yielding information about e.g, machine and human hazards (e.g. dust size and amount, toxicity). Such information was vital for the design of habitat, transport, and ISRU processes and machinery.
- A progression of more complicated and larger-scale landed missions focused on ISRU technology demonstrations were needed, before full-scale ISRU mining and processing could commence and enough of the critical resources could be produced on Mars for stable human habitation. This involved much iteration between the reconnaissance and characterization of the martian environment, and development of the machinery and processes.

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TOWARD THE COMPLETE CHARACTERIZATION AND MITIGATION OF THE EARTH IMPACT RISK BY 2050.

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Introduction: Although tremendous progress has been made in recent decades quantifying the risk of an Earth impact by a Near-Earth Asteroid, a complete understanding and mitigation of this risk has yet to be realized. This presentation will outline an approach to fulfill this important task by 2050, covering both the needed infrastructure for the complete detection of NEOs down to sizes where an impact could have regional effects (~20m), and a plan to fill the gaps in our understanding of the underlying geophysical parameters needed for a robust mitigation approach – with obvious benefits to a more complete understanding of the formation and evolution of rubble pile small bodies. In addition to the benefits for planetary defense, a complete catalog and substantially improved understanding of NEOs has significant benefits for human exploration and resource utilization.

Detection and Remote Characterization: The first step in mitigation of the impact risk is to find, characterize, and catalog the orbits of all potentially hazardous NEOs, a task that is already underway. To date, NASA's Near-Earth Object Search Program has successfully discovered more than 90% of NEOs greater than 1 km in diameter, and is making progress toward the current goal of discovering more than 90% of objects great than 140m in diameter. Space-based observatories such as NEOCam [1] and ground-based survey telescopes like LSST [2] will realize this goal within the next decade.

But as seen by the Chelyabinsk airburst event in 2013, even the impact of an object 20m in size (which likely occurs every ~10^2 years [3]) can cause city-scale devastation. However, completion of the catalog of NEOs down to this size is a goal that can be realized by 2050. A dedicated IR space-telescope of the scale of HST or WFIRST (both 2.4m aperture) has the capability to detect NEOs as small as 20m from a distance of ~0.5 AU; when coupled with next-generation dedicated ground based telescopes for follow-up, such infrastructure has the potential to discover over 90% of NEOs down to 20m by 2050.

Remote characterization of asteroid properties is also critical for accurate trajectory refinement. Spin state, size, shape and albedo all factor in to the dynamical modeling of forward trajectory propagation. Space-based and ground-based assets that measure such properties as part of the follow-up observations of potentially hazardous objects is a necessary part of any future observation network. Of particular importance is the continued upgrade of ground based radar observatories such as Arecibo that are uniquely capable of remotely measuring these parameters. In short, there is a need for dedicated ground and space-based systems roughly an order of magnitude more sensitive than currently being planned today, including Earth-based radar.

In Situ Geophysical Characterization: Once catalogued, mitigation of any discovered impact threat likely requires detailed knowledge of multiple geophysical parameters that can only be obtained by spacecraft reconnaissance. As mentioned previously, spin state, size, shape, and albedo all play a role in the forward propagation of trajectories. Thermal properties of the target asteroid (emissivity, thermal inertia, and their spatial distributions) also feed into accurate trajetory prediction, albiet as second-order effects. But a detailed understanding of how these characteristics can subtlely affect orbital parameters is critical to accurate prediction of long lead-time mitigation strategies, such as gravity tractor or kinetic impactor approaches. Perhaps more critically, we need a much better geophysical understanding of the nature of "rubble piles" – aggregations of granular material that are theorized to be the underlying structure of most NEOs – to make accurate predictions of the consequences of a kinetic impactor. Missions such as AIDA will provide excellent emperical information to refine our understanding of how such objects respond to a kinetic impact. However, follow-on missions will be needed to answer questions that are sure to be raised in this experiment.

A unique opportunity to further refine impact mitigation design, as well as our fundamental understanding of how small rubble-pile asteroids form and evolve, will occur in 2029 when the near-Earth asteroid Apophis will fly by the Earth at a predicted distance of 4.6 Earth radii – inside the orbit of geostationary satellites [4]. This close approach should significantly perturb the asteroid, including significant tidal stretching, spin state change, and possibly body-wide turnover of the asteroid regolith. A second close approach with Earth will occur in 2036, a perfect opportunity to refine our understanding of the coupling between geophysical parameters and forward trajectory prediction.

Realizing a Mitigation Approach: Once long-lead-time mitigation flight experiments such as AIDA and follow-on missions have been demonstrated to provide the required precision in changing the orbital parameters of the target asteroid (e.g., demonstrated by 2040, either by kinetic impact or gravity tractor), it is possible to envision by 2050 the mitigation of any predicted long-lead asteroid impact discovered by current or next-gen survey capabilities. Ideally, such a mitigation mission would need to include a spacecraft flying in tandem or in orbit around the object to help monitor and verify the change in asteroid orbital elements.

One class of potential hazardous impactors that is far more difficult to detect with long lead times is long-period comets. Presumably, future larger survey telescopes for detecting small NEOs would also detect such incoming hazards; but detection of a 100m-class object beyond 10AU requires a dedicated observational system much larger than that described above. In addition, even if a comet on an impact trajectory were detected at 10AU, the lead-time prior to impact could be as short as 2-3 years – too short a time to build and implement any new mitigation system. If the mitigation of long-period comets is to be included in this framework, an existing rapid-response system would need to be operational and in-flight, presumably with substantial delta-V capability (>20km/s) and high thrust to provide the needed momentum transfer to the incoming target in the short window of time available to deflect such an impact.

Benefits to Human Exploration: The substantial increase in the number of known NEOs that would result from building a catalog of all objects >20m also has important benefits to human exploration. To date, just over 15,000 NEOs have been detected with existing systems [5]. But the number of NEOs greater than 20m in size is believed to be well-above 10^6 objects [6], meaning that we have detected only ~1% of all objects in this population. If future human missions plan to exploit the resources in the NEO population to lower the cost of future space architectures, this advanced catalog of possible targets makes the sustainable implementation of such an approach much more realistic than it is today.

Summary: Most of the technology to realize the goal of full characterization and mitigation of future asteroid impacts exists today, at least at a fundamental level. However, basic infrastructure will be needed beyond that currently planned to fulfill this goal. Key elements include: 1) Completion of a NEOCam-class mission, coupled with advanced ground-based capability such as LSST, to first characterize the impact risk of objects larger than 140m, 2) the implementation of a dedicated next-generation IR space survey (WFIRST class) in the 2030s, dedicated to the detection of all NEOs larger than 20m, 3) advanced, dedicated ground based assets for robust detection and follow-up of potentially hazardous objects, including advanced radar systems, 4) long-term spacecraft reconnaissance of the asteroid Apophis, covering both the 2029 and 2036 Earth fly-bys, to fully understand the geophysics of rubble pile asteroids, and 5) implementation of AIDA and follow-on impactor/mitigation test missions, culminating in the implementation of any needed mitigation missions for long-lead potentially hazardous asteroids.

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Historical Recurring Slope Lineae: A Potential Not-Special Region to Search for Life

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Introduction: One of the great challenges we will have in the next 35 years of the exploration of Mars will be the issues associated with planetary protection. We have understandably and necessarily strict planetary protection protocols that we place on any robotic landers and rovers that could come into contact with reservoirs of water on the surface. This stands in stark contrast to our desire to send humans – essentially walking bags of microbes – to those same locations. Thus, it would be ideal to investigate those regions for signs of life with robotic landers or rovers prior to their exploration and utilization by human astronauts. Such an investigation would allow us to either "clear" those regions for future human explorers – or, in the positive detection of life-forms, adjust our plans for human exploration in the context of knowledge of indigenous Martian life. This presents us with a paradox: planetary protection protocols may make such an investigation prohibitively expensive, yet ignoring those protocols may compromise the purpose of and risk any value to sending a mission to search for signs of life in advance of human explorers.

In this abstract, we present a preliminary idea for a potential way around this paradox. We propose that we should search for sites at or near the surface of Mars which may have the potential for relatively recent biological activity, but for which there is little or no potential for active Martian life. One example of such sites would be "historical" recurring slope lineae (RSLs) that are similar to those observed on modern Mars but that are no longer active. Such sites could harbor the remnants of life that lived in Martian groundwater prior to exposure to the surface, and be subject to a chemical and physical search for such remains. We propose a series of investigations to first predict whether any such sites exist, then search for them from orbit, and finally to assess their accessibility to life detection experiments.

The first step in pursuing this idea is to determine whether any such sites could exist. This would begin with climate modeling of the Martian surface, to determine whether there are local climatic conditions associated with the presence and absence of RSLs on otherwise similar geomorphological features. If any such conditions are discovered (or already known), we can simulate whether there are any places where those conditions do not currently exist, but may have existed in the past. This may be due to changes in the atmospheric composition of Mars, changes from its orbital forcings, or a combination of these effects. The ideal site would be one for which past orbital/climate conditions would predict it to have had RSLs and for which modern conditions make RSLs impossible. If models predict the existence of any such sites, there would be a desire to make predictions of observations from orbit that could confirm their existence, and to repeatedly observe them to ensure they do not contain modern RSLs at the surface. This could include detection of salt/mineral deposits created during the evaporation and sublimation of the water in the RSLs. Finally, the means of accessing these locations must be considered. Even if any historical RSLs exist, they will likely not be easily accessible to life detection experiments. And even if we design a platform that can reach these sites, they may present us with sampling challenges, including a need to avoid the very groundwater we are trying to avoid in the first place.

In this presentation, we will introduce this concept, go over the work needed to develop it further, and begin a discussion of its many challenges and limitations. Because this idea is very preliminary, we welcome feedback on its feasibility and on the best way to proceed in our investigations of it.

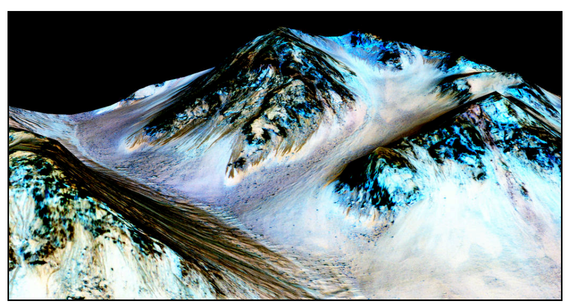

Image Credit: NASA/JPL-Caltech/Univ. of Arizona

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THE NEXT GENERATION OF OBSERVATIONS OF PLANETS BEYOND OUR SOLAR SYSTEM.

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This presentation will give an overview of the capabilities of the Large UV-Optical-Infrared (LUVOIR) Surveyor, a mission concept being studied by NASA in preparation for the 2020 Astrophysics Decadal Survey. LUVOIR is a general-purpose space-based observatory with a large (8+ meter) aperture and a wavelength range spanning from the far-UV to the near-infrared. This observatory will enable revolutions in many areas of astronomy, including planetary science within and beyond our Solar System.

Because LUVOIR is being considered for the next decadal survey, is must be capable of advancing our understanding of astronomical targets, including exoplanets, far beyond what will be achieved by the next two decades of observations from other space- or ground-based facilities. This means that the mission must move past the detection of potentially habitable worlds and their astrophysical characterization. Detection of such worlds is happening now with Kepler and ground-based measurements and will continue with TESS (Transiting Exoplanet Survey Satellite) and WFIRST (Wide Field Infrared Survey Telescope). It must also move beyond the chemical characterization of gas giants, which is something that has begun with observations from Spitzer, Hubble, and ground-based telescopes and will see major advances with JWST (James Webb Space Telescope) and WFIRST with a coronagraph. What will remain is the chemical characterization of potentially habitable worlds, and through that characterization an assessment of their habitability and a search for signs of global surface (or very near surface) biospheres.

Therefore, one of LUVOIR's main science objectives will be to directly image rocky-sized planets in the habitable zones of other stars, measure their spectra (Figure 1), analyze the chemistry of their atmospheres, and obtain top-level information about their surfaces. Such observations will allow us to evaluate the habitability of these worlds, and search for potential signs of life in their spectra. We will review the specific observational strategies needed for astrobiological assessments of exoplanetary environments, including the wavelength range and spectral resolution required for these habitability analyses and biosignature searches. For comparison with Solar System science, we will discuss how the strategies required by LUVOIR to search for habitability and life are similar and different to assessments of potentially habitable environments within our Solar System. Further, we will discuss how the observational requirements to make measurements of "Earthlike" worlds in the habitable zone will allow high-quality observations of a wide variety of extrasolar planets that are outside the habitable zone or too large to be considered potentially habitable. The survey of the atmospheric composition of hundreds of worlds will also bring about a revolution in our understanding of planetary formation and evolution, and help place the chemical analyses of planets inside our Solar System in a broader comparative planetology context.

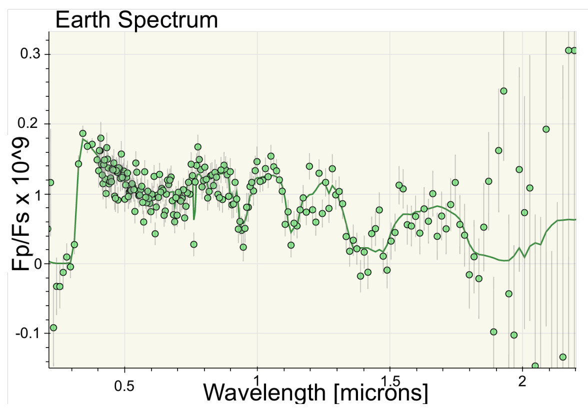

Figure 1. The spectrum of Earth at 10 parsecs observed by a 10-m LUVOIR-class telescope in 24 hours. The resolution (R) for $\lambda < 0.4$ μm = 20; R = 150 for $0.4 < \lambda < 1$ μm; and R = 100 for $\lambda > 1$ μm. Molecular features from water and O_2 and O_3 can be easily detected at wavelengths shortward of 1.8 μm, but an assumed telescope temperature of 270 K makes measurements impossible for $\lambda > 1.8$ μm.

Determining Planetary Tectonic State Through Time Using Observations of the Terrestrial Planets. M. S. Duncan[1] and M. B. Weller[2]; [1]Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Rd. NW, Washington, D.C. 20015, mduncan@carnegiescience.edu; [2]Institute for Geophysics at University of Texas, Austin, 10100 Burnet Road, Austin, TX 78758, mbweller@ig.utexas.edu.

The current and past tectonic states of the planets are directly related to the processes that are active and visible on their surfaces today. In particular, changes in large-scale tectonic behavior, e.g., the transition from a stagnant lid regime to a mobile lid regime, have the potential to significantly influence the current geomorphology, geochemistry, and surface state (e.g., atmosphere composition and temperature) of a planet. We must understand what controls a change in global tectonic regimes, as well as the current differences in tectonic states for the planets that we can most easily observe (Earth, Mars, Mercury, and Venus). Therefore, understanding the planets in terms of the feedbacks between its geodynamic and geochemical histories, for example, is critical to make predictions of the future states of planets as well as the potential habitability of intra- and extra-solar planets.

One method of combing the geochemical and geodynamic is via determinations of mantle potential temperature (T_P) through time in concert with mantle convection models. We use measurements of surface basalts of these planets to calculate their mantle T_P through time, with appropriate assumptions, and feed these temperatures into the geodynamic models in order to describe past, present, and future lid state. These kinds of determinations are relatively easy for the Earth, due to the wealth of measured surface basalts, but are necessarily limited for the other terrestrial planets. In particular, the level of information that exists for Venus is abysmally low, and while significantly more information exists for Mars, and even Mercury, the number of assumptions required to make these predictions is uncomfortably large. With the current level of data we can make preliminary calculations of mantle T_P of the terrestrial planets (Fig. 1). Overall the Venus T_P values show overlap with the Earth values, while the calculation based on martian meteorites show much lower mantle temperatures and the Mercury values are quite scattered.

We run mantle convection experiments of fixed parameter values that allow for transitions in lid states (Fig. 2) that provide information about how the internal temperature (T_P) changes as a function of lid state rather than by specific parameter values. Using these results with well-known internal temperature-heat production scaling arguments [9], we have shown that shown estimates of mantle potential temperatures can be used as a diagnostic of lid-state and lid-state evolution [1]. The caveat is that these results are currently tantalizing, but informed by very limited datasets, particularly in regards to Venus.

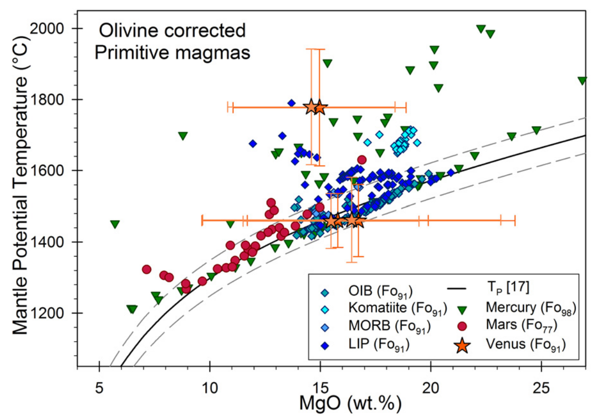

Figure 1: Calculated T_P of mantle based on olivine corrected ‘primitive’ melt compositions, mantle ‘equilibrium’ olivine Fo values in parentheses [1]. Calculated potential temperatures based on Ti partitioning between bulk silicate mantle and melt, compared to the parameterization of [2]. Earth T_P values (blue diamonds) calculated from basalts in various tectonic settings tabulated from the GEOROC database. Mercury T_P values (green triangles) determined from MESSENGER data [3-5], Mars T_P values (red circles) determined from martian meteorites and measurements of surface basalts [6,7], and Venus T_P values (orange stars) determined from surface compositions measured by the Venera and Vega landers with the 2σ error [8].

In order to understand the planets in a comparative evolutive sense demands at the very least a comparable amount of data to use in baseline observations. In the case of Venus, this indicates that analysis and understanding of the basaltic plains, which encompass the vast majority of the planetary surface (upwards of 80%) [10], need to be a priority for mission design and development. For Mercury, a vast improvement for future missions would be to specifically measure the major and minor elements independently of each other [3-5], and include a focus on in situ measurements for cross-correlation within major regions (each of the geologic terrains). For Mars, while there is a cornucopia of surface data, the focus has been on water. For our purposes (thermal-tectonic evolution) we need to focus on regions that have not undergone significant (or any) hydrothermal alteration such as Tharsis, Thaumasia/Solis Planum, and northern lowland locations.

With higher spatial and temporal sampling of the inner terrestrial planets, we have the ability to infer the tectonic history of these bodies. Armed with this new found knowledge, we can not only test hypotheses of Earth's evolution, but also infer its eventual fate. These results can further be used to extrapolate habitability through time in our Solar System, and infer the potential for habitability in the ever increasing catalog of extra-solar planets being discovered.

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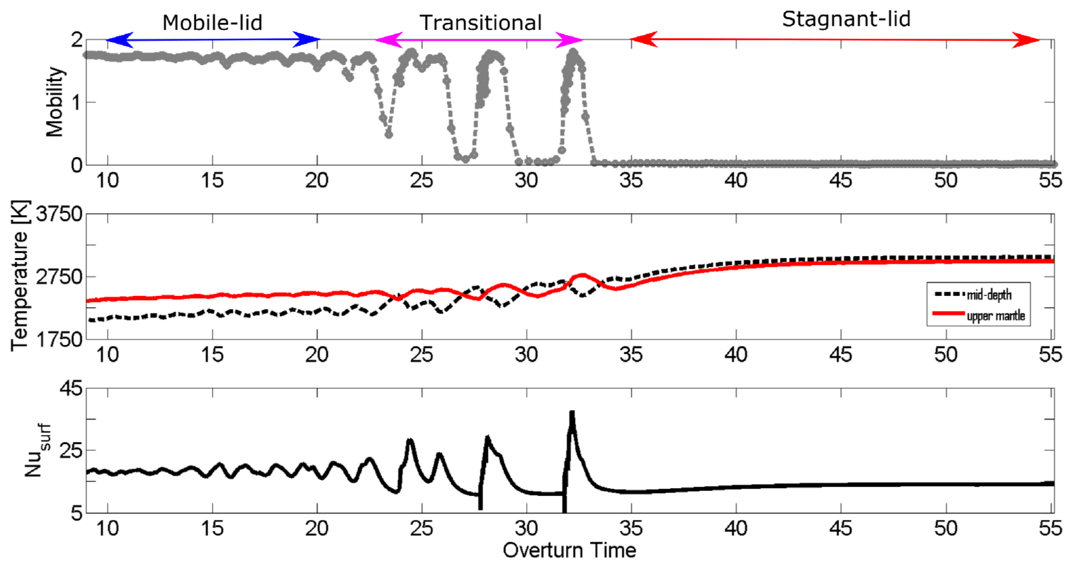

Figure 2: Results from 3 dimensional spherical mantle convection code CitcomS [11] showing a global tectonic regime evolution (for fixed model parameters). Top panel Mobility, is a measure of surface velocity versus system velocity (Mobility = Surface V_{rms} / Total System V_{rms}, where V_{rms} is the root mean square velocity). Middle panel Temperature, are temperatures in the upper mantle (red line) and lower mantle (dashed black line). Temperatures are dimensionalized using a total system temperature contrast of 3000 K (for use in T_P calculations). Bottom panel, Nu_{surf}, non dimensional surface heatflow. The overturn time (x-axis, all panels) corresponds to the time a parcel takes (on average) to traverse the mantle (computed from the V_{rms}). The Rayleigh number (standard definition for basally heated systems using the viscosity at the system base) is 3e5, with an input internal heating rate set at 65 (moderately high levels of internal heating).

THE MOON AS A LABORATORY FOR BIOLOGICAL CONTAMINATION RESEARCH. J. P. Dworkin[1], D. P. Glavin[1], M. Lupisella[1], D. R. Williams[1], G. Kminek[2], and J. D. Rummel[3], [1]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA [2]European Space Agency, Noordwijk, The Netherlands [3]SETI Institute, Mountain View, CA 94043, USA.

Introduction: It is possible that humans will return to the Moon as a staging for human exploration of Mars and other destinations. One of the guiding principles for exploration is to pursue compelling scientific questions about the origin and evolution of life. The search for life on objects such as Mars will require careful operations, and that all systems be sufficiently cleaned and sterilized prior to launch to ensure that the scientific integrity of extraterrestrial samples is not jeopardized by terrestrial organic contamination. Under the Committee on Space Research's (COSPAR's) current planetary protection policy for the Moon, no sterilization procedures are required for outbound lunar spacecraft, nor is there a different planetary protection category for human missions, although preliminary COSPAR policy guidelines for human missions to Mars have been developed, and additional research and development of future regulations for human exploration is underway[1].

Exploration of the Recent Past: Future *in situ* investigations of a variety of locations on the Moon by highly sensitive instruments designed to search for biologically derived organic compounds would help assess the contamination of the Moon by existing lunar spacecraft [2,3]. These spacecraft have also had their structural materials and components exposed to the space environment for decades. An analysis of the materials properties of hardware exposed to space for 50 years could be invaluable in the engineering of future colonies or mines on airless bodies.

Moon, Mars, and Elsewhere: These studies could also provide valuable information for Mars sample return missions and help define planetary protection requirements for future Mars-bound spacecraft carrying life detection experiments. In addition, studies of the impact of terrestrial contamination of the lunar surface by the Apollo astronauts could provide valuable data to help refine future Mars surface exploration plans for a human mission to Mars or other bodies.

The Moon can also serve as a high-fidelity test environment for evaluating detailed analytical and operational contamination control protocols that may ultimately be useful at airless bodies, or even Mars.

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JUpiter MagnetosPheric boundary ExploreR (JUMPER). R. W. Ebert[1] F. Allegrini[1,2], F. Bagenal[3], C. Beebe[1], M. I. Desai[1,2], D. George[1], J. Hanley[1], N. Murphy[4], and A Wolf[4], [1]Southwest Research Institute, 6220 Culebra Rd., San Antonio, TX USA 78238 (rebert@swri.edu) [2]University of Texas at San Antonio, One UTSA Circle, San Antonio, TX USA 78249 [3]Laboratory for Atmospheric and Space Phyiscs, University of Colorado, 1234 Innovation Dr, Boulder Colorado, USA 80303 [4]Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena California, USA 91109.

Mission Summary: We present the JUpiter MagnetosPheric boundary ExploreR, JUMPER, a Jupiter orbiting SmallSat mission concept to explore the planet's magnetospheric boundaries and image its energetic neutral atom (ENA) emissions. JUMPER's science objectives focus on how the solar wind interacts with Jupiter's magnetosphere and the contribution of ENAs to mass loss from the jovian space environment. These objectives will be met with a science payload consisting of two ion sensors, a magnetometer, and an ENA imager. Measurements from these instruments will complement simultaneous observations of Jupiter's magnetosphere from a primary spacecraft (e.g. Europa Multiple Flyby Mission, Jupiter Icy moons Explorer, Io Observer, etc.), providing a multi-point platform from which to study the dynamics of this system. The science objectives, which have yet to be addressed by any other Jupiter mission, are responsive to the NASA Planetary Science Division (PSD) science goal – Advance the understanding of how the chemical and physical processes in our solar system operate, interact, and evolve –as defined in NASA's 2014 Science Plan.

JUMPER's science objectives drive several top-level requirements on mission design. The most important is an orbit that includes several passes through Jupiter's bow shock and magnetopause on the dayside of Jupiter. Mission design is also constrained by the necessity to ride share on a primary vehicle, at least until after Jupiter orbit insertion.

The JUMPER spacecraft design derives heritage from SmallSats developed for the Southwest Research Institue (SwRI)-led Cyclone Global Navigation Satellite System (CYGNSS) mission. It consists of an Evolved Expendable Launch Vehicle Secondary Payload Adapter (ESPA) compatible frame supporting four double-deployed solar array panels, ESPA ring interconnections, four science instruments, and a radiation vault to house the spacecraft avionics and payload subsystem electronics. JUMPER will use its perijove periods to transmit data to the primary spacecraft and execute ranging activities. It will de-orbit into Jupiter at end of mission.

While the JUMPER mission focuses on Jupiter, this concept can be applied, with modifications, to any planetary system, preferably one where there's an interaction between the solar wind and the planet's intrinsic or induced magnetic field.

Mission Science: JUMPER addresses open questions related to (i) how the solar wind couples to the jovian magnetosphere and (ii) influences magnetospheric dynamics, and (iii) how energetic neutral atoms contribute to mass loss from Jupiter's magnetosphere. These questions are addressed through the following science objectives:.

Objective 1) Characterize the solar wind upstream of Jupiter's magnetosphere and provide context for studying magnetospheric dynamics by a primary spacecraft. One of the more hotly debated questions related to Jupiter is to what extent does the solar wind influence its magnetosphere? While the dynamics of the magnetosphere are largely driven by the planet's 10-hour rotation period, the contribution from the solar wind is not well understood. Magnetospheric processes with evidence of solar wind influence include the motion of Jupiter's bow shock and magnetopause [1], the opening and closing of magnetic flux in the outer magnetosphere [2, 3], the transport of mass, energy, and momentum into the magnetosphere [4], variations in ultraviolet (UV) auroral emissions and morphology [5], auroral radio emission enhancements [6,7] and current sheet asymmetries in the magnetotail [8]. While the solar wind and interplanetary magnetic field (IMF) at Jupiter's orbital distance have been studied in detail [9, 10], our lack of understanding stems from, in part, the absence of a solar wind monitor upstream of Jupiter when the magnetosphere was being observed.

JUMPER will address this topic by placing a SmallSat into orbit around Jupiter with an apojove beyond the nominal position of Jupiter's bow shock. JUMPER will measure the solar wind ions and IMF upstream of Jupiter's magnetosphere to complement simultaneous observations of the magnetosphere and/or aurora from a primary spacecraft. These simultaneous observations will be key to obtaining a more complete understanding of the physics governing this system.

Objective 2) Investigate the modes of solar wind coupling (e.g. magnetic reconnection, Kelvin-Helmholtz waves) along Jupiter's dayside magnetopause. Another important open topic is how the solar wind interacts with Jupiter's magnetopause. This has important implications for outer magnetosphere dynamics, especially the transport of mass, energy, and momentum into the magnetosphere and the circulation of open magnetic flux. The two primary modes of interaction are thought to be magnetic reconnection [11] and shear-flow driven instabilities [4]. Evidence of magnetic reconnection has been limited to a few magnetopause crossings with signatures observed primarily in the magnetic field observations [12, *1*3] and more recently in the form of accelerated ions flows [*14*]. Evidence of wave activity at Jupiter's magnetopause, such has the Kelvin-Helmholtz instability, is essentially non-existent. Our lack of knowledge on the processes operating at Jupiter's magnetopause is primarily due to the limited number of spacecraft observations taken over a limited spatial extent [15].

JUMPER will help address this key question by measuring the ion velocity distributions and flows and the magnetic field in the vicinity Jupiter's dayside magnetopause to look for signatures of these processes. JUMPER's orbit places the spacecraft in a favorable location to cross the magnetopause multiple times as it drifts along Jupiter's dayside magnetosphere.

Objective 3) Determine the flux, energy spectra, and spatial distribution of energetic neutral atoms escaping from Jupiter's magnetosphere. Jupiter's moon Io provides a 1-2 ton/s source of neutral material to the jovian magnetosphere that is redistributed into a neutral cloud around the moon's orbit and is ultimately lost from the system. As these neutrals become ionized to form the Io plasma torus, an estimated 1/3 of the ions are transported outward to Jupiter's plasma sheet while 1/3 – 1/2 of them are expected to escape as fast neutrals [16]. These fast neutrals are produced from two sources: (i) charge exchange between inward-diffusing energetic (> 10 keV/nucleon) ions and the extended H_2 neutral cloud near Europa's orbit and (ii) charge exchange between the < 1 keV ions in the Io's plasma torus and Io's neutral cloud. The estimate loss rate for these fast or energetic neutral atoms (ENAs) is ~ 0.3 – 1.7 tons/s [*16*] although direct measurement of these particles are needed to verify these values. One approach is to remotely measure the distribution of ENAs emitted from the magnetosphere. Unfortunately, only a very limited number of ENA observations from Jupiter's magnetosphere have been made [17] and none at energies below 10 keV.

JUMPER will address this topic by remotely measuring the flux, energy spectra, and spatial distribution of ~0.5 – 10 keV ENAs from a vantage point on the dayside of Jupiter's outer magnetosphere. These measurements, coupled with physical chemistry [18] and neutral transport [19, 20] models, will provide new insight on the physical processes that produce the fast neutrals in Jupiter's inner magnetosphere and help constraint their contribution to the mass budget of Jupiter's magnetosphere.

Mission Design

The most important mission design requirement for JUMPER is an orbit that includes several passes through Jupiter's bow shock and magnetopause on the dayside of Jupiter. Our baseline concept is a 1 year mission with six orbits, each having an apojove a distance of ~140 R_J.

The baseline spacecraft design consists of an ESPA compatible frame supporting four double-deployed solar array panels, ESPA ring interconnections, and four science instruments positioned to accommodate their field-of-views (FOVs). Embedded within the frame is an electronics vault that will house a majority of the electronics for the spacecraft avionics and payload subsystems. The nominal flight system consists of 5 subsystems: 1) Command and Data Handling (C&DH), 2) Electrical Power System (EPS), 3) Communication and Data System (CDS), 4) Attitude Determination and Control System (ADCS), and 5) Orbital Propulsion System (PROP).

The baseline JUMPER payload will carry two ion sensors, a magnetometer, and an ENA sensor. This nominal payload will be based on high heritage instruments that can be or have been scaled to fit the SmallSat envelope while providing the high quality ion, magnetic field and ENA measurements needed to address the JUMPER science objectives.

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MARS EXPLORATION SCIENCE IN 2050. B. L. Ehlmann[1,2] S.S. Johnson[3], B. Horgan[4], P.B. Niles[5], E.S. Amador[6], P.D. Archer[7], Jr., S. Byrne[8], C.S. Edwards[9], A.A. Fraeman[2], D.P. Glavin[10], T.D. Glotch[11], C. Hardgrove[12], P.O. Hayne[2], E.S. Kite[13], N.L. Lanza[14], M.G.A. Lapotre[1], J. Michalski[15], M. Rice[16], A.D. Rogers[10] [1]Division of Geological and Planetary Sciences, California Institute of Technology (ehlmann@caltech.edu), [2]Jet Propulsion Laboratory, California Institute of Technology, [3]Dept. of Biology/STIA, Georgetown University, [4]Dept. of Earth, Atmospheric, & Planetary Sciences, Purdue University, [5]NASA Johnson Space Center, [6]Dept. of Earth & Space Sciences, University of Washington, [7]Jacobs, NASA Johnson Space Center, [8]Lunar & Planetary Laboratory, University of Arizona, [9]Dept. of Physics & Astronomy, Northern Arizona University, [10]Solar System Exploration Division, NASA Goddard Space Flight Center, [11]Dept. of Geosciences, Stony Brook University, [12]School of Earth and Space Exploration, Arizona State University, [13]Dept. of Geophysical Sciences, University of Chicago, [14]ISR-2, Los Alamos National Laboratory, [15]Dept of Earth Sciences, University of Hong Kong, [16]Western Washington Univ.

A Look Forward to 2050: In 2050, the authors will be 60-75, at the end of long careers in Mars exploration. In 2050, a week of mission ops work could be working via virtual link—not just with rovers and orbiters—but with Mars astronauts, either present on Mars or based on Earth and prepping for a future mission. Mars astronauts may have conducted one or more sorties and brought samples back to Earth for examination in terrestrial labs. Mars astronauts may also assist in operating robotic explorers on Mars: monitoring weather and seismology, drilling the polar ice and extracting water for chemical and isotope measurements, imaging the surface, and collecting surface samples and drill cores for analyses in the astronaut habitat. Thus, some of the Mars astronauts will work with geologists on Earth (as did Apollo astronauts); others will be working as Mars geologists on-site (perhaps some of us). Below we discuss some existing programmatic aspects and steps to create this 2050 vision.

Key Mars science questions for post-2020: Some pressing questions for ancient and modern Mars can be solved via either robotic or human missions; others necessitate robots, with human explorers providing little added value (Table 1).

Table 1. Major open Mars science questions, derived from the 2014-2023 NAS Decadal Survey

	The 4 Major Mars Science Questions	Methodology (least to most informative, cost notwithstanding)
1	What are the nature, ages, and origin of the diverse suite of geologic units and aqueous environments evident from existing data; what climatic conditions were they formed under; and were any of them inhabited?	High-resolution orbital measurements, in situ rovers, robotic sample return, human-facilitated measurements/sampling
2	What is the present climate; is liquid water present; how does climate change under timescales of orbital variation; is there present-day life?	Orbital monitoring, landed weather station network, landed measurements, sample return
3	What are the inventory and dynamics of carbon compounds and trace gases in the atmosphere and surface; what processes govern their origin, evolution, and fate?	In situ rovers, orbital characterization of polar CO2 and H2O reservoirs, sample return, human-facilitated measurements
4	What are the internal structure and dynamics and how have these evolved over time?	Landed network seismic and heat probe; in situ rovers, sample return, human-facilitated measurements

While upcoming missions like Mars 2020 will help to address some of these questions, all will still require further investigations. The search for life on Mars is crucial and deeply coupled to fundamental questions of its evolution, embedded in Questions 1-2. Nonetheless, chemical and physical processes that lead to uninhabited habitats are equally important for understanding the prevalence of life in the universe.

HEOMD strategic knowledge gaps: Human exploration of Mars requires deeper understanding about the planet's physical environment in addition to new technical capabilities. For instance, key knowledge gaps for both NASA-sponsored and commercial human exploration include a) the availability of water resources (ice, hydrated minerals, atmospheric harvesting), b) the extent of weather variability (e.g., dust storms), c) local winds and thermal tides, which affect the ability to land safely, and d) evidence that extant life is not widespread in martian surface materials. Key technologies include e) a Mars communication and positioning network, f) successful demonstration of a human-scale landing system, and g) in situ production of purified oxygen and fueling of an ascent stage.

Importance of joint HEOMD-SMD missions, commercial collaboration: At this juncture in 2017, a subset of science questions and human exploration needs naturally merge, specifically, science questions 1-3 and human-exploration related knowledge gaps a-d. Synergistic measurement opportunities include: i) refined mapping of hydrated minerals at <10m/pixel with improved IR spectroscopy to quantify precise mineral and water abundance, ii) measurements of ice inventories, including in the near-subsurface at <20m/pixel scale where pole-facing slopes can still be ice-rich at low latitudes, iii) a suite of weather-related data, and iv) continued characterization of martian surface materials to determine whether extant life is present as well as identify potential chemical hazards to astronauts. Barriers exist to HEOMD/SMD/commercial collaboration (cultural, commercial-government mixed funding rules, and programmatic budgeting). Nevertheless, the coupling of needed measurements makes combined missions a resource-efficient approach for the mid-2020s to early 2030s. SMD could take the lead on some with HEOMD contribution, and vice versa. Science and HEOMD payloads, perhaps even including rovers, can be carried by SpaceX craft. Collaboration to obtain data of mutual interest or a paid berth for investigations ("pay for the ride") may be appropriate in certain instances.

Importance of independent SMD Mars science. Mars exploration cannot operate solely within the sphere of HEOMD, however. The NASA mission of pioneering the future of space exploration and expanding scientific discovery requires a continued focus by SMD on measurements that add new knowledge to our understanding of the workings of our Sun, Earth, solar system, and the universe. Mars occupies a key scientific position, not only to understand whether there may have been an independent origin of life, but also to understand the processes governing the fates of terrestrial planets. Such is of heightened importance in light of ongoing discoveries of extrasolar rocky planets with atmospheres and the desire to understand their long-term habitability. Although many HEOMD and science-driven measurements overlap, some science questions are fundamentally different from those solely in service of exploration. For example, rather than solely "what?" and "how much?", scientific questions about a hydrated mineral deposit are also "when?", "how", and "why?". Thus, while a subset of measurements are synergistic, measurements for understanding the timing and processes behind early planetary evolution fall largely within the province of science and remain crucial to our expanding knowledge. As such, a robotic and sampling program at Mars can and should continue, incorporating the enhancements that human capabilities can provide as they become available. A notable example is complex sampling techniques, including deep drilling beyond a few meters to collect samples of rock and ice. In 2030 and beyond, even as commercial and government human exploration of Mars may expand, SMD should play a critical role in designing the precursor measurements prior to astronaut exploration (e.g., the search for life; see below), prioritizing the measurements and extravehicular activities to be made by astronauts to key locales, and the criteria for human selection and return of samples.

Role for robotic sample return The demonstration of a successful launch off of Mars lends credence to the technical ability to do the same successfully with much more massive human craft. Critically, robotic sample return could facilitate uncontaminated return of samples from Mars special regions, where the chance for extant life is highest—in contrast to other terrains for which collection by a human is less likely to interfere with scientific measurement. Return of samples to Earth need not be purely robotic: an in Mars-orbit human-assisted capture of samples launched off the surface could simplify containment verification and safe sample landing on Earth. With both commercial and government programs oriented toward human exploration, the search for indigenous Mars life, prior to introduction of Earth organisms, becomes a scientifically pressing issue that is critical for evaluating the possibility of an independent origin and evolution of life on our neighboring planet. Thus, a single or multiple late 2020s/early 2030s sample return, perhaps facilitated by humans, is a logical exploration step. Sample return from multiple sites is preferable. In general, the scientific value of sample return is likely to be greater with humans on the martian surface, as semi real-time human decisions are not likely to be surpassed by advances in machine learning on the timescale of the next few decades.

Importance of more 2020-2050 Mars science mission opportunities: Exploration from orbit has identified hundreds of key locales of geological significance for understanding ancient Mars, information on volatile cycling and loss, and important data on daily and seasonal weather changes. Orbiters have also identified key resources for human exploration. The last decade of data have demonstrated that, like Earth, Mars is diverse. True exploration requires measurement at multiple locales, varying in space and time. This dictates a future mission architecture with many more craft to interrogate these locations. One might ask: doesn't this cost more money? Not necessarily. Consider two cases. First, modern Mars atmospheric dynamics – tides, dust, temperature, volatile cycling – can be examined with relatively simple instruments, geared specifically toward these purposes. Multiple identical craft are beneficial because temporal and spatial resolution provided by diverse orbits are vital, and they are presently missing. The instruments carried by these multiple crafts would be less expensive than multi-purpose instruments (e.g. THEMIS, TES, and CRISM), which have been designed for geological, polar, and atmospheric studies. A mid-size orbiter for detailed water resources information will likely still precede astronaut exploration but the fleet of small sats providing weather information would also serve as communications relays, populating the Mars system in the 2030s. As infrastructure around Mars grows, these "standard" small sats might transition away from the science community to commercial space companies. Second, the highly successful MER rovers were plural: two distinct sets of science data from two different sites cost less than or equivalent to the single-site Mars 2020 rover. A similar approach was highly successful historically (e.g., Mariners, Vikings, Voyagers). Our knowledge of the environmental diversity of ancient Mars has expanded in tandem with advances in instrument miniaturization, meaning that even the simple MER-like rovers at multiple sites would enormously expand our knowledge of Mars. By standardizing the "spacecraft bus" (in this case not an orbiter but a rover) and requiring instruments to accommodate themselves to it, the costly systems-instrument interface problems on MSL and M2020 can be avoided. These rovers could be sent independently, or coupled with a human program, allowing for the measurement and sampling, controlled in semi-real time. Multiple smaller missions also can expand participation in Mars exploration, opening it up to many more commercial, international, and academic participants than currently possible.

Conclusions: Time is of the essence for developing a synergistic SMD/HEOMD architecture with regard to Mars exploration to support humans in coming decades. A collaborative program could enable the Mars planetary science community to work alongside the engineers developing enabling technologies, deepening opportunities for engagement. The 2020s could focus on an orbital mapping effort for localized exposures of current and past volatiles (and resources) as well as astrobiological investigations for extant life, which should be pursued vigorously before humans begin *in situ* exploration. This could be accomplished by a mid-size orbiter and multiple small, MER-class rovers with next generation instrumentation to meet science needs. The focus in the late-2020s and into the 2030s could shift toward return and analysis of samples from Mars, perhaps facilitated by humans on a Mars flyby mission, and emplacement of the weather/comm small sat. network. In the 2040s and 2050s, human exploration of the surface would be performed, enabled by robotic drills, rovers, stations, and instruments, and include human return of samples, greatly enhancing our capacity to carry on outstanding science in the Mars system.

NEW FRONTIERS-CLASS MISSIONS TO THE ICE GIANTS. C. M. Elder[1], A. M. Bramson[2], L. W. Blum[3], H. T. Chilton[4], A. Chopra[5], C. Chu[6], A. Das[7], A. Davis[8], A. Delgado[9], J. Fulton[8], L. Jozwiak[10], A. Khayat[3], M. E. Landis[2], J. L. Molaro[1], M. Slipski[8], S. Valencia[11], J. Watkins[12], C. L. Young[4], C. J. Budney[1], K. L. Mitchell[1], [1]Jet Propulsion Laboratory, California Institute of Technology, [2]University of Arizona, [3]NASA/Goddard Space Flight Center, [4]Georgia Institute of Technology, [5]University of Washington, [6]University of Alaska Fairbanks, [7]Purdue University, [8]University of Colorado at Boulder, [9]University of Texas at El Paso, [10]Johns Hopkins University/Applied Physics Laboratory, [11]Washington University in St. Louis, [12]California Institute of Technology

Introduction: Ice giants are the least understood class of planets in our solar system. The little data available for the ice giants come solely from ground-based observations and the solitary fly-by of the Voyager 2 spacecraft. Unlike gas giants, which are composed primarily of hydrogen and helium, ice giants are thought to be composed primarily of ices and rocks [1]. However, the phase, distribution, and exact composition of these ices and rocks are unknown [1]. The magnetic fields of Uranus and Neptune differ substantially from Jupiter and Saturn with their strong quadrupole moments and significant tilt relative to their spin axes [2]. Furthermore, Uranus and Neptune differ from each other in puzzling ways; for example, Uranus has an extremely high obliquity (98°) [3] and a low heat flux (close to negligible) compared to the similarly sized Neptune [3]. Neptune has just one large satellite, Triton, which is thought to be a geologically active captured Kuiper belt object [4]. Only half of Triton and half of each Uranian satellite were imaged by Voyager 2.

A return to the ice giants is perhaps more important now than ever before. The Kepler mission has found that ice giant sized planets are the most commonly observed type of planet [5]. Observational biases are expected to underreport terrestrial planets; nevertheless, it is striking that ice giants are more common than gas giants in the Kepler data set. Kepler has also discovered many super-Earths which are smaller than ice giants but larger than Earth [5]. Observations show that planets larger than 1.6 $R_{\oplus}$ are too low density to be comprised of iron and silicates alone [6], so perhaps the ice giants in our solar system are the closest analog for these newly discovered smaller planets.

Both the discovery of over a thousand extrasolar ice giants and the drive to explore our local solar system necessitate another mission to Uranus and/or Neptune in the near future. If Uranus is selected, such a mission should be timed to arrive during a different season than Voyager 2 to maximize science return. Uranus' high obliquity results in extreme seasonal changes which affect several aspects of the Uranus system including: large variations in the intensity of atmospheric dynamics [7]; half of each satellite in shadow during solstices; and changes in the interactions between the magnetosphere and the solar wind as the angle between them changes. Voyager 2 flew past Uranus in 1986, one year after southern solstice. Uranus' next southern solstice will occur in 2070. To study the effect of seasons on the Uranian system, a mission should arrive at Uranus significantly before 2070, preferably close to equinox in 2049. Arriving later than 2049 will mean some portions of the satellites in shadow when Voyager 2 arrived will once again move into shadow until after the next southern solstice in 2070.

OCEANUS: The 2011 decadal survey [8] suggests that the third highest priority Flagship mission in this decade should be a mission to an ice giant. We agree that while a Flagship mission is preferable, a New Frontiers-class mission could supplement such a mission or achieve a subset of the science objectives in the event that a Flagship-class mission is not available. We will discuss the New Frontiers-class mission concept OCEANUS: Origins and Composition of the Exoplanet Analog Uranus System. OCEANUS is the result of the 2016 Planetary Science Summer School (PSSS) hosted by the Jet Propulsion Laboratory (JPL), California Institute of Technology, which aims to offer participants an authentic but primarily educational experience of the mission proposal process [9]. This exercise resulted in a mission concept for a Uranus orbiter with a limited payload that would still be able to achieve several of the highest priority Decadal Survey goals for Uranus.

OCEANUS would be an orbiter, which would enable a detailed study of the structure of the planet's magnetosphere and interior that is not possible with a flyby mission. The instrument suite would include a magnetometer for measurements across the bow shock and magnetopause and of temporal variations in the magnetosphere. Detailed study of the structure of the magnetic field would also constrain models for dynamo generation. OCEANUS would also use the on-board communications antenna for radio science enabling measurements of Uranus' global gravity field to degree and order six, constraining models for the interior structure of Uranus. Our mission concept would also employ an atmospheric probe for in situ measurements of noble gas abundances and isotopic ratios as well as temperature and pressure profiles. This simple instrument suite would enable OCEANUS to achieve four of the decadal survey's science objectives for Uranus (including one of the two highest priority objectives).

The parameters for the 2016 PSSS Uranus orbiter mission included the option to include a "donated" probe. We decided to include this probe despite the additional mass and risk, because it would enable the determination of noble gas abundances and isotopic ratios. These were deemed sufficiently important, because they could reveal where in the solar system Uranus formed and constrain solar system formation models, which have not reached a consensus on how far planets migrated since their formation [10].

Future New Frontiers-Class Missions to Ice Giants: In one week at JPL, the graduate students and postdocs of the 2016 PSSS were unable to develop a mission concept for a Uranus orbiter within the cost constraints of a New Frontiers-class mission as suggested by the decadal survey; this was due to the high cost of reaching Uranus within the next few decades and powering the spacecraft while in orbit. With more time and resources, it is possible that one could develop a viable mission concept to Uranus or Neptune within a New Frontiers budget, but to achieve a competitive pool of multiple New Frontiers proposals for ice giant missions, change is necessary. OCEANUS identified three key areas where advancement could lead to improved mission concepts: power systems, propulsion capabilities, and cost-sharing collaborations.

Solar power is now sufficiently efficient to power some missions to distances as far as the Saturnian system [e.g. 11], depending on their operational needs, but missions to the far-outer solar system continue to face power and cost challenges more significant than missions to the inner and near-outer solar system. For example, OCEANUS would spend over 20% of its budget on Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs). These challenges could be ameliorated by increased investment by NASA in heat source plutonium production by the Department of Energy, and efforts to lower the cost and/or increase the efficiency of MMRTGs, such as the potential enhanced MMRTGs. These developments would also aid larger mission concepts for the inner and near-outer solar system, which may need more power than solar power options can provide.

The current orbital configuration and extreme distance between the ice giants and Earth present additional major hurdles to New Frontiers-class missions to Uranus or Neptune. In particular, opportunities for a Jupiter gravity assist to Uranus or Neptune are rare in the next two decades. OCEANUS overcame this challenge through two Venus gravity assists and an Earth gravity assist along with the use of Solar-Electric Propulsion (SEP) within 1.5 AU. However, the SEP stage would be more than 10% of the total mission cost. Efforts to continue development of SEP technology, potentially lowering the cost, could enable missions to the far-outer solar system without requiring a Jupiter gravity assist. Alternatively, more powerful launch vehicles could also facilitate travel to the outer solar system, but a shorter cruise time would result in a faster approach velocity making orbit insertion more challenging. Continued ground-based observations to characterize the atmospheres of Uranus and Neptune could help to lower the risk of orbit insertions utilizing aerobraking.

Finally, the notable absence of a dedicated mission to an ice giant is felt not just by NASA, but also by ESA [e.g. 12]. The high cost of a mission to the far outer solar system could be shared between NASA and ESA even on a New Frontiers budget. For example, our OCEANUS concept included a donated probe from an unspecified partner for the purposes of the educational exercise, but a mission with a small payload and donated probe could in fact be a model for a collaboration between NASA and ESA, or another space agency.

Conclusion: Missions to Uranus or Neptune are still very difficult to achieve on a New Frontiers budget, although OCEANUS showed that, with a highly-focused mission, current technologies can come close. Continued efforts to develop technologies enabling travel to the outer solar system with the goal of lowering cost could enable robust New Frontiers-class missions to Uranus and Neptune before 2050. Although an exploration-based Flagship-class mission analogous to Galileo or Cassini should be a priority, a more focused New Frontiers-class mission could achieve a significant fraction of the science objectives highlighted by the decadal survey, or could supplement a Flagship mission through a yet-to-be-determined creative approach galvanized by the competitive nature of the New Frontiers program.

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Moving form Earth Science Technologies to Planetary and Exoplanet Visions. M.K. Elrod[1] and P. Conway[1], [1]NASA Goddard Space Flight Center, Greenbelt, MD.

Introduction: In conducting search for habitable worlds both in our own solar system and beyond, the key parameters of life detection begin with detecting the minutae of life and habitability at home. Exoplanet and atmospheric planetary modelers have begun to narrow the extensive set of parameters for conditions necessary for the creation of habitable worlds. The next logical step in our science is to build the technology to obtain the necessary data to begin testing these models.

With Earth as our initial testing grounds for developing technologies to seek out life developing chemistry like amino acids, DNA, and other significant hydro-carbons, we can modify these technologies for detection within our solar sytem. By developing the capabilities to detect these critical habitability key factors within out own solar system and flying them on spacecraft to key targets like Mars, Titan, Enceladus, Europa or Triton, we can test some of the planetary models.

Having developed both remote sensing and insitu technology capable of detecting habitable world markers for planetary tragets, the next goal is to then develop these technologies for exoplanet detection. As insitu exoplanet technologies will not be reasonable in the near future, remote sensing and crossover science between insitu and remote sensing learned from our nearby neighbors will help us to develop newer technologies to find habitable exoplanet candidates.

A FRAMEWORK FOR ORGANIZING A LONG TERM PLANETARY SCIENCE PROGRAM.

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Introduction: The rapid rate of growth of the cost of flagship missions in planetary science (~15%/year, [1]) has created a crisis for the field. My primary field of astrophysics suffers from the same fundamental crisis [2]. The crisis can be seen clearly in the NASA flagship program. The 2011 US decadal survey for the field [3] listed three top priority destinations: Uranus, Europa and Mars. NASA could only afford to say "choose one". This automatically makes even this short list a generation-long program. Mars was chosen, with Europa following a decade later, most likely. Outer solar system science will therefore suffer an almost career-length gap. Who then will be able to do that science if is re-started 20 years from now? The New Frontiers program of medium sized (~$1B) missions is similarly generational: NASA has listed 6 areas that it designates as priorities for study with this program, and may soon add two more. But the agency expects to launch this class of missions once every 5 years, making this list a 30-40-year program [4]. In this situation we are not truly exploring the Solar System at scale.

It is the growing cost of missions relative ot the conomic growth that underpins the funding (1% - 3% p.a. [5]) that has trapped us into a serial approach to exploring the Solar System rather than the parallel approach we really need.

To escape this problem the costs per mission must be brought down substantially. Here I discuss a framework for doing so [6]. First we must strengthen our programs by choosing deliberately a set of prudent science program design principles. Second, the cost discipline provided by profit-making enterprises in space, commercial space, is forcing down prices. Significant changes in this area are happening well within our current planning horizon, let alone a 2050 one.

Prudent Program Principles: The Decadal review process is traditionally tasked with providing prioritized lists of large, medium and small missions [3]. This approach is sub-optimal as, without guiding principles, the strong temptation for any scientist will be to use any savings on launch and spacecraft to enhance the science payload: "payloads grow to fill the budget available". This is the path of least resistance. To restrain the scientists from spending all the gains on more payload rather than on another mission will need discipline.

This discipline may be mandated by the space agencies, or it may be a self-imposed discipline based on a community consensus. A combination of both approaches may be required. Without community buy-in agency rules may not affect the decadal priorities; without agency-imposed rules the community will not be challenged to become more creative.

It is helpful to view the needed discipline in terms of well-accepted design principles for individual missions, and for engineering in general, extended to an entire science program. These principles can then be flowed down to particular missions and sets of missions.

Triple-A rating: Ambitious, Achievable, Affordable Mission design is always a balance between the unlimited demands of scientists with the practical capabilities of the latest technologies. Each mission needs: (1) a goal that is *ambitious*, a major step beyond what has already been done; (2) a technical readiness leval (TRL) that is high before committing so that it is *achievable*; and (3) the cost must be *affordable*, so as not squeeze out all other comparable missions. The art is in achieving all these demands simultaneously. Applied to a program this means assessing the AAA rating of all missions equally objectively.

Opportunity Cost: One big mission is always likely to achieve a lot of great science. But that gain needs to be weighed against the sum of the science achievable by a set of smaller missions at the same total cost. Big missions collect a large following and so are heard loudly, but the full set of smaller missions may have more supporters. A means of balancing, or "tensioning", the choices is essential.

No Single Point of Failure (SPOF) that can stop the mission functioning can be allowed. A program with a built-in single point failure is not robust. If we put all our eggs in one basket by going all out for a single giant mission, then we expose the science program to single point failure risk. Had on-orbit servicing not been possible to correct the spherical aberration in its optics, *Hubble* would have been, if not a failure, then not the great success it now is. This principle caps the maximum fraction of the program budget that any one mission can use.

Science Requirements Flowdown: All missions have to demonstrate that their specifications flow down from the science the mission is required to carry out. Science requirements for the entire program should be similarly formulated. For example, visiting each class of world at a good cadence may be one such requirement. But the community should decide what the requirements should be.

Single Viewpoint Failure: A special version of SPOF applies to science programs. Science needs debate and multiple sources of information that can cross-check initial results. If we only have one experiment every decade-plus then poor conclusions will stand for many years, and often the reason they are believed will be almost forgotten. Slow-paced debates stifle good science.

Use Commercial Space to Lower Costs: Taking advantage of improved, lower cost, technology is an obvious design principle. But it has not been relevant in space for the past 30 years, as there have been no significant changes in the costs of space technology. Now, however, rapid, near-term, changes are taking place in commercial space activities. These should be taken advantage of by planetary science to cut the costs of launches, spacecraft and science payloads.

Launch costs per kilogram to low Earth orbit have already dropped to about 1/3 of historical levels [7], and may drop to 1/5 with first stage re-use [8]. Using this cheaper mass to orbit, could allow a relaxation of the stringent mass limits on spacecraft and instruments, thereby potentially cutting costs by factors of several [9]. Paths to achieve this improvement, given the special demands of interplanetary flight, need to be investigated.

Commercial crew flights open up the possibility of cost-effective TRL-9 testing of large instruments in LEO in the Crew Dragon trunk [10]. This capability will allow for the use of more cutting-edge instruments at higher reliability.

Interplanetary cubesat-class spacecraft are undergoing rapid development. The first interplanetary test flights are expected by 2020 [11]. The cost of these spacecraft has to be low to make them cost-effective as prospecting missions for their developers, who are aspiring asteroid miners. If they are successful they could enable a new paradigm of "many but simple" planetary missions.

The effects of these advances combine to allow multiple highly capable planetary missions to be built in parallel at a variety of scales.

Conclusion: The fundamental mis-match between the cost growth rate of astrophysics and planetary science missions and that of the underlying economy remains large. Eventually we will hit this funding wall. Best to bite the bullet and adoprt prudent program principles while taking advantage of the new developments in commercial space while they are fresh. Embracing them could have a huge pay off. Certainly it would not be wise to ignore them.

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IF IT HAS A MAGNETIC FIELD WE WANT TO MEASURE IT: PLANETARY MAGNETOMETRY OF THE FUTURE. J. R. Espley[1], [1]Solar System Exploration Division, Goddard Space Flight Center, Greenbelt, MD 20771, Jared.Espley@nasa.gov

Introduction: Planetary magnetometry has had tremendous success over the past few decades of Solar System exploration (e.g. Voyager to current missions like MAVEN). Looking to the future it is clear that there are numerous science and exploration challenges that would benefit from the observations made by magnetometers. These goals include objects throughout the Solar System and across numerous major scientific themes including the workings of the Solar System, the search for life, and the characterization of resources necessary for human exploration. Some of the conceivable investigations make use of existing instrument technologies and near-term mission designs while others would require instrument miniaturization and radically new mission designs. I discuss a few of these mission designs and the associated mission goals. See the table for a summary.

Planetary subsurface sounding networks: By using networks of electromagnetic sensors such as magnetometers it is possible to probe the subsurface of planetary bodies such as Mars. Such subsurface characterization would allow the identification of aquifers and the interior structure of the object which informs the *search for life*, is vital to understanding *planetary systems*, and important for *resource identification* for human exploration. Such networked landed missions are theoretically possible now but would require mission design work to efficiently distribute the landers.

Aerial geomagnetic surveys: Similarly, by placing magnetometers on aerial platforms such as gliders or ballons, detailed geophysical characterization of the planetary surface can be conducted. This would allow us to explore of the *geophysical history* of the surface with respect to events that altered the magnetization of the crust. Examples include volcanism, plate tectonics, and impact cratering. Furthermore, such surveys are routinely used on Earth to *characterize the materials* in the near subsurface structure (i.e. for mineral prospecting) – we could do similar work at other planets. Depending on the size and scale of the aerial platform chosen, significant investment might be required to have a sufficiently robust mission plan for this type of investigation.

Multi-point measurements of planetary magnetospheres: Many phenomena in magnetospheric physics are highly dynamic and it is often difficult to distinguish between time-variable and spatially-variable phenomena. Examples include magnetic reconnection, escaping atmospheric plasma strutures, and plasma waves (which carry the energy in collisionless regimes like magnetospheres). By using multiple spacecraft with magnetometers and associated plasma spectrometers, it is possible to be able to much more fully address these questions of *how the dynamics of planetary magnetospheres* work. Similar missions have been conducted at Earth. Using groups of smallsats (e.g. CubeSats) would allow such missions to be more easily conducted at planetary targets as the spacecraft could be conveyed to their targets as secondary payloads.

Ice Giant Exploration: The magnetospheres of Neptune and Uranus have received only cursory exploration. Understanding how these truly unique (with dipoles strongly tilted from their rotation axes) *magnetospheres work* would be a major accomplishment of basic Solar System exploration. A large flagship mission to fully explore these systems would be one way to accomplish this.

Ocean Worlds Exploration: Characterizing the the global oceans on worlds such Europa is likely to be a major theme of the coming decades. Magnetometry is key part of this exploration as magnetic field measurements allow *characterization of the depth and location* of subsurface oceans which are potentially *habitable environments*. Measurements conducted from multiple-fly-by or orbital missions are best suited for identifying the global characteristics of such oceans whereas measurements from landed assests can describe the local subsurface conductivities including local aquifers and layers. The development of such missions to Europa is currently underway but numerous other targets are likely to be explored in the coming decades.

	Mission possible in the:			Mission addresses:		
Magnetometry Mission Type	2020s	2030s	2040s	Solar System Workings	Search for Life	Resources
Planetary subsurface sounding networks	?	✓	✓	✓	✓	✓
Aerial geomagnetic surveys	?	✓	✓	✓		✓
Magnetospheric multi-point measurements	✓	✓	✓	✓		
Ice giants exploration		?	✓	✓		
Ocean worlds exploration	?	✓	✓	✓		

Table 1. A variety of different types of missions making magnetic field measurements are possible in the coming decades. Each mission type addresses different types of exploration goals and each mission type has different possible timeframe for implementation. In all cases, magnetometry will continue to play a key role in exploring the Solar System.

EVOLUTION OF CIRCUMSTELLAR AND CIRCUMPLANETARY DISKS. P. R. Estrada[1,2], O. M. Umurhan[1,2] and U. Gorti[1], [1] Carl Sagan Center, SETI Institute, Mountain View, CA, USA; [2] NASA Ames Research Center, Moffett Field, CA, USA; (Paul.R.Estrada@nasa.gov).

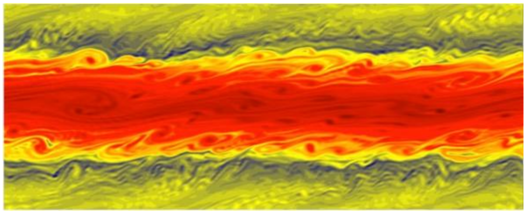

Figure 1: *Vortex field from a fully-developed Vertical Shear Instability in a secondary transition [11-12].*

Introduction: Planet formation appears to be extremely robust and moreover lead to a very diverse set of outcomes [1]. Our understanding of how planetary systems form and their resulting architectures and compositions is severely limited by the complexity of their natal environments. Planet formation is concurrent with star formation, a process where gravity, magnetic fields, radiation, chemistry and dynamics, all play significant roles, making this a highly coupled and non-linear problem that appears almost intractable. The disks that result after gravitational collapse during star formation and build the star at early stages, ultimately provide the raw material out of which planets form; they are therefore the ideal targets of study to help us provide the insights we need. Furthermore, the fact that all of the giant planets of our own solar system harbor “mini-solar systems” of their own suggests that satellite formation is an inevitable consequence of giant planet formation, and the structure, diversity and apparent order we see in these systems may also be informative to their circumstellar analogs. It is then essential to address these two promising avenues of study together in going forward – circumstellar or protoplanetary disks (PPD, hereafter), and their analogs, circumplanetary disks (CPD).

The dynamical state of PPDs (as well as CPDs) directly influences the manner and location of planetesimal (satellitesimal) formation. Indeed, the concept of planets forming in a static minimum mass nebula where the local temperature uniquely determines the chemistry through some invariable cosmic abundance has been replaced in favor of a continuously active disk in which structure and composition evolves both on local and global scales. This is because our understanding of the dynamical state of PPDs has undergone profound revision based on exciting new observations alongside theoretical and numerical advances over the last decade. This talk aims to broadly discuss theoretical understanding of PPD (CPD) structure, review new developments in the understanding of disk turbulence and its influence on particle growth, and examine the issues that confront the question of disk evolution and its pertinence to planetesimal (satellitesimal) growth.

Planetesimal formation in evolving disks: Herschel, Spitzer and now ALMA have demonstrated that PPDs are very diverse. Since the bulk of the mass in the disk is contained in the gas component, and since growth from small dust particles into planets depends on the gas surface density profile, understanding the evolution of gas is paramount in understanding planetesimal formation. Gas disks evolve primarily through accretion over most of their lifetime. Accretion transports mass onto the central star, and angular momentum outwards. Material at the disk surface can be launched into a wind, thermal and magnetically driven, which results in the disk eventually losing its gas. The availability of gas as a function of radius and time, in turn, affects ongoing planet formation in the disk. Some of the key questions facing our understanding PPD evolution include: (a) Quantifying the efficiency of angular momentum transport which, in turn, involves identifying and constraining the spatio-temporal sources and intensities of turbulence in PPD which influences (b) the gas mass in disks as a function of r and time. Our current estimates of the gas content are uncertain by orders of magnitude [2]. Data derived from future far-infrared facilities (e.g., SOFIA, SPICA, OST) will inform us, but this issue will remain a challenge for decades to come. On the other hand, the gas mass in CPDs at the time of satellite formation may be easier to infer [8,9], and given the inevitability of detecting satellites around giant exoplanets, this is sure to be an area of study ripe for exploration.

Turbulence: PPDs are generally classed into regions that are sufficiently ionized to merit a magnetohydrodynamic description or those that are sufficiently neutral to be considered as a hydrodynamic flow. Magnetized disks are known to support dramatic dynamical activity in the form of jets and MRI turbulence [5-7]. However, the zones supporting MHD processes are either too close to the parent star (<1-5 AU) or too far out (>100 AU) [10] leaving out the bulk of the disk where the majority of planet construction is thought to take place -- this has remained an outstanding theoretical issue for almost a decade.

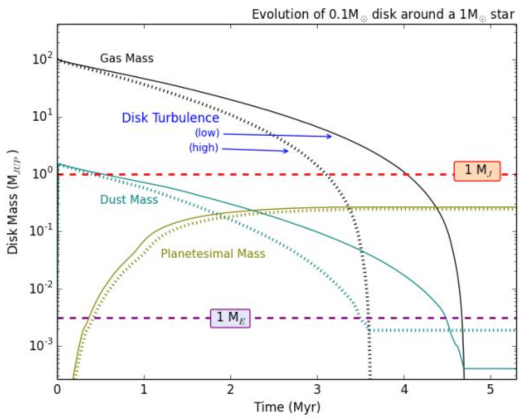

Figure 2: *Evolution of disks with different levels of turbulence, incorporating dust collisional processes, gas photoevaporation and plannetesimal formation by the streaming instability.*

Non-ionized zones of PPDs, once considered "Dead Zones" [6] because no turbulence inducing instabilities had been theoretically identified to robustly operate in Keplerian sheared stratified environments, have recently been shown to be susceptible to three new linear instability mechanisms and demonstrated to lead to a moderate degree of turbulence. The mechanisms involved will be reviewed [12-14] and a picture of their secondary cascade to turbulence in a PPD environment will be discussed (see Fig. 1). Additionally, we examine settings and locations where these processes are thought to occur and discuss their dependence on the thermodynamic properties of the disk, including opacity and temperature structure.

Particles in turbulent environments: [15] have recently published models following the growth and fate of particles in quasi-two dimensional PPD models following the growth of various species of grains under the influence of turbulent viscosity, and other environmental factors affecting the mean Rosseland opacities, temperature structure and density distribution of the disk. The turbulent mixing of grains of a given size influence the effective gas opacities of the disk material which, in turn, affect the continuance or abatement of the aforementioned linear instabilities that lead to turbulence. We discuss the physics of this process and highlight its importance in understanding how planetesimals lead to asteroid scale bodies.

Evolution of gaseous and dusty disks: Recent disk evolutionary models [3-4] show that planetesimal formation occurs in a very dynamic environment. While our knowledge of how gas in the disk is dispersed and how small sub-micron sized dust particles accumulate to form planets remains incomplete, these results highlight the importance of turbulence in the disk not just in how it influences particle growth, but also global transport of solids and condensables; gas disk dispersal times depend on the level of turbulence, as does the rate at which particles grow and drift radially with time (see Fig. 2). Once planets have formed, the available mass reservoir dictates the likelihood of gas accretion to form Jovian analogs, their final mass, that of the CPD and ultimately the total mass of satellites and perhaps even their structure (see Fig. 3).

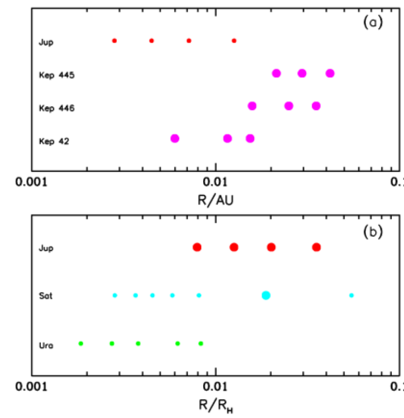

Figure 3: *(a) Architecture of selected Kepler systems. Jovian system included for comparison. Adapted from [16]. (b) Giant planet systems in terms of Hill sphere.*

Dynamical structure of exoplanet systems: Exoplanetary system discoveries will continue to revolutionize our understanding of planet and satellite formation. Most systems discovered to date are observationally biased in the sense that the lion's share of systems discovered are compact (see Fig. 3a). It is still not clear whether exoplanet system architectures like our own are common or not, but future observations should fill in the gaps between these compact systems and those (some directly imaged) with giant planets very far from their parent star. But there is potentially much to learn from within our own solar system because CPDs have produced compact systems that perhaps display a "progression" of structure which may be linked to CPD gas mass, and the amount of gas in the nebula at the time of their formation (see Fig. 3b). Understanding more about the Uranian system at the same level as Jupiter and Saturn would be an important step.

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NOMADIC EXOPLANETS AND THE NASA STRATEGIC VISION FOR 2050 T. Marshall Eubanks[1], [1]Asteroid Initiatives LLC, Clifton, VA 20124 USA; tme@asteroidinitiatives.com;

Introduction: NASA's strategic goals include the search for planets around other stars, the characterization of their properties, and the identification of exoplanets that could possibly harbor life. In addition, with the discovery of Proxima b, an exoplanet orbiting in the habitable zone of the star Proxima Centauri, the closest star to the Sun, long range planning is beginning to consider its possible *in situ* exploration by spacecraft. These strategic goals should be extended to include nomadic (or rogue) exoplanets, planets not orbiting any star.

While Proxima b will remain the closest exoplanet orbiting a star, microlensing surveys indicate that there are likely to be closer nomadic planets [1]. To date, discovered nomads have been mostly either distant objects found through microlensing, or young, warm, nomads found near star formation regions. However, there should be significant numbers of mature nomadic exoplanets close enough to be discovered with existing or future astronomical resources, including possibly dozens of planets closer to us than Proxima b. Although mature nomads will appear to be very cold astronomically, superEarth nomads can retain heat, be Ocean Worlds and conceivably support exobiologies [2, 3].

Nearby nomadic planets are thus extremely relevant to the Origins, Workings and Life goals of the NASA strategic vision for 2050. Finding the closest nomadic exoplanets should become an important part of NASAs strategic goals, particularly the exoplanets closer, and thus easier to reach, than Proxima b. In order to facilitate the search for nomadic planets, NASA should support a large far-IR (100 μm wavelength) space telescope and support planet searches with long wavelength (1 - 10 meters) radio arrays. Nomadic planet number statistics remain very uncertain for sub-Jupiter masses, and should also be improved through support of high cadence microlensing surveys.

The Expected Distance to the Nearest Nomadic Planets: Gravitational microlensing surveys have shown that Jupiter-mass nomads are more populous than main sequence stars. Sumi *et al.* [4] estimated the ratio of the number density of Jupiter-mass unbound exoplanets, n_J, and the number density of main sequence stars $n_\star$, with $n_J / n_\star = 1.9^{+1.3}_{-0.8}$ from microlensing data. The stellar number density is well known near the Sun [5], yielding an estimate for n_J [1] of

$$n_J = (6.7^{+6.4}_{-3.0}) \times 10^{-3}\,\mathrm{ly}^{-3} \qquad (1)$$

and thus an estimate for the expected mean distance to the nearest Jupiter mass nomadic planet, R_{min}, of

$$R_{min}(M_{Jupiter}) = 3.28^{+0.7}_{-0.6}\,\mathrm{ly}\ , \qquad (2)$$

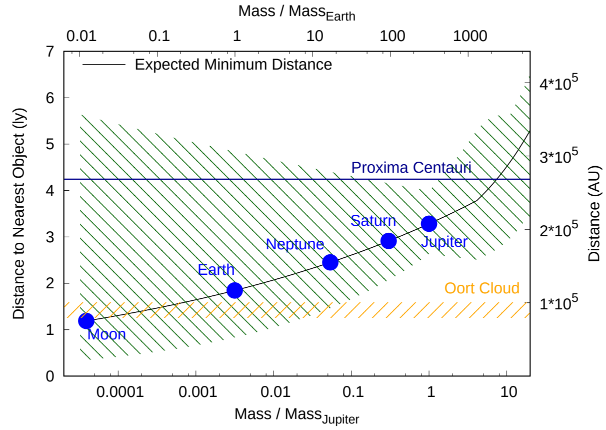

Figure 1: The expected minimum distance, R_{min}, as a function of nomadic planet mass, based on microlensing power law number-density models [1]. Although the uncertainties are fairly large, the nearest nomadic planets are expected to be as close or closer than Proxima Centauri for a wide range of masses. The estimated extent of the Oort cloud and the distance to Proxima Centauri are shown as horizontal lines.

the expected distance of the nearest "dark-Jupiter" being ~77% of the distance to Proxima Centauri. Sumi *et al.* [4] also provide a power law model for nomadic planet number density as a function of mass. Figure 1 shows the expected minimum distances, R_{min} and these uncertainties as a function of nomad mass [1]. It is necessary to extrapolate the power law density models for masses $\ll$ the mass of Jupiter [6], leading to a factor of almost 6 uncertainty in R_{min} for Earth-mass nomads. Reducing the uncertainty in the nomadic planet number density function at lower masses is essential for better modeling of R_{min} for Earth mass planets. The planned WFIRST telescope should be able to detect and characterize the population of nomadic superEarths in the Galactic bulge with microlensing [7]; it is important that NASA support microlensing surveys by this or a comparable space telescope.

Finding Nearby Nomadic Exoplanets: Figure 2 shows the black body flux density expected from a set of hypothetical planets, matching the Earth, Uranus, Neptune, Saturn and Jupiter in mass, radius and internal heat flux, with each assumed to be at R_{min} for a body of its mass. A super-Jupiter with 10 times the mass of Jupiter is included based on a heat flux scaling model [1]. Figure 2 also shows flux density limits for the ALMA [8], cooled WISE [9], cooled Spitzer [10]), SPICA [11] and JWST [10] instruments. Existing instruments should

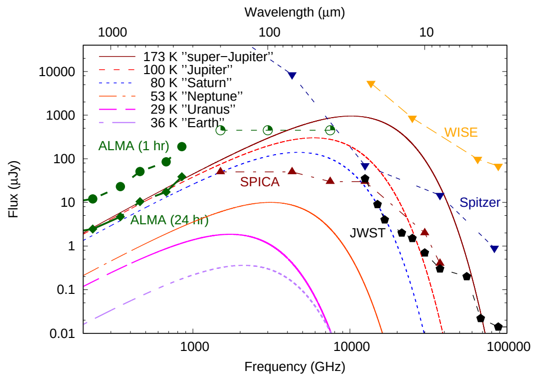

Figure 2: The IR flux density for black bodies with the same radius and internal power generation as the actual Earth, Uranus, Neptune, Saturn and Jupiter, plus a model-derived "super-Jupiter" with a mass of 10 $M_{Jupiter}$, each modeled as a black body at their expected R_{min} [1], together with flux density limits for various actual (ALMA, cooled Spitzer, cooled WISE) and planned (SPICA and JWST) telescopes and arrays.

be able to detect nearby nomadic gas-giants, while detection of nearby nomadic Earths and superEarths will likely require surveys by a new generation of space telescopes, such as the Far-Infrared Surveyor Mission (FIRS) [12] currently under consideration.

A different means of discovering nearby magnetized planets is through the detection of their non-thermal radio emissions. The strongly magnetized bodies in the solar system (the Earth plus the 4 giant planets) all exhibit strong non-thermal radio emissions driven by the electron Cyclotron Maser Instability (CMI) [13]. CMI emissions are generated by celestial bodies moving through a plasma, with either the body or the plasma, or both, possessing a significant magnetic field [14, 15, 16], or even from the rapid rotation of a magnetized body [17]. Such emissions provide a non-thermal means of detecting magnetized exoplanets [18], including magnetized nomads [19, 1]. In the solar system, Jupiter produces a very strong "unipolar" CMI radio flux, primarily due to electrons flowing through the Jupiter-Io flux tube. A Jupiter-Io analogue at the expected distance of the nearest Jupiter-mass exoplanet (see Equation 2) would have a maximum flux of $\sim$10 milliJanskies (mJy) at about 40 MHz [1] with a duty cycle of $\sim$14%. Such sources should be detectable by the LOFAR [20] and other low frequency arrays; if these source mechanisms are common with nomadic planets, the search for CMI emissions may provide the best near-term prospect for discovering neighboring nomadic giant planets from ground-based observations.

Astrobiologies on Nomadic Exoplanets: Nomadic planets could be ocean worlds, with insulated oceans surviving with no stellar heat input [1]. Stevenson [2] proposed that Earth-mass planets could have surface oceans of liquid water, and thus conceivably biologies, with radioactive heat being retained by thick Hydrogen-Helium (H-He) atmospheres with pressure induced far-IR opacity. The discovery that for $M \gtrsim 4\, M_{Earth}$ terrestrial planet radii are roughly $\propto$ mass strongly suggests that H-He atmospheres are common for at least these super-Earths [21, 22]. Nomadic "Steppenwolf" planets, with $M \gtrsim 3.5\, M_{Earth}$, could instead have internal liquid water oceans insulated by a thick shell of ice [3]. There are of course a number of candidate ocean worlds, warmed by tidal heating, in the Solar System [23]; similarly tidally-heated oceans could exist on nomadic exomoons [24]. The exploration of nearby nomadic planets thus has the potential to both benefit from and inform the NASA effort for the exploration of the biological potential of Ocean Worlds in our solar system.

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EXTRA-TERRESTRIAL SPACE ELEVATORS AND THE NASA 2050 STRATEGIC VISION T. Marshall Eubanks[1], C.F. Radley[1], [1]Asteroid Initiatives LLC, Clifton, VA 20124 USA; tme@asteroidinitiatives.com;

Introduction: Extra-terrestrial space elevators can provide a transportation network to help fulfill NASA's strategic exploration goals for the next three decades. While a terrestrial space elevator is not currently possible without developments in material science, space elevators for the Moon and Mars are possible with existing and commercially produced tether material. Elevators for Ceres and other asteroids are also technically feasible and may become relevant within the next three decades. We have proposed a Deep Space Tether Pathfinder (DSTP) to provide a solid scientific return while testing tether engineering in deep space, a Lunar Space Elevator (LSE) Infrastructure (LSEI) for deployment as a functional lunar transport system, and a Phobos-Anchored Mars Space Elevator (PAMSE) for delivery of material to and from the Martian surface. This paper discusses how these elevators can be integrated into the NASA Strategic Vision for 2050.

The Deep Space Tether Pathfinder: The DSTP would be a 5000 kilometer long "rotovator" tether [1]. The DSTP would fly by the Moon with a sampling probe on the far tip to collect lunar samples in a touch-and-go manner [2], rotating every 2.44 hours to match the velocity of its sampling tip with the lunar surface (see Figure 1). The sampling capability of the DSTP would enable sample return from difficult to reach and scientifically interesting regions of the Moon, such as the permanently shadowed regions at the lunar poles [2]. Approximately 2 hours after sample collection the DSTP would use its rotational velocity to sling-shot the sample back to Earth for a ballistic reentry with a minimal expenditure of fuel.

The primary scientific justification of the DSTP mission would be lunar sample return; its lunar science objectives address every one of goals in the "Lunar Polar Volatiles and Associated Processes" white paper submitted to the 2011 Decadal Survey [3]. Current DSTP mission planning has focused on sampling volatiles on the shadowed floor of Shackleton Crater at the lunar South Pole, which is a cold-trap and should collect substantial amounts of surface volatiles from collisions and out-gassing on other areas of the Moon [4].

The DSTP would have a tether taper comparable to future space elevators (see Figure 2), providing an in-space test of the crucial technology of tether tapering, providing a substantial advance in the technological readiness of tether-based space tethers.

Prototype Lunar Space Elevators for the Near and Farside: A LSE is an efficient means of cargo transport if there is enough demand for delivery of materials to and from the lunar surface. The LSEI would

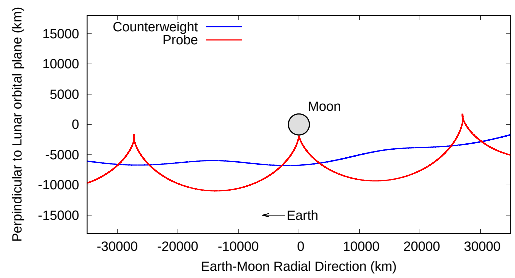

Figure 1: Trajectories of the two tips of the DSTP during a sample collection from the Lunar South Pole, as seen from a selenocentric reference frame [2]. The counterweight is considerably more massive than the probe and is thus closer to the tether center-of-mass, which executes a smooth ballistic motion. This Figure represents ∼6 hours of total motion.

be a very long tether extending from the lunar Surface, through the Earth-Moon Lagrange L1 point (EML-1) 56,000 km above the Moon, and deep into cis-lunar space [5]. Table 1 indicates the enormous scale of even a prototype LSE; once deployed it could be used to transport materials to and from the lunar surface through the use of solar-powered climbers traveling up and down the tether, and to provide measurement stations at non-inertial locations in deep space. The LSEI prototype, scaled to be deployable with one launch of a heavy lift vehicle, would be able to lift roughly 5 tons of lunar samples per year, deploy a similar quantity of equipment onto the lunar surface, and provide lunar surface samples to astronauts orbiting in cis-lunar habitats.

The LP attached to the tether descends to the lunar surface in the initial prototype deployment, referred to after landing as the Landing Station (LS); the planned nearside LS location is Sinus Medii, near 0° Latitude and Longitude. The primary initial science goal of the LSEI prototype mission would be the return of the lunar samples to Earth, returning up to 100 kg of samples at a time using a reusable solar-powered lifter. Return to Earth from a nearside LSE can be done in principle without fuel, as a sample return capsule could be simply released at the right moment for a direct reentry trajectory to a desired landing location; anything separated from the LSE an altitude $\gtrsim$ 220,670 km above lunar surface will re-enter the Earth's atmosphere in ∼1.4 days at a velocity of ∼10.9 km s^{-1} without any expenditure of fuel. This same technique can be used to return high

Parameter	Elevator			
	DSTP	Nearside LSE	Farside LSE	PAMSE
Length (km)	5000	278544	297308	5828
System Mass (kg)	3043	48700	48700	5355
Surface Payload (kg)	150	128	110	150
Total Taper (max / min area)	3.50	2.49	2.49	7.67
Maximum Force (N)	988	517	446	4107
Landing Site	Lunar Poles	0° E	180° E	Equatorial

Table 1: Prototype Space Teathers and Elevators [5, 6].

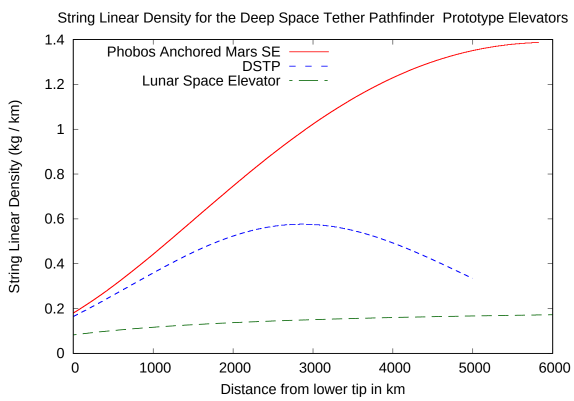

Figure 2: The linear density (taper) of various optimum tether models, the full length of the PAMSE (the solid red curve) and the DSTP (the dashed blue curve) and the near surface part of the much longer LSE (the dot-dashed green curve). See Table 1 for more details on these models. (These tethers use Zylon with a design maximum stress of 4.64 Gigapascals.)

value ore samples or mining products from a lunar mining enterprise.

An elevator on the lunar farside could fulfill many of the scientific and logistical goals of a nearside LSEI, but would also provide unique advantages of its own [6, 7, 5], including facilitating farside sample return. The farside landing point would also be an ideal location for a farside radio telescope sensitive to the virtually unexplored radio spectrum at frequencies $\lesssim$ 10 MHz [8]; an EML-2 LSEI would considerably reduce the cost of building and supplying a lunar farside radio telescope system, enabling both the installation of antennas on the surface at the LS, as well as vertically using the lower portion of the elevator as a antenna tower [7]. Decametric and kilometric radio astronomy could be conducted during the lunar night, when radio interference from the Sun is also blocked and when solar powered climbers would not be using the near surface part of the LSE.

The Phobos Anchored Martian Space Elevator: A logical follow-on to the DSTP and the LSEI would be a Phobos-Anchored Mars Space Elevator (PAMSE) [9, 10], which would use the mass of the Martian moon as a counterweight, considerably shortening the length, and reducing the total mass required, at the cost of not being able to anchor to the Martian surface. A PAMSE with the same carrying capacity of a LSE would have only ∼12% of the mass of the prototype LSE.

Although a PAMSE would not have a zero velocity relative to the Martian surface, the average relative velocity between the PAMSE lower tip and the surface of Mars is ∼530 m/sec, roughly Mach 2 in the cold Martian atmosphere, slow enough that it should not cause significant heating of the tip even near the Martian surface. With a height of 14 km the Pavonis Mons volcano is by a good margin the highest feature underneath the elevator. This mountain could serve as a surface base for elevator logistics, or the elevator tip could use its velocity to act as a fast transport near the surface, potentially even rendezvousing with aircraft in the Martian atmosphere.

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AUTONOMOUS SPACE VEHICLES OF THE FUTURE. L. M. Fesq, R. R. Some, N. E. Lay, R. Castano, I. A. Nesnas, J. C. Castillo-Rogez, R. J. Doyle, and P. M. Beauchamp Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Ave, Pasadena, CA 91109 (Lorraine.M.Fesq@jpl.nasa.gov)

Introduction: Based on recent discoveries, some of the most intriguing science will demand more physically- and cognitively-capable robotic space explorers to push the boundaries of exploration. Examples of such exploration include searching for life by navigating the rugged surfaces of Ocean Worlds [1] (Europa, Enceladus, Titan, to name a few), sampling their plumes, and accessing and exploring their oceans. They may also span spelunking into the caves of Mars and the Moon, browsing the atmospheres of Titan and Venus, assessing the resource potential for exploitation of near Earth objects [2], and cruising to the Oort cloud or even a neighboring planetary system. Such ambitious missions will face similar challenges: (a) they will seek destinations and new worlds where little is known *a priori*, (b) they will need to conduct more sophisticated and complex operations for extended periods of time or under the stress of short durations to achieve their goals, and (c) they will need to react to unpredictable events and outcomes.

Advances in sensing, computing, communication, reasoning, design and materials will usher a new generation of explorers that will increasingly rely on their cognition to react and adapt to unknown environments and situations. *Smart sensors* will be capable of data processing with large paralellelism. Their abundance on a spacecraft will be enabled not only by their smaller footprint and decreasing power requirements but also by a wireless-communication backbone that will eliminate the complexity and weight of large connectors and harnesses. These highly capable robots will be able to see, touch, taste, and even smell their environment. This increased sensory and cognitive load will be handled through *advanced computing* and reasoning that will enable these robots to have situational and self-awareness. They will be able to detect, isolate, and diagnose faults and failures from their redundant sensing suite and be able to take appropriate action. They will be able to react immediately to events, rapidly optimizing their science return and replanning their missions consistent with overarching science goals and changing situations. Interplanetary robots to nearby bodies will communicate back to Earth via a deep space relay system at extremely high optical data rates compared to what can be done today while scientists, in a Virtual Reality room observe, interact, plan, analyze, command and suggest activities.

By 2050 many of the technologies identified in NASA's Technology Roadmaps [3] will be tested and available for routine use. The vehicles of the future will be highly capable and will be able to autonomously perform science goals and collect scientific data as defined by those goals. These vehicles will have computing capablilities that are orders of magnitude better than we have now. Three key technology areas will provide vehicles with these autonomous capabilities, and will be discussed in this paper.

High Performance Spaceflight Computing: Autonomy relies on capable avionics to host advanced algorithms. Recent investments in high performance computing by NASA's Space Technology Mission Directorate [4] are showing promising progress in developing low-power board-level flight computing products that will a) decrease downlink requirements for extended exploration to the Kuiper Belt, the Oort cloud and beyond, by orders of magnitude through onboard data processing, b) enable real-time processing needed for terrain relative navigation and hazard detection/avoidance during entry, descent and landing onto planetary objects, and c) increase detection of dynamic, transient events from 10% to 75%, thereby increasing science return.

Beyond 2050 we will likely have transitioned from standard Silicon, Gallium Arsenide based electronics to graphene, nanowires, spintronics and beyond. Neuromorphic computing will be established, and computer vision, machine learning (including deep learning) and scalable data analytics will be routinely hosted onboard and handled by custom hardware that is built into every computer. We will have extremely high density, high performance memories, processor-in-memory architectures and all that goes with a highly capable flight computing ecosystem: adaptable, composable and extensible.

Wireless Communication: Ubiquitous, wireless network connectivity will be a core element of future spacecraft autonomy. In much the same way that the "Internet of Things (IoT)" is permeating our daily lives with sensors and control for work and home, a highly connected, wireless ecosystem will become routinely available for use in spacecraft systems. Wireless interconnect will largely eliminate the need for custom wiring and harnessing, and opens the door for adding sensors without the mass and volume costs due to additional cabling. The extent of these additional sensors will enable fine-grained and continuous inspection of spacecraft health, resources and remote sensing observations. Dynamic access to this information will be driven by autonomy algorithms that control spacecraft operation and science planning. Beyond computing horsepower, extremely high density sensors and sensor processing – imagine a robotic skin - kinesthetic sensing, in general, will be significantly more capable than today's sensors – think vision into the deep UV and IR, audio into the deep ultrasound and, on the other end, extreme long wavelength. Power distribution will still require wiring but this is minimal and can be used for data distribution as well – primarily for intelligent power systems but also as a backup/back door for wireless, and perhaps for fault tolerance. This will eliminate much of the cost and difficulty of assembly, integration and test of new sensors and subsystems, (re)configuration of spacecraft electronics, and enable software defined spacecraft and similar concepts. It will also enable greater modularity, in particular, for self-assembling and self-organizing assets, such as large telescopes [5] or deployable solar arrays. The building blocks for realizing wireless network connectivity on spacecraft is now under development [6],[7].

Self-aware and Self-directed Reasoning: Autonomous space explorers will be able to perceive their environment and their internal state through the additional sensors that the wireless communications allow, to see, hear, touch and even smell in real-time. These explorers will be guided by higher level goals that can be flexibly executed instead of low-level, single-path commands. They will amass large volumes of data at high rates, and possess onboard abilities to organize and model the world around them. For example autonomous navigation must rely on the visual and gravitational knowledge gained while approaching a target, and build the reference shape and gravity model on approach in order to achieve orbit and map the target. They will have huge databases of knowledge at their disposal, and the intelligence to use these data both individually and as a team for learning, analysis, and decision making. These vehicles will have the ability to continuously monitor the system state, resources and health of its hardware including fault/failure detection, isolation, diagnosis, prognosis and repair/response through regrowth via 3D printing. Recent progress in health state estimation [8], planning and scheduling [9], and risk-aware execution systems [10] are now being integrated through internal research efforts at JPL to achieve system-level autonomy capabilities that will provide self-awareness and self-directed reasoning.

Summary: In the next 35 years, we envision current technological advancements trends to accelerate, especially in the areas of a) high performance computing – a natural technology multiplier for space missions that will provide orders of magnitude performance improvement over current spacecraft processors, b) wireless on-board communication that will eliminate the need for onboard data harnesses and thereby excellerate the proliferation of sensors, and c) self-directed and self-aware reasoning software that will assess vehicle state and its environment, determine what goals are achieveable, and plan activities to optimize science operations. These key technology areas will be instrumental in realizing NASA's vision to send robotic space vehicles to autonomously travel to the far reaches of and possibly beyond our solar system, in the quest to seek out life in the shadows of caves, under the water on icy moons, and in the atmospheres of alien planetary bodies.

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SMALL IS BEAUTIFUL – TECHNOLOGY TRENDS IN THE SATELLITE INDUSTRY AND THEIR IMPLICATIONS FOR PLANETARY SCIENCE MISSIONS, Anthony Freeman, Fellow IEEE, Manager, Innovation Foundry, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA, USA, Email: Anthony.freeman@jpl.nasa.gov, Tel: (818) 354 1887.

Abstract: It's an exciting time in the space business – new technologies being developed under the 'NewSpace' umbrella have some profound implications for planetary science missions over the next three decades. For example, its easy to anticipate that by 2050 small spacecraft with mass 50-200 kg will be able to do what today's 500-1000 kg spacecraft can do. It will also soon be common practice to incorporate cubesat/nanosat ride-alongs on flagship missions to enable science measurements at close range and in environments that would be considered too risky for the primary spacecraft. NASA's EM-1 and ESA's AIM missions will lead the way on this before the end of this decade. Science results from the ride-along nanosats may have a higher profile than results from the primary mission, and attract much greater public attention – as Philae did on Rosetta. Recent trends also suggest launch costs/kg will be at an all-time low and capabilities at an all-time high.

Telecom, always a problem for deep space missions to the outer planets, will benefit from downlink rates using optical comm that will match today's rates for inner planet missions using RF. Information bandwidth will have increased dramatically as onboard science data reduction becomes commonplace. Space-qualified data processing capability on deep space missions (currently strangled by the 1990's era Rad750) will be just a few years behind the ground-based processing capability of 2050, which will be blindingly fast. As a result, software functionality (AI, autonomy, fault protection, data processing and analytics) on board spacecraft will have grown exponentially from the present date.

In addition, hardware upgrades for long-lived spacecraft in Earth orbit using Additive Manufacturing technology or Satellite Servicing will be as common as uploading S/W upgrades is today. We should expect that additive manufacturing will be used successfully in a low-gravity environment to construct large-scale structures, e.g. a habitat, or a space telescope or a very large antenna.

Spacecraft structures will be multifunction without exception – providing structural integrity, thermal conduction, comm lines, power distribution, and even RF/optical reflecting surfaces. All spacecraft subsystems and instrument components will be 3-D printed. Integration and test will be almost 100% automated. The formulation/design phase will take the 2-3 years it does now – but fabrication, integration and test will be done in a time-span of just a few weeks.

Solar cells efficiencies will have reached a plateau, and batteries will be available that operate efficiently in all expected temperature regimes for deep space missions, from Venus out to beyond Pluto. We will have demonstrated an electromagnetic tether power generation system on at least one outer planets mission. Advances in power and propulsion technologies based on nuclear processes beyond present-day capabilities will depend on whether the US decides that nuclear power is the preferred solution to clean energy (which will trigger significant DoE investment.)

Attitude determination and control systems will continue their advance towards micro arcsec pointing control and cm level precision in formation flying, to the point where such requirements are no longer considered a risk item. Science remote sensing instruments will continue to shrink in power requirements and physical size, with the exception of measurements requiring large apertures. In those cases the mass of the structure forming the aperture will continue to decrease.

Taken together, these projected developments mean that, despite the 'tyranny of the rocket equation', planetary science missions in 2050 will go further and faster than they do today, touch more objects in our solar system, return far more information, and be implemented for budgets and schedules we can only dream of today.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

ORGANIC SYNTHESIS IN THE SOLID STATE – IN THE SEEMINGLY FORBIDDING, HARD, DENSE MATRIX OF OLIVINE AND SIMILAR MINERALS Friedemann T. Freund, SETI Institute, Carl Sagan Center, 189 Bernardo Ave, Suite 200, Mountain View, CA 94043, USA friedemann.t.freund@nasa.gov

Introduction: Over that past decades, research into the abiotic synthesis of organic compounds has focused reactions that can occur in gas or fluid phases, at gas-solid and gas-liquid interfaces [1-3], and during intercalation into the soft solid matrix such clays [4]. It is widely – but wrongly – assumed that the dense, hard matrix of minerals is a medium, in which organic synthesis just cannot take place.

The reason for this misconception is that the behavior of the low-z elements C-H-O-N-S, present in magmatic systems as gas/fluid phase components, is not understood. Specifically: How do $H_2O/CO/CO_2/N_2/SH_2$ dissolve in the solid state? How do the solute C-H-O-N-S species interact chemically in the solid matrix?

Thermodynamics mandates that, whenever a mineral crystallizes from a fluid-laden magma, the fluid components enter as "impurities" into solid solution. The most common solute is hydroxyl such as Si-OH, introduced through dissolution of H_2O. However, all other components $H_2O/CO/CO_2/N_2$ also form solutes in the mineral matrix. During cooling, the solutes exsolve. At the same time a widely ignored redox conversion takes place [5], best known from the reaction Si-OHHO-Si ⇔ Si-OO-Si + H_2, where H reduces from H^+ to H^0 while O oxidizes from O^{2-} to O^- [6]. All low-z solutes are subject to the redox conversion leading to chemically reduced C, N and S in solid matrix [7].

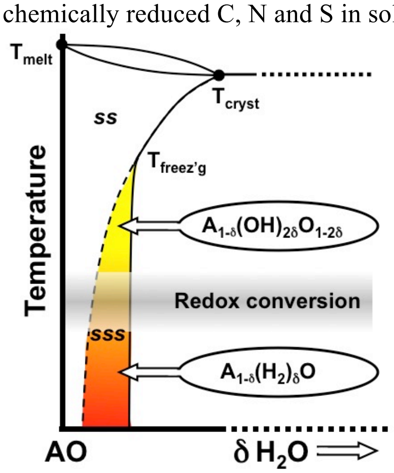

Figure 1: Binary AO–H_2O phase diagram: ss stands for "solid solution", sss for "supersaturated solid solution". In the sss state, under metastable conditions, the redox conversion transfers electron density from O^{2-} pnto the low-z's.

Thus chemically reduced H, C and N bonded to O^- exist in the O^{2-} natrix. Supersaturation means that these low-z elements H, C and N continue to be driven to exsolve to the extent possible by their diffusive mobility. Dislocations are perferred sites for exsolution, offering "extra room" to accommodate the [-C-C-C-] entities, which assemble in the 3-D constrained space available in dislocations with C bonding to H, O^-, N and S [8]. It has been proposed that C atoms diffuse in dense matrix by coupling to O^- [9].

The outcome is an assembly of low-z elements precipitating in the core of dislocations in compliance with the 3-D environment of the host matrix. As generic formula we write $[C_nH_xO_mN_yS_z]^{m-}$. The complexity of the heteroatomic, predominantly aliphatic proto-molecular entities is controlled by the geometry of the dislocations and by how many $[\text{-C-}]_n$ can precipitate.

There is clear spectroscopic evidence for proto-molecular entities in solid matrix. Figure 2 shows the aliphatic $\nu_{C\text{-}H}$ stretching bands seen in the IR absorption spectrum of a laboratory-grown MgO and a mantle-derived olivine single crystal.

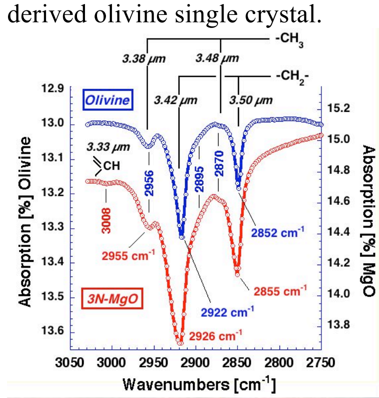

Figure 2a: $\nu_{C\text{-}H}$ IR stretching bands of a melt-grown MgO and a magma-grown olivine single crystal indicating the presence of aliphatic organics in the matrix of these crystals,

The C-H bonds can be pyrolyzed by heating the MgO crystal. Upon annealing at RT the aliphatic signature returns within short time, a few weeks, rebuilding the original diagnostically distinct IR spectrum. This observation implies (i) that the $–C_n–$ backbone was not destroyend by the pyrolysis and that (ii) the H atoms were able to return to build the [–CH], [$–CH_2–$] and [$–CH_3$] bonds with an amazingly short time.

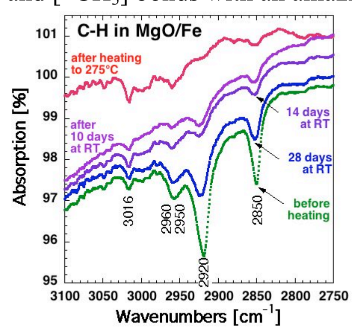

Figure 2b: Rapid return of the $\nu_{C\text{-}H}$ stretching bands during RT annealing, indicating that the broken C-H bonds are reconstituted in the structurally very dense MgO matrix.

Solvent extraction of crushed MgO crystals leads to carboxylic and dicarboxylic acids, $H_3C\text{-}(CH_2)_n\text{-}COOH$, $HOOC\text{-}(CH_2)_n\text{-}COOH$, to urea and glycolamide $(NH_2)CO$ and $H_2COH\text{-}CO\text{-}NH_2$, and to homologous families of higher molecular weight CHONS with up 40 C atoms.

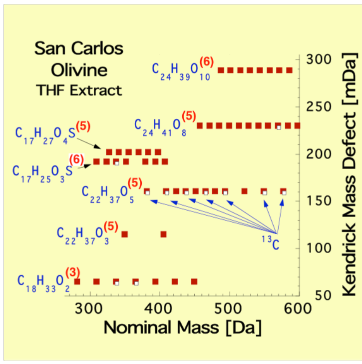

Figure 3: Families of O-rich high molecular weight aliphatic hydrocarbons solvent-extracted from crushed gem-quality olivine crystals, indicative of assembly of $[C_nH_xO_mS_z]^{n-}$ entities inside the dense olivine structure.

Discussion: The observations reported here provide very strong support for a hitherto overlooked synthesis mechanism by which abiogenically complex organic compounds, O-rich, N-bearing and S-bearing with molecular weights of at least up to 600 amu can be assembled, namely in the seemingly forbidding, hard, dense matrix of olivine, the most abundant mineral in the universe. In fact, the dense matrix provides the strongest driving force for the segregation of relatively large atoms such as carbon [9]. An additional feature of this abiotic synthesis is that the 3-D matrix of the host mineral structure will obviously control the stereochemistry of the $[C_nH_xO_mN_yS_z]^{m-}$ that are assembled.

This is a universal synthesis pathway. In all likelihood it will be operational in any structurally dense mineral matrix, in particular in olivine crystals that have incorporated finite concentration of the low-z elements C, H,N and S by crystallizing from fluid-laden magmas or recrystallizing in other high temperature, fluid-laden environments. The same synthesis pathway may also apply to situations where nanosized olivine grains condense out of the gas phase in the gas-rich outflows of dying stars. This mechanism has been proposed to account for the presence of complex organic matter associated with interstellar dust [9]. It probably also applies to organic molecules associated with comets [10].

In the experiments described here we used crushing of gem-quality, melt-grown MgO and upper mantle-derived olivine single cyrstals as the method of choice to expose some $[C_nH_xO_mN_yS_z]^{m-}$on fracture surfaces and make them accessible for solvent extraction.

In nature weathering would be the dominant mechanism by which the organic compounds are released from the matrix encasement. In order to convert the $[C_nH_xO_mN_yS_z]^{m-}$ into free $C_nH_xO_mN_yS_z$ molecules during aqueous weathering, additional reactive steps will be required – steps that may change the C:H ratio while maintaining the integrity of the –C_n– backbone.

The solid encasement, i.e. the assembly of polyatomic $[C_nH_xO_mN_yS_z]^{m-}$ precipitates along dislocations and other extended defects in a host mineral structure, provides for a highly unusual mechanism to assemble large CHONS with interesting properties: (i) they can be O rich with one or more functional groups such as –COOH and other reactive sites, (ii) they are stereochemically selected because the structured 3-D environment provided by dislocations restricts the ways how the –C_n– chains can assemble either in a linear fashion or with sidechains.

No chemical reaction pathway in the unconfined gas or liquid phase, nor on solid-gas or solid-liquid interfaces, can provide such preselection of the organic molecules to be synthesized, neither with respect to the number of atoms forming the –C_n– backbone nor with respect to the shape of the CHONS.

The questions raised here are very important in the context of setting the stage for achieving higher orders of complexity through the assembly of CHONS into larger, secondary structures. We may even speculate that, in order to build structures that could self-assemble and achieve replication, hence, a first form of life, it would be good to start from a selection of relatively few, but functionally diverse CHONS available in relatively high concentrations in the environment. This is better than having a greater diversity, but less functionality in the smaller molecules that can be assembled under prebiotic conditions through chemical reactions in the gas or liquid phase or at gas-solid and liquid-solid interfaces. Even the intercalation of small molecules ointo the soft matrix of clays [4] does not come even close to the efficacy of synthesizing stereochemically pre-selected macromolecular CHONS in the structurally dense mineral matrices.

Organic synthesis in the solid state, drawing on the solutes of the common gas/fluid phase components, may have been the best way, possibly the only way, to produce the complex CHONS necessary to give Life a chance here on Earth more than 3 GYrs ago, on other solid bodies in the solars system, and in suitable exoplanetary environments.

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PLANETARY OXIDATION AND OTHER UNSOLVED RIDDLES. Friedemann T. Freund, SETI Institute, Carl Sagan Center, 189 Bernardo Ave, Suite 200, Mountain View, CA 94043, USA friedemann.t.freund@nasa.gov.

Introduction: It is widely believed that the Great Oxidation Event (GOE) some 2.4-2.7 GYrs ago was made possible by microorganisms, presumably cyanobacteria, that had "discovered" oxygenic photosynthesis and started to inject large amounts of O_2 into the Earth atmosphere. While this is a grandiose idea, Gaia-inspired, it leaves several questions unanswered that are critical for understanding the role of oxygen in the evolution of Life.

These questions are: (i) isn't oxygen highly toxic to primitive forms of Life that formed in the pervasively reduced environment of the early Earth? (ii) How can primitive organisms, had which supposely never experience anything but a reducing environment, suddenly "invent" the complex biochemistry that is necessary to deal with pernicious O_2 and to use free O_2 to run a more efficaceous energy-producing metabolism? (iii) How can it be rationalized that the geological record provides evidence for early oxidation before the GOE?

Despite the near-universal acceptance in the science community of a biological origin of O_2 in Earth's atmosphere, the question must be allowed whether this Gaia-inspired idea is really supported by the evidence and whether an alternative source of free O_2 may exist, an abiotic source for free O_2 rooted in geology.

Evolutionary changes in biology never happen without a reason. Major changes always occur in incremental steps driven by selective pressure towards adaptation to changing environments. The universal laws of Natural Selection surely apply to such a fundamental change in the basic machinery of Life as the transition from reducing to oxidizing conditions. Hence, before early microorganism were able to use potentially lethal O_2 to their benefit and even produce O_2 as part of their metabolism, they first had to learn how to cope with the presence of O_2.

It therefore stands to reason to doubt the validity of belief that the transition from reducing to oxidizing conditions during GOE was made possible by microorganisms having "invented" oxygenic photosynthesis. No microorganisms would have been able to do so without evolutionary pressure provided, for instance, by a trend toward an ever increasing oxidation imposed by the geological environment. Such a scenario is supported by the observation that one of the genetically oldest antioxidant enzymes, superoxide dismutases, is found in prokaryotes, which are among the oldest and most primitive microorganisms that evolved more than a GYr before GOE and before the O_2-tolerant eukaryotes.

Discussion: Thermodynamics mandates that all minerals that crystallize from an H_2O-laden magma incorporate some H_2O in solid solution, commonly in the form of impurity hydroxyls such as OH^- or Si-OH. During cooling, the hydroxyls exsolve up to the point, when diffusional processes become so sluggish, that the system can no longer maintain thermodynamic equilibrium. Around 500°C a redox conversion takes place, in the course of which pairs of hydroxyls rearrange electronically: the two H reduce from H^+ to H^0, forming H_2, while the two O oxidize from O^{2-} to O^- forming peroxy: Si-OHHO-Si ⇔ Si-OO-Si + H_2.

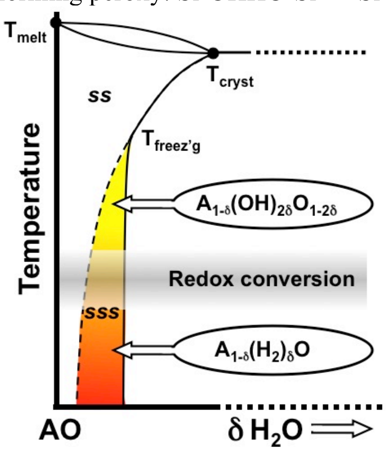

Figure 1: Binary AO–H_2O phase diagram: ss stands for "solid solution", sss for "supersaturated solid solution". In the sss state, under metastable conditions, the redox conversion generates peroxy bonds plus H_2 [1].

As a result of this redox conversion igneous rocks and high-grade metamorphic rocks are "loaded" with H_2 on interstitial sites in the constituent minerals [2]. Inside the minerals peroxy's lurk. H_2 and peroxy defects are inconspicuous and have indeed been widely overlooked – ignored – by the geoscience community. At present little is known how much H_2 and peroxy is present in typical crustal rocks. Concentration levels on the order of 1000 ppm may be typical [3].

While the reaction Si-OHHO-Si ⇔ Si-OO-Si + H_2 is reversible at elevated temperatures, the H_2 molecules are diffusively mobile, even in dense mineral structures, making this reaction unidirectional. In addition, H_2 can outdiffuse from the mineral matrix, in which they were produced, enter the intergranular space and get lost to either H_2–consuming microbes in the deep biosphere or to space [2].

Importantly, H_2 will no longer react with peroxy during weathering at Earth surface temperatures. Instead the peroxy bonds hydrolyze to produce hydrogen peroxide: Si-OO-Si + H_2O => 2 Si-OH + H_2O_2 [4]. Since H_2O_2 decomposes to H_2O + ½ O_2, it can carry out other oxidation reactions such as, for instance, oxidizing ferrous iron, Fe^{2+}, co-released during weathering, to ferric, Fe^{3+}, precipitating it in form of Fe^{3+}–bearing minerals such as FeOOH and/or Fe_2O_3.

As long as the geoscience community did not take notice of the redox conversion by which solute hydroxyls in rock-forming minerals turn into H_2 plus peroxy, the oxidation potential of rocks during weathering could not be assessed. Therefore it was unknown that weathering can lead to oxidation beyond the thermodynamically controlled redox couple of, for instance, Fe^{2+}/Fe^{3+} in aqueous solution.

If average peroxy concentrations in common rocks are on the order of 1000 ppm, weathering of every km^3 will inject approximately 2 x 10^{12} g free oxygen into the Earth's surface environment. Today's weathering rate is about 3 km^3/yr. Assuming that the weathering rate on the early Earth was higher by a factor of 2 (a very conservative estimate), the amount of free O_2 injected into the early Earth's environment via this mechanism would have been on the order of 10^{13} g/yr.

Obviously, all of this oxidizing potential would first have been consumed to oxidize sinks such as Fe^{2+} and other reduced transition metals as well as sulfur co-released during weathering. After 1-2 GYr, as the continental rocks became ever more granitic-andesitic [5]{Rudnick, 2013 #3996}], weathering of rocks would release lesser amounts of Fe^{2+} and other reduced components. At this point peroxy defects would have become available in the near-surface environment, the habitat of early life forms. The microorganisms would then have been exposed to highly reactive, highly oxidizing radicals such as produced during Si-OO-Si hydrolysis, in particular •O and •OH [6, 7].

This scenario suggests that early life must have been under continuous attack by Reactive Oxygen Species (ROS) during the weathering of rocks. They would have been under evolutionary pressure to develop enzymatic defenses such as superoxide dismutase, an anti-oxidant already found in prokaryotes [7, 8].

We might thus expect that, after a lengthy period of time – possibly hundreds of millions of years – some microorganisms would become adapted to the oxidative assault in their environment by developing a new biochemical machinery, which allowed them to not only cope with free O_2 but to use O_2 to their advantage.

Such a scenario of a plausible path towards oxygenic photosynthesis implies that this major step in the evolution of Earth's biosphere was driven by a purely geological process. The Gaia-inspired idea that Life can have a profound effect on the evolution of the planet as a whole would then apply to the subsequent time, when photosynthesis started to inject massive amounts of free O_2 into Earth's atmosphere.

The processes which lead to the introduction of peroxy into rocks are universal [9]. Therefore, wherever Life might have started on some other planetary body under conditions not too dissimilar to Earth's, its evolution will be marked by the same evolutionary pressure from highly oxidizing as outlined here.

The presence of peroxy in rocks is important also in other respects, in particular in geophysics. The reason is that, when peroxy defects break up, electronic charge carriers are generated, electrons and holes. One way of achieving the break-up is through mechanical stress such as produce in the Earth's crust prior to earthquakes. The electrons remain in the stressed rock volume, while the holes have the remarkable ability to flow out of the stressed rock volume, into the adjacent less stressed or unstressed rocks. The holes propagate fast and far, at speeds up to 100 m/s and over distances on the order of tens of kilometers [10]. Because of their unusual properties they are called positive holes.

Deciphering these processes has led to profound changes in the understanding of earthquake and pre-earthquake phenomena [11].

When the positive holes arrive at the Earth surface, they cause a variety of follow-on reactions. For instance, they can recombine returning to the peroxy state. In the process energy is released, which leads to vibrationally highly excited surface atoms and the emission of spectroscopically distinct infrared photons in the region of the thermal infrared (TIR) bands – a process that is also of interest in the contect of pre-earthquake science [12, 13].

Monitoring the TIR emission by satellite-based remote sensing may be a useful method to identify deep interior stresses waxing and waning on Mars.

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THE ASTEROID BELT CYCLER (ABC) CONCEPT: A COMPREHENSIVE ASTEROID BELT SAMPLE RETURN CAMPAIGN ENABLED BY CREWED PRESENCE IN CISLUNAR SPACE.

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Introduction: The Asteroid Belt Cycler* (ABC) is a mission concept that capitalizes upon a crewed presence in cislunar space to comprehensively sample the asteroid belt using robotic sample return (SR) spacecraft. In place of current single-use SR spacecraft, ABC spacecraft would be re-usable and would visit the asteroid belt to collect samples and contextual scientific data from selected bodies and then return the sample(s) to a crewed platform in cislunar space (e.g. the Earth-Moon L1 Lagrangian point). The astronaut crew would refit and refuel the ABC spacecraft to sample another target, and would then carry the sample to Earth inside the crewed vehicle. This system allows comprehensive sampling of the Asteroid Belt, re-use of the SR spacecraft, and improved protection of samples from thermal effects of re-entry than are possible in a small sample return capsule (SRC). The ABC concept may also have important technological and operations parallels with future efforts to obtain resources from Asteroid Belt sources, and the sample suite obtained would be useful for resource identification towards that end.

It is important to note that ABC is not intended as a cost-savings activity versus single-use SR, but rather it leverages a future crewed presence in cislunar space to enable comprehensive scientific exploration of the entire Asteroid Belt. ABC targets might also include Near-Earth Objects (NEOs) and Jupiter-family comets (JFC). The basic concept might also facilititate SR missions to bodies requiring especially distant apihelia (due to reduced spacecraft mass versus single-use SR) and/or stringent Planetary Protection requirements (through crewed interaction with samples prior to Earth return).

*The word "Cycler" as used here is intended as shorthand for a re-usable spacecraft that makes repeated trips between cislunar space and Asteroid Belt targets.

Nominal ABC Mission Architecture:

1) A SR spacecraft visits a target in the Asteroid Belt (or NEO, or JFC, etc.) and collects sample(s) and contextual science data.
2) The SR spacecraft then delivers samples to a crewed platform in cislunar space. The astronauts' Earth return capsule would accept the samples, carry them internally, and provide refrigeration if necessary.
3) Astronauts service the SR spacecraft, refueling and refitting it. Refit would include emplacement of clean sample collection hardware and may include addition/subtraction of scientific instruments, addition of small solid rockets for post-sampling escape from larger bodies (e.g. Ceres), replacement of ion engine electrodes, etc.
4) The SR spacecraft departs to sample its next target body.
5) The crewed spacecraft returns the sample(s) to Earth protected inside the capsule, as was performed in the Apollo program.
6) Repeat steps 1-5.

Scientific Rationale: Sample return from asteroids is a very important means of understanding the early history of the Solar System. The Asteroid Belt is composed of 26 classes of asteroids, as defined by the Small Main-Belt Asteroid Spectroscopic Survey (SMASS) [1]. This is material left over from the early assembly of the Solar System but it was spared incorporation into large planets and so retains much of the chemical, mineralogical, morphological, and isotopic signatures of the young Solar System. The asteroids range from silicate-rich "S" type bodies in the inner Asteroid Belt to carbonaceous "C"-type bodies which predominate at the reaches of the Belt closest to Jupiter. While inferred matches can be surmised between asteroid spectral classes and meteorite types, only SR can establish definitive ground truth that a given asteroid spectral class is appropriately assigned to a meteorite type.

Once an asteroid is matched to a given meteorite, NASA's and the scientific community's investment in the chemical, mineralogical, morphological, isotopic, and other research into meteorites can be directly applied to known asteroid bod(ies). This provides the parent-body context that is largely missing in meteorite studies, improving our ability to describe the processes that formed our present-day solar system. Gaining the ability to tie research on a given meteorite to a known parent body immediately and dramatically expands our understanding of the parent body and its asteroid spectral class. To date, only one asteroid has been definitively matched to a meteorite type by SR; S-type asteroid 25143 Itokawa which JAXA's Hayabusa-1 mission paired with the LL ordinary chondrites [2,3]. The OSIRIS-REx and Hayabusa 2 SR missions may also provide a meteorite type match for their respective targets 101955 Bennu of asteroid class B and 162173

Ryugu of asteroid class Cg. Currently, twenty-four asteroid reflectance classes are unpaired with known meteorite types, comprising the vast majority of the Belt in both mass and number of bodies.

In addition to the 26 reflectance classes of bodies in the Asteroid Belt, there are a number of individual targets of special scientific interest to include Ceres, Psyche, Vesta, etc. which could be specific targets of ABC sorties. NEO and JFC bodies may also be targets depending on mission architecture considerations.

Operations/Architecture Rationale:

Mass/Complexity Considerations: Current NASA SR missions focus on a single target and include all the SRC hardware necessary to return sample(s) through the Earth's atmosphere to a waiting Curation facility. The ABC concept removes the SRC mass and components from the SR spacecraft design, decreasing SR mass and complexity. The use of replaceable sample collection hardware also allows re-use of the expensive SR spacecraft for multiple SR missions. Visits to multiple bodies are currently possible, as demonstrated by the Stardust-NExT extended mission to comet Tempel-1 after the primary Stardust mission ended [5], visits to both Vesta and Ceres by the Dawn mission [6], and visits to both Pluto and 2014 MU69 (in January of 2019) by New Horizons [7].

Delta-Velocity Considerations: Since the SR spacecraft does not have to decelerate to a velocity survivable for SRC entry but only to within capture velocity for cislunar space, higher return velocities might be permissible. This may translate into higher allowable aphelion distances for SR missions and may support SR from outer Solar System objects.

Cold Sample Handling Considerations: In the case where mission science goals require cold or cryogenic SR, hardware must currently be included to protect the samples from the thermal pulse introduced by Earth atmospheric entry. This produces the ironic condition where the mission must carry relatively complex hardware through the entire mission just to deal with effects that occur after the samples that are returned to Earth (but before they are collected). Experience with the Apollo mission shows that returning samples in a large, crewed capsule offers significantly greater thermal protection than small SRCs such as those used in the Genesis and Stardust missions. By passing off the requirement for end-stage thermal protection from the SR spacecraft to the crewed vehicle, risk to the samples is reduced and the complexity/cost of the SR spacecraft is reduced significantly. This may prove to be an important enabling technology for returning cold samples.

Cost Considerations: The ABC concept draws its value not from cost savings but from leveraging a future crewed presence in cislunar space to enable comprehensive sampling of the Asteroid Belt and other inner solar system bodies. SR mass savings, sample thermal protection, and cislunar entry velocity aspects of ABC may also facilitate SR missions to bodies that are beyond current capabilities. In terms of general cost considerations, however, costs would be reduced by re-use of SR spacecraft for multiple missions and elimination of the launches needed for single-use SR missions. Costs would be increased if dedicated crewed missions were required.

Additional Missions: It is worth noting that the core concept of utilizing a crewed presence in cislunar space to facilitate farther, more capable SR missions is not restricted to the ABC concept. One-off SR missions to distant or difficult targets such as Saturn's rings (McCubbin F. et al, this meeting) or Mars sample return (Lewis R. et al, this meeting) could be enabled by passing off some traditional SR spacecraft functions (Earth atmosphere entry, Planetary Protection functions, etc.) to an astronaut crew.

Relevance to the Planetary Science Vision 2050 Workshop: This abstract most directly serves several themes of the workshop, namely Origins, Life, and Threats/Resources.

Origins: Obtaining a comprehensive suite of Asteroid Belt samples will substantially improve our understanding of the formation and evolution of the inner solar system through both direct sample analysis and by facilitating matching asteroid spectral classes with meteorite types.

Life: Obtaining a comprehensive suite of Asteroid Belt samples will assist in constraining the type and quantity of volatiles delivered to the early Earth from Asteroid Belt sources.

Threats and Resources: The comprehensive sample suite ABC provides would inform resource prospecting in the Asteroid Belt. ABC missions to NEOs would also directly serve understanding of the composition and structure of hazardous bodies.

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VISIONS FOR THE EXPLORATION OF VENUS IN THE COMING DECADES. J. B. Garvin[1], L. S. Glaze[1], N. Johnson[1], A. M. Parsons[1], P. Mahaffy[1], P. Conrad[1], and M. Trainer[1], [1]NASA Goddard Space Flight Center; james.b.garvin@nasa.gov (301-646-4369).

Introduction: Although it is Earth's closest neighbor, we know very little about the compositional profile of Venus's dense atmosphere, the elemental composition and geochemistry of Venus' surface materials, and the nature of the planet's internal structure and overall geological evolution [1,2]. The limitations of previous measurements of Venus' atmosphere and surface emphasize the tremendous opportunities for leaps in scientific understanding that would be achieved with a coordinated scientific exploration plan for Venus, including investment in techologies that will enable unprecedented *in situ* measurements of its surface, atmosphere, and interior. Our desire is to understand why Earth and Venus are so very different, even though they are nearly the same size, are located in the same region in the inner solar system, and presumably formed from identical primordial materials. The differences between Earth and Venus must therefore provide clues about the evolution of terrestrial planets in general and will place constraints on the potential habitability of such planets in this or other planetary systems. M-dwarf rocky planets are modeled to be Venus-like, so better characterizing this planet will enable the development of approaches to understanding M-dwarf planets' habitability potential, a problem of interest within the astrobiology and exoplanetary science communities in the era enabled by such upcoming missions as JWST, TESS, and WFIRST. In addition, the possibility that Venus is a keystone example of a terrestrial planet that harbored an "ocean" which was subsequently lost as recently as 0.75 to 1 Ga [3] offers potential for understanding so-called "lost ocean worlds".

Here we provide a brief description of our integrated vision for the exploration of Venus through ~2050, with emphasis on the 2035-2050 "vision horizon". Our plan follows the NASA Mars Exploration Program's *Seek/In Situ/Sample* paradigm [4] and is initiated by a deep atmosphere compositional probe such as the Discovery Step 2 finalist known as DAVINCI [5]. We will describe pathways for the scientific exploration of Venus that build upon DAVINCI *in situ* analytical chemistry results and lead to science-driven mission measurements for the 2035-2050 time frame with associated enabling technologies and critical modelling capabilities. Since the harsh Venus environment presents severe engineering challenges, we will consider mission implementations that do not *require* Venus surface sample return as a culmination of the next 30+ years of scientific exploration., i.e. *in situ* investigations integrated with synergistic orbital observations that vastly extend current capabilities, as well as new physical models.

Concepts Currently Under Development: Work on Venus exploration concepts has been ongoing since the early 1980s, including, for example, surface geophysical network missions, long-lived middle-atmosphere balloons, mobile surface explorers, integrated flagship missions with orbiters, powered airborne platforms, landers, as well as ruggedized landers. Such concepts have been described in VEXAG reports over the past 10 years, and were critical test cases for technology roadmap analyses that VEXAG sponsored over the past ~ 5 years [2]. <u>Some important examples include:</u>

- *Venus geophysical/geochemical networks*
- *Mobile Venus surface/near-surface explorers (bellows-based or others)*
- *Tether-based Venus exploration approaches*
- *Ultra-high resolution orbital reconnaissance of Venus (similar to MRO at Mars but with SAR)*
- *In situ analytical chemistry beyond current New Frontiers goals (i.e., beyond VISE* [1]*)*
- *"Grace does Venus" concepts for shallow interior studies via multiple-orbiters or gravity gradiometers*
- *Long-lived balloon-borne concepts*
- *RPS-powered long-lived landed laboratories*
- *Tessera-accessible analytical laboratories* [6]
- *Venus upper atmosphere and orbital Cubesats*

These examples offer either vantage point or measurement advantages over the state of current capabilities, many of which have been proposed to recent open competitions at NASA and ESA (e.g., Discovery, New Frontiers, ESA M-class etc.).

Stretch Scientific Goals at Venus: Assuming an initial "gateway" mission that addresses the atmospheric composition and evolution goals described in the past two NRC Decadal Surveys [1,5], what must we "visioneer" as a Venus scientific exploration capability by circa 2050? This raises some critical questions about scientific strategy in the current absence of new information about the surface and deep atmosphere composition.

Past habitability via relic mineralogical and geochemical records: The evolution and decline of the Venusian critical zone is recorded in its stratigraphic record. Former environmental dynamics are also addressable in the rock record in part, requiring a benchmark against contemporary measurements of environmental dynamics, e.g., magnetic variation, radiation environment, wind speed and direction, etc.

The stratigraphically resolved assemblages will provide documentation of diagenesis, particularly aqueous alteration, which is key to understanding the presence and timing of subaqueous paleoenvironments. This goal could make use of mobile surface exploration with Mars (i.e., MSL/*Curiosity*) quality measurement systems, as well as orbital reconnaissance with sub-meter resolution. Key advances would require long-lived high temperature operations, mobility involving short "hops" or flights, and ultra-wide bandwidth orbital radar sensors beyond the current state of the art in planetary sciences.

In situ geochronology of plains vs tessera*:* Venus' thick atmosphere prevents the accumulation of a significant cratering record for relative age-dating of the major surface units, such as the tessera (uplands) which are hypothesized to be remnant continents formed from nascent plate tectonics, or the plains which are suspected to be more recently resurfaced. *In situ* geochronology measurements to determine absolute dates of formation would provide critical information on the surface history of Venus as well as inform terrestrial planet formation and evolution. This goal would require landed measurements of the quality currently being demonstrated on Mars via MSL's SAM suite (with APXS) with sufficient time for sampling, context analysis, and measurements ideally at more than one locality.

Other key goals involving the character of the shallow interior of Venus, its lower atmosphere dynamics (and role of super-critical CO_2), and how the planet may have "lost" a global ocean would ideally require a strategic program of orbital, airborne, and surface based observations in a coordinated architecture, as was developed for Mars, together with enhanced laboratory and modelling capabilities.

Missions to Address These Scientific Questions: These (and other) scientific goals will require the development of new mission concepts that stretch our current technical capabilities and will only become possible with technology and engineering demonstration flight experiments. Defining these science capability and measurement goals and their engineering requirements now will help us formulate the technology development over the next decades that will make such missions possible, either in the framework of competed missions (Discovery, New Frontiers, Cubesats) or via occasional strategically-directed missions ("Flagships" similar to MSL).

Studying the past habitability potential of Venus via its rock record will require a mission that operates on Venus with an approach similar to the MSL/*Curiosity* Rover but with a different style of mobility. A study of the geochronology of the spatially-dominant basaltic plains versus the complex-ridged terrain uplands (tessera) will require a surface mission capability that permits reaching multiple sample locations in the plains and/or tessera with *in situ* geochronology instrumentation of the scale of complexity of current GCMS/elemental analyzers (*i.e.* MSL/SAM and its descendent geochronology optimized pyrolysis mass spectrometers). Studies of the shallow Venus interior and dynamics may be advanced by longer-lived, landed 3-axis seismometers, as well as via multi-frequency ground penetrating radar measurements. A multi-orbiter approach similar in operation to the ongoing GRACE Earth Science mission [7] would offer an incredible increase in the understanding of the shallow interior of Venus and the record of late heavy bombardment – executing such a mission with advanced gravity gradiometers and high-frequency radar altimeters would require attention to spacecraft orbit maintenance at very low altitudes and with high-precision radial orbit determination.

Ultimately, we can imagine science-guided missions in 2035 to 2050 time-frame that are catalyzed by the next mission to Venus, whatever that will be. Together with JAXA's *Akatsuki*, the near-term flight mission observations of Venus will promote technology and engineering investments in architectures that connect Venus' unique history to the evolution of the entire solar system and beyond. Such near-term missions would set in motion a direction with specific hypotheses and measurement and vantage point requirements that would culminate in the missions required for the 2035-2050 era. Ultimately, an innovative implementation for Venus surface-based sample return must be considered, just as it is for Mars and the Moon. Assessing the habitability and biological potential of Venus will be an essential element of any strategy for the ~ 2050 timeframe, but it will depend on our next few steps in the robotic scientific exploration of Venus and key investments.

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ACKNOWLEDGEMENTS: Special thanks to the memory of Dr. Noel Hinners for inspiration (Venus).

WHAT CAN THE FIELD OF OCEANOGRAPHY CONTRIBUTE TO OCEAN WORLD EXPLORATION?

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Introduction: Increasing numbers of ocean worlds are known or suspected throughout our solar system leading to the tantalizing question: could those other ocean worlds also harbor life? In the coming decades it may not be feasible to visit goldilocks planets orbiting other stars but the very real possibility exists to search for evidence of life – and, more profoundly, an independent origin for life – much closer to home, within our outer solar system. Already, two candidate systems, Jupiter's moon Europa and Saturn's moon Enceladus, have revealed striking evidence that they host global-scale salt-water oceans underlain by a rocky seafloor. To a first approximation, this description can also be applied to the largest contiguous habitat for life on our own planet. [More than 50% of our Earth's outer silicate veneer also lies beneath >3000m of salty ocean, but unless you visit from space you might not notice!]

This is important because, in the outer reaches of the solar system, it is not anticipated that energy from the Sun would be sufficient to drive the photosynthesis that sustains a profusion of life here on Earth, particularly across the surfaces of our continents and sunlit upper oceans. Even here on Earth, however, life is not uniquely dependent upon photosynthesis. As one alternate example, thriving ecosystems can also be found in association with sites of active fluid flow on the deep, dark, ocean floor where chemical energy sustains microbial metabolisms at the base of hydrothermal food chains. Of course, the process of chemosynthesis is not new – the first discoveries of submarine venting were contemporaneous with the first Voyager transects through the outer solar system. But continuing exploration of our deep oceans continues to reveal entirely new geologic settings that, in turn, give rise to different styles of seafloor fluid flow, exhibit different geochemical characteristics and sustain a distinct and diverse array of chemosynthetic microbial metabolisms.

In planning for the most compelling research to be conducted 20 to 30 years hence, therefore, I consider it timely to think beyond missions that will orbit or even land upon the surface of other Ocean Worlds to investigate for evidence of life. Rather, now is the appropriate time to begin to prepare the path toward investigating those oceans' interiors. Importantly, recent developments in both ocean science and ocean technology suggest that the field of oceanography may be reaching key levels of maturity at just the right time to be able to make significant contributions if harnessed constructively in mutually beneficial partnerships.

Recent Developments in Ocean Science: As recently as when the Galileo mission was helping determine that Europa hosted a global salty ocean, all examples of known submarine venting on Earth hosted ecosystems that were dependent upon the presence of oxygen-generating photosynthesis to function. Thus, there were no clear links available, in our scientific vocabulary, between seafloor venting to astrobiology or the origins of life. Fifteen years later that has quite changed. Explorations along some of the "least promising" sections of the global mid-ocean ridge crest have led to the discovery of a much more diverse array of hydrothermal settings than had previously been anticipated. Most notable are those involving serpentinization reactions, at temperatures spanning from 100-500°C. These systems have revealed a capacity to abiotically synthesize at least primitive organic molecules while simultaneously sustaining a diversity of microbial metabolisms under much more chemically reducing conditions than had been reported during the first 20-25 years of seafloor hydrothermal research. Notably, the lithologies that give rise to the most energetically promising conditions at the seafloor, today, are also those that are predicted to have been abundant in Earth's earliest history, when life first appeared.

Mid Cayman Rise: ultramafic-hosted venting on an ultra-slow ridge. 20 years ago, this "could not exist".

But the majority of Earth's ocean floor remains uninvestigated and even the newest discoveries have only come from ever more efficient investigations of two specific settings – the mid ocean ridge systems at the "front end" of plate tectonics, which are anomalously shallow compared to most of the deep ocean floor, and along comparably shallow continental margins. Vast tracts of geologically active seafloor, including deep ocean fracture zones and hadal deep ocean trenches, have been known to have the potential to host seafloor fluid flow for decades (indeed, since the plate tectonic revolution) yet have continued to be overlooked, to date. I do not consider this a negative observation. Rather, as one begins to consider what potentially habitable environments might exist on other ocean worlds, as they have begun to be discovered elsewhere in our solar system, I consider it particularly exciting to have been actively involved in exploration and discoveries, over the same past 10-15 year timescale, which have revealed that the potential for such habitable zones on our own planet may be far more abundant and diverse than had previously been appreciated. Of course, key to some of those most exciting recent finds has not been serendipity so much as a new found, technologically facilitated, capability to search systematically.

Emerging trends in Ocean Technology: One of the most exciting developments in Ocean Research since the start of the new millennium has been the advances made in the use of robotic systems to investigate the deep ocean interior. While the robustness, range and sensor payloads of such vehicles remain rather modest, it is now more than a decade since the first demonstration was completed, using an autonomous underwater vehicle to search for, identify, and characterize new sites of submarine venting in ocean basins where no venting had previously been observed. In the limit, we have most recently pioneered the investigation of the Arctic Ocean floor, in both autonomous and remotely operated mode, with a vehicle moving independently of its surface-ocean support ship. That study, in turn, developed directly from an approach that allowed first systematic investigations of Earth's deepest ocean trenches. No region of Earth's ocean floor remains technologically beyond our reach.

First deep AUV launch of HROV Nereid Under Ice beneath the ice-covered Arctic at 87°N, Oct. 2016.

In the coming decades, I predict that a clear trend will continue in which increasing levels of autonomy coupled with judicious use of telepresence will allow ever greater levels of seafloor and deep ocean investigation to be conducted independent of a supporting research ship. The first demonstration projects have already been completed in which a seafloor robotic system can conduct investigative research, report back to scientists remotely, and be reprogrammed via a collaborative autonomous vehicle providing relay communications while simultaneously tracking and providing navigational information to the submerged robot from the ocean surface. In parallel, at least one entire research cruise has now been conducted in which all scientific operations were directed by a cohort of early career scientific PIs, via telepresence – none of the PIs directing robotic research operations on the remote ocean floor were present aboard the support ship.

It seems clear that this migration of research away from a tradition of ship-based expeditions will be an imperative for the future of oceanography: there will be a need to improve our understanding of Earth's oceans on a much accelerated timescale to predict the impacts anticipated upon our changing natural environment in a timely manner. But that same vision: of increasingly complex and sophisticated combinations of autonomous vehicles, equipped with appropriate sensor payloads, to characterize entire ocean basins is hopefully also one that will resonate with the themes of the Planetary Science Vision 2050 Workshop. While missions to Ocean Worlds currently being planned for launch in the 2020s will be reliant upon systems and sensors that have already reached advanced levels of technical readiness, the time is ripe to anticipate the styles of missions that will follow, a generation hence. How does one characterize a previously unexplored ocean basin? What are the appropriate sensor suites to employ? And how should those sensors be deployed? From individual highly capable vehicles, or via collaborative swarms that offer redundancy?

Looking ahead: My vision for the future, for 20-30 years hence, is one in which the exploration of Earth's Oceans and the exploration of Ocean Worlds are progressing in close (symbiotic!) partnership, both scientifically and technologically. But for that to be achieved, we will need to build stronger cross-linkages between researchers already active in each field, and to train the next generation of researchers to be equally comfortable in both lines of endeavor. Let's begin!

ADVANCING THE SCIENCE OF ISRU. L.S. Gertsch and K.A. Morris, Missouri University of Science and Technology, Rock Mechanics and Explosives Research Center, 1006 Kingshighway, Rolla, MO, USA, 65401, GertschL@mst.edu.

Introduction: The sustainable exploration of space requires *in situ* resource utilization (ISRU). Successful ISRU depends on a solid science foundation; consequently, the planetary science landscape must include comprehensive basic and applied science investigations in support of ISRU by 2050.

Major misconceptions exist regarding the extraction and use of mineral resources in space. One is the belief that mining is a straightforward development from basic principles and can be done on an *ad hoc* basis with little preparation. Another is underestimating the profound effects of the terrestrial environment, specifically a strong unidirectional gravity vector, a thick atmosphere, and abundant oxygen and water, on mineral production practice. These, and similar, perceptions impede the effective use of space for the long-term survival of humanity.

The foundation needed for successful ISRU is not being constructed at present, so for space exploration (and planetary science) to continue to advance, that will have to change before 2050. Science in support of ISRU is science in support of sustainable minerals production everywhere, including on Earth. The effort will begin here on Earth and continue in space.

Background: Agriculture and minerals production are the enablers of civilization. Geologic materials have been produced systematically from the Earth's surface by humans for 1-2 million years (Stiles, 1998; Paddayya *et al*., 2002; Vermeersch, 2002). Means of identifying, locating, accessing, extracting, and processing these materials have been constantly evolving as technology, deposit accessibility, and human desires have changed.

These methods are direct products of the science and engineering of the times in which they were developed. The drive to extract value from mineral resources has driven technological development since before the 16th century (Hoover and Hoover, 1912); one well-known example is the invention of the steam engine (Frenken and Nuvolari, 2004).

Fields of Inquiry: Minerals production and manufacturing have drawn from all the physical sciences throughout their histories: chemistry, physics, geology, materials science, and even astronomy (*e.g.*, Brownlee *et al*., 1984) as well as from many of the non-empirical sciences: mathematics, economics, statistics, computer science, decision and game theory, and others.

Adapting the current state of the practice in these industries to space will require hypothesis-driven research to advance fundamental understanding (basic), as well as to develop the required technological capabilities (applied). Applied science and engineering require the existence of a body of knowledge created by basic science.

Basic Sciences for ISRU: Specific fields of inquiry needed for producing minerals off the Earth, at least in the early stages, include economic geology, surface chemistry, electrostatics, electromagnetics, and many topics of low-gravity condensed-matter physics. Nearly all mineral production-related inquiry to date in these disciplines has been conducted on Earth's surface, with all the biases inherent in the environment that exists there. We have discovered fundamental processes that occur throughout the space and time of the universe, but many of the details (where the devil resides) are not completely clear, especially in unfamiliar environments.

Understanding the natural processes that concentrate desired materials to levels above their natural average has been the traditional focus of the discipline of economic geology. This field needs to expand beyond a focus on finding the next orebody. For example, the theory of mineral evolution (Hystad *et al*., 2016; Hazen *et al*., 2011) enables and requires a focus well beyond Earth. Eventually, economic geology must be linked robustly to the processes active during solar system formation and evolution.

Other examples abound. Separation of the target material (*e.g.*, water) from everything else with which it is found (*e.g.*, mercury, sulfur, abrasive silicate grains) in space will require utilization of different processes than presently employed on Earth. The formation and the fragmentation of rock and cohesive soil masses are affected by the presence of thick, nitrogen-rich atmosphere. Questions regarding the constitutive behavior of these materials in space are difficult to answer on Earth's surface.

Applied Sciences for ISRU: This field is at present the most active of those discussed here, as it contains the design and development of equipment for space science and exploration (Gruntman, 2004), as well as the development and adaptation of processes and equipment to achieve industrial goals in space.

Successfully adapting terrestrial mining practices and technologies for extra-terrestrial use requires that they be disaggregated, examined, modified, and reassembled to preserve their essential capabilities. Simple technological adaptation and substitution may serve for a short time, but ultimately new mining methods (mineral production architectures) must be developed. Doing so requires fundamental understanding of the geological, technological, and economic factors involved.

Some of the environmental aspects on which terrestrial mineral production relies interact in ways that are only partially understood. On Earth they are handled in a highly empirical, labor- and/or mass-intensive fashion that will not be feasible in space.

The opportunities provided by the fundamentally different environments of space bodies, however, offer opportunities for new ways to produce mineral resources to meet human goals. These must be developed and evaluated *in situ* where possible.

Other Sciences for ISRU: History, sociology, economics, and policy studies all have played, and continue to play, important roles in planning mineral production. These sciences will be even more important to the successful development of ISRU because failure, though common in mining (Ferguson *et al*., 2011), is an even more expensive luxury in space. The impact and scope of these sciences will expand again when mineral products from space begin to rival those from Earth in terms of cost and availability on Earth.

Recommendation: The most effective approach for addressing the science needs of ISRU would be a multi-disciplinary, multi-sponsor, multi-national institute devoted to the organization, planning, and performance of ISRU-focused science investigations.

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PLANETARY SCIENCE EXPLORATION THROUGH 2050: STRATEGIC GAPS IN COMMERCIAL AND INTERNATIONAL PARTNERSHIPS.

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Introduction: Planetary Science has emerged from a symbol of the cold war Space Race to a platform for cooperation between Nations. In the coming decades, Planetary Science will see greater participation from the Commerial Sector and International Space Agencies. Thus, NASA is likely to find partners in certain activities, but there might be either a lack of business case or a lack of capability for others tasks. Strategic investments by NASA in selected capabilities and services can facilitate the entry of Commercial Space players and smaller space agencies.

Commercial Space Companies: Though the present generation of Commercial Space Companies depend primarily on federal contracts for survival, it is conceivable that in future, that such companies will be able to access the market: either the B2B market (e.g. Asteroid mining) or the B2C market (Space Tourism). Large strides in Planetary Science can be made when such a market is created, driven, not just by vision and philantrophy, but by expectation of returns on investment. Though such a scenario appears unlikely in the present decade, it might be a reality in the 2040s: if some of the ongoing initiatives aimed at lowering the cost of space (like reusable launch vehicles and ISRU initiatives on Mars) will be successful. Although Elon Musk's stated goal[1] of reducing the cost per ton by five million percent might not be successful, cost of access to space is expected to decline significantly if not precipitiously.

Nations with emerging space capabilities: Planetary Science exploration delivers multiple objectives for a nation: from brand building, development of technology capability and national pride. Countries which have adequate resources but no significant capability in Space Exploration are trying to participate in planetary exploration.Thus, the UAE is planning a mission to Mars: whereas Saudi Arabia, Singapore, South Korea, Nigeria and Brazil are considering developing a capability to launch satellites.

Low Cost Space Industry: The Google Lunar X-Prize and the increasing use of cubesats are in very different ways developing the capability of low cost space exporation. The long term financial viability of the Companies participating for the Google Lunar X-Prize is far from certain: there might be market delivering payloads to the Moon, for example. But, there is a likelihood that this industry will find support from their respective government programs in their own countries and will help develop a class of low cost planetary missions.

What most international players or private players will not undertake: In 2030, it is conceivable that countries like India or UAE, might develop the capability of landing rovers on Mars or the Moon: thus, NASA could collaborate with such entities if there was a need for locatized data. However, there is an array of tasks that require a higher degree of technology capability and/or are >$1 billion in cost that will not be a strategic fit given the risk profile as well as the financials of most non-NASA entities. A prime example of such a task is the development of a propellant plant for generation of rocket fuel on Mars as outlined by Musk. For Musk's plan to come to fruition, NASA has to demonstrate the technology viability of ISRU, the logistical viability of large scale extraction, liquification and storage of rocket fuel at a specific location on Mars.

NASA as an enabler of the next generation of the Solar System: A generation of small companies and space agencies will appear in the next two decades: that are financially capable to share some of NASA's goals of Planetary Science exploration. However, such entities will face a learning curve of a decade or two, since there is a significant barrier to entry in Planetary Exploration. If NASA could facilitate the entry of the commercial sector and of smaller space agencies, a mutually beneficial scenario will be created. Thus, NASA could provide a select technology package, either as a paid service or as a contribution, the likelihood of success of new entities will increase. For example, if NASA is able to provide assistance in Navigation, Communication, help in flight qualification of earth based technology and Landing Systems for Mars, the new entrants will be able to successfully conduct, in 5 – 10 years, a science campaign on another planet or satellite.

Timeline of development of capability of non-NASA entities : It is conceivable that in the 2030s, India, UAE and a commercial entity like SpaceX or a Google X-Prize competitor, will be able to conduct a surface mobility mission on Mars, Martian satellites or the Moon. It is conceivable that by 2025, entities like Virgin Galactic will be able to launch their first flight to space as a cost <$1 million per passenger. By 2045, it is conceivable that such flights will extend to the Moon, and that a small market for Space tourism and development of better reusability and better technology capability, will drive the per passenger cost to <$100,000. It is conceivable that a payload for technology demonstration of asteroid mining, will be launched in the 2030s. If there was a business case for return of a category of mined materials to earth (driven either by a scarcity of such materials on Earth and/or the cheaper cost of access to space at the time), commercial space mining might become a reality by 2050.

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REACHING WATER: PLANETARY DEEP DRILLING. B. Glass[1], D. Bergman[1], R. Davis[2], C. Hoftun[3], B. Johansen[3], and P. Lee[1,3] . [1]NASA Ames Research Center, Moffett Field, CA 94305, USA, Email: brian.glass@nasa.gov [2]NASA Headquarters, Washington, DC 20024, USA; [3]Mars Institute, NASA Research Park, Moffett Field, CA 94035, USA.

Abstract: Deep drilling to >km depths is commonly achieved on Earth, but an extreme challenge on other Solar System bodies. Deep planetary subsurface access may be possible with new drilling concepts operated together with an automated coiled-tubing drill. This light weight, energy efficient concept could enable ice wells for liquid water access for future Mars surface stations, enable low-weight asteroidal and lunar drilling, as well as penetration through Europa's icy crust.

Introduction: Existing or proposed planetary exploration drills are shallow (few cm to 2m) mechanical augers, and terrestrial drills used for oil and gas exploration (Figure 1) require drilling lubricants (muds) and megawatts of energy input, so going deeper on other Solar System bodies will require a new approach. Lightspeed communication delays require a fully-automated planetary drilling approach, or else the nearby (surface or on-orbit) presence of astronauts [1]. We propose that an automated coiled-tubing drill, redesigned for low mass and power consumption, can reach depths of hundreds of meters through ice and rock layers, deep enough to reach massive subsurface ice deposits on Mars and well below the irradiated icy surface of ocean worlds. Currently at a TRL of 2, these concepts could be raised to flight-level prototypes within 15 years.

One primary architectural motivation is that hydrogen and oxygen are very expensive to carry to Mars, yet available there from H_2O. Over the past decade, investigators have looked at ways of producing in-situ resources from processing Mars surface soils or atmospheric gases. These have been incremental and evolutional technologies developed over the past decade. But they consume large amounts of energy for the small quantities of water or methane produced, and are complex, multi-stage processes. Evidence is abundant that large amounts of water have existed near Mars' surface in the past [2] and it is expected that large quantities remain in the subsurface cryosphere and possible hydrosphere [3]. A Martian ice well will cost a significant amount of energy to drill, but then could produce substantial, relatively inexpensive supplies of water from the Martian cryosphere for use in further exploration and space-based facilities.

Deeper drilling is also crosscutting, and would enable highly valuable planetary science investigations, such as direct evidence of past or present microbial life (the Mars cryosphere will be a COSPAR Special Region), characterization of the volatile content of the regolith and cryosphere (including organic molecules and ice densities), and measuring the mineralogy and isotopic chemistry as a function of depth to better understand the climate and geologic history of Mars.

Fig. 1. Current DOE 4.75in diam. coiled-tubing manually-controlled drill (capable of 3km depth)

Drilling Approach: An intelligent, automated deep drilling mission on Mars (see Figure 2 for an example combining a coiled tubing drill, with a future commercial space Mars lander) would probably aim at acquiring samples and cores from a depth of one to five hundred meters where, unless a region of near-surface water can be located from orbital sensing, cold temperatures will be consistent with ground ice only. A robotic coiled-tubing deep drill will be limited in mass, probably to less than 1 ton payload and to a power consumption of 10 kWh per sol. Under these circumstances it will be necessary to minimize the energy expended in rock comminution (pulverizing). One possible approach would be to extract segments of continuous core, perhaps at a rate of about 1 meter per day. Mission length on Mars would typically be about 200 sols if the precursor lander was solar powered. With RTG power, the drill penetration rate could increase and the mission duration could be extended. And the technology developed for the first deep (100m-class) drilling robotic precursor mission would be intended to be scaled up to penetrate to kilometer depths, presumably as an element of a later human exploration mission when more robust power systems would be available.

Another way to reduce the time and energy spent grinding rock at the head-end would be to fracture the rock. The NASA-Honeybee Mars rotary-percussive prototype drills, CRUX and the Icebreaker series [4] (Figure 3), use mechanical hammering as well as rotary grinding. Zaptec has developed several electric-percussive (electropulse) drills for ESA [5] that shock the rock face to break it for more-efficient drilling and cuttings removal. The basic principle of electropulse drilling is to charge an electrode in the drill bit which then discharges an electric spark into the rock face. The plasma channel created in the rock then vaporizes microscopic parts of the rock which expand and explodes the rock from inside. Fracturing is assisted by the acoustic pulse from the spark.

Drilling Site: Although deep drilling systems should be developed with built-in robustness against subsurface unknowns, the anticipated performance of the proposed drilling approaches will depend significantly on the selection of optimal drilling sites. Areas on Mars where the cryosphere might be thinner due to higher regional or local geothermal gradients, for instance, might allow significantly easier access to the deeper aqueous hydrosphere. Similarly, regions with more continuous subsurface ground ice might be significently more amenable to drilling than rock glaciers which, on Earth at least, often present mechanically challenging surface barriers to subsurface access and sampling.

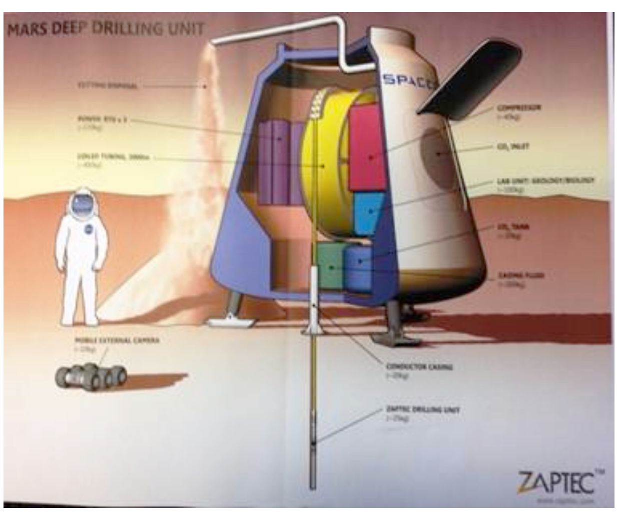

Fig. 2. A 100-200m-capable deep drill concept deployed from a 1-ton-payload Red Dragon or equivalent. (From [5]) *(Human figure for scale)*

Potential Impact: Access to the Martian hydrosphere and cryosphere would greatly reduce the cost and increase the habitability of the future human exploration presence on Mars. Deeper drilling would answer otherwise-unaddressable Mars science questions. And the technologies developed would also enable deep drilling on other Solar System bodies. Electropulse drilling would be particularly helpful for contact drilling into asteroids and other small bodies, due to its very low downward force needs (and hence low/no anchoring).

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Fig. 3. NASA/Honeybee Icebreaker-3 drill tested with Spanish SOLID instrument (black case) and sample transfer arm at Rio Tinto in July 2015.

THE RE UIREMENT FOR A RETURNED SAMPLE CURATION FACILITY IN EUROPE. Monica. M. Grady[1,2], Sara S. Russell[2] and the EURO-CARES team, [1]School of Physical Sciences, The Open University, Robert Hooke Building, Milton Keynes MK7 6AA, UK (monica.grady@open.ac.uk), [2]Dept. of Earth Sciences, The Natural History Museum, Cromwell Road, Londom SW7 5BD, UK. http://www.euro-cares.eu/

Introduction: There is a large and dynamic planetary sciences community in Europe, based at universities, research institutes and museums. The activities of the community include data gathering from instruments on orbiting, lander and roving spacecraft and ground- and space-based telescopes. Data are modelled using theoretical simulations and analogue materials, and great emphasis is placed on making results and discoveries accessible to non-specialists through outreach and education programmes. Underpinning all these activities is a strong foundation of laboratory-based analysis. Samples from comets and asteroids, the Moon, Mars and Earth are analysed to provide information that can help to understand the origin and evolution of the Sun and Solar System, and the processes that led to the origin of life.

Most of the samples that fuel the laboratory-based planetary science investigations are from meteorites. Almost all European countries have at least one internationally-acknowledged collection of meteorites maintained at a major museum or other academic centre. There are also at least two specialist collections of meteorites and one of micrometeorites returned from Antarctica by Europe-led expeditions. Most importantly, there is also the collection of Luna samples returned from the Moon, and held by the Russian Academy of Sciences in Moscow.

Role of the European Union EU : At the moment, there is no single European Sample Curation Facility (ESCF), and no call for one for the samples currently available within Europe. However, European scientists are very hopeful that within the next decade, they will need such a facility, to curate material recovered by a new generation of sample return missions. Any such facility will certainly be an international initiative, and require substantial investment – not just in financial terms, but in infrastructure and training. In its most recent strategic research programme, Horizon 2020, the European Union (EU) recognized the importance of facilitating the work of ESA by funding a programme of space-related activities. One of the activities is EURO-CARES (European Curation of Astromaterials Returned from Exploration of Space; http://www.euro-cares.eu/). This is a three year, multinational project, in which a team of experts from academia and industry is developing a roadmap for a European Sample Curation Facility (ESCF). A complementary activity is EuroPlanet (http://www.europlanet-eu.org/) which coordinates inter-institutional access to laboratory instrumentation, as well as outreach and networking activities.

Role of the European Space Agency ESA : ESA's long-term plan, *Cosmic Vision 2015-2025* (http://sci.esa.int/cosmic-vision/46510-cosmic-vision/) continues previous strategic planning activities, and provides the scientific background to the Large (L)-, Medium (M)- and Small (S)-class missions that make up the agency's space operations programme. The designators L, M and S reflect the budget caps placed on the missions, and within each funding period (approximately 3 years), a mix of mission types are planned, developed, launched and operated. ESA does not pay for the cost of mission instrument development – that is down to individual national agencies, and neither does it pay for exploitation of data from the missions. Again, that is the responsibility of national space agencies.

ESA has a rolling programme of calls for mission proposals, and although no sample return mission is currently selected, proposals for return of material from an asteroid, the Moon and Mars are either under consideration, or are sketched into future international collaborative efforts. The success of the recent Rosetta mission to comet 67P/Churyumov-Gerasimenko has also re-ignited the desire amongst European scientists for a cometary nucleus sample return mission.

In preparation for extraterrestrial sample return, ESA has recognized the requirement for a European sample curation facility, and has funded preparatory studies of its own, as well as taking part in international sample curation activities - e.g., iMARS [1]. The studies focus very closely on planetary protection issues, as well as trying to forecast what state-of-the-art analytical instrumentation should be a part of the the SCF. This second area also leads to debate about where the preliminary examination of a sample for curation and characterization purposes ends, and where research on a sample starts – a debate that is not readily resolved.

Given the way that ESA arranges its operations, it is not easy to see how a facility to curate extraterrestrial materials might fit into a specific programme. A Curation Facility is not a 'mission' in the way that Rosetta or the HST are missions, with infrastructure funded by ESA. Neither is it an instrument, in the way that a camera or a mass spectrometer is an instrument, funded by national agencies. Any proposed sample return mission would very rapidly exceed the planning cap if the entire cost of a curation facility were to be included in the budget. One possibility, still to be fully explored, is that a Curation Facility might become an ESA Centre, like the ESOC, ESA's Space Operations Centre in Darmstadt, Germany.

The start of EURO-CARES in January 2015, is, we hope, the first phase of a long-term project. Our aim is a SCF that will act as a centre for the curation of samples returned from space missions; models for such a facility are NASA's Johnson Space Center in Houston, USA and JAXA's Curation Centre for Hayabusa Materials in Sagayama, Japan.

The ESCF would not just be a place where samples were curated. It would also act as a centre for outreach, education and training. One possible model for this is a 'Discovery Centre', analogous to that which runs alongside the Astrophysics Department at the University of Manchester (http://www.jodrellbank.net/). Such a Centre would welcome visitors of all ages, especially groups of school students for directed learning activities and would hold open days and other events for the general public (e.g., the very successful Bluedot Festival held at Jodrell Bank in summer 2016; http://www.discoverthebluedot.com/). There shouls also be exhibitions within the Facility, with 'hands-on' activities.

Part of the aim of EURO-CARES is to outline the instrumentation required within a Facility to effect preliminary examination of returned materials for research. The presence of such equipment will allow staff to carry out their own research on the material. Visiting researchers would also be welcome, both to work with staff in selection of materials, or to undertake individual short-term research projects using the instrumentation. The Curation Facility would also become an international training facility for students, giving them direct experience of working with planetary materials.

The roadmap that the EURO-CARES team is tasked with producing for the EU should lead to more detailed follow-up activities in terms of building design, instrumentation selection, curation policies, etc. By starting design of an ESCF in advance of selection of a specific sample return mission, ESA will be able to train staff in the specialist sample handling techniques required for safe and confident curation of material. It will also be able to develop its documentation procedures, cataloguing and storage policies, as well as policies for storage of returned samples. The first samples in an ESCF are likely to be planetary analogue materials; specimens collected by future Europe-led meteorite collecting expeditions could also be curated there, in preparation for materials returned from space missions.

Acknowledgements: The EURO-CARES project received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 640190.

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Thermal Mapping to Achieve 3-D Structure and Dynamics of Planetary Atmospheres Throughout the Solar System.

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Introduction: As instrumentation on the ground and in space continually improve, we are now beginning to open up a new chapter in the understanding of planetary atmospheres. Recent ground-based high-spectral resolution mapping observations of Jupiter show the stratosphere to be a region of intense wave activity [1]. This activity forces winds and controls globally dynamics. There is much to be learned from studying the dynamics of the Outer Planets which lack the solid surfaces that drive orthographic waves on terrestrial planets, and have size scales that dwarf the Earth. At the same time, studies of atmospheric dynamics on the tenuous atmosphere of Mars and the dense opaque atmosphere of Venus offer atmospheric dynamisits a plethora of unique laboratories to test theories and models. However, to test those theories and models we require data. As stated initially, work of this nature has been growing over the years, but the build up of unique thermal datasets of jupiter's stratosphere is beginning to uncover fine details about Jupiter's dynamics and structure. Looking from today, forward 30-35 years into the 2050 time frame, one could imagine retrieving datasets from constellations of satellites orbiting any given planet in the Solar System, much like weather satellites at earth (i.e., an Earth style A-Train for Jupiter). The question is not are the other planets interesting enough to warrant such attention, but how to overcome the technological hurdles that such missions currently pose.

We plan to report on some unique groundbased observations of Jupiter's atmosphere which show that even today we can retrieve detailed information that is revolutionary in the constraints it offers for current dynamical models. We will then look to ways of instrument miniaturization and simplification which could allow such measurements to be made from orbiting spacecraft. However, even with building such an instrument we will run into further issues such as instrument cooling to increase sensitivity, data downlink restrictions, radiation hardening, and powering such instruments, especially those orbiting the outer planets so far away from the sun. Additional issues include solutions to accurate position knowledge of both the spacecraft and the observed features in the atmosphere (the need for global positioning satellites for all of the planets). While some of these things may sound like dreams now, we believe all of the individual hurdles have solutions. Only by acknowledging the need for research to overcome these hurdles will we then focus our attention to solving them. Just imagine a future where we would be able to produce daily weather predictions for not only Earth, but also for Venus, Mars, Jupiter, Saturn, Uranus, and Neptune.

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A FUTURE MARS ENVIRONMENT FOR SCIENCE AND EXPLORATION.

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Introduction: Today, Mars is an arid and cold world with a very thin atmosphere that has significant frozen and underground water resources. The thin atmosphere both prevents liquid water from residing permanently on its surface and makes it difficult to land missions since it is not thick enough to completely facilitate a soft landing. In its past, under the influence of a significant greenhouse effect, Mars may have had a significant water ocean covering perhaps 30% of the northern hemisphere. When Mars lost its protective magnetosphere, three or more billion years ago, the solar wind was allowed to directly ravish its atmosphere.[1] The lack of a magnetic field, its relatively small mass, and its atmospheric photochemistry, all would have contributed to the evaporation and loss of its surface liquid water over time.

The Mars Express and MAVEN missions have determined that Mars has been losing a significant amount of atmosphere due to the direct solar wind interaction with the exosphere, ionosphere, and upper atmosphere, in part, since it no longer has a magnetic field providing an important standoff distance or buffer with the planets atmosphere. MAVEN observations have shown two major escape channels for charged particles: 1) over the northern polar cap involving higher energy ionospheric material, and 2) in the equatorial zone involving a seasonal low energy component with as much as 0.1 kg/s escape of oxygen ions.[2] The atmospheric loss into the solar wind is somewhat balanced by the outgassing of the Mars interior and crust that contributes to the existing atmosphere leading to a surface atmosphere of about 6 mbar pressure.[3]

Future Vision: A greatly enhanced Martian atmosphere, in both pressure and temperature, that would be enough to allow significant surface liquid water would also have a number of benefits for science and human exploration in the 2040s and beyond. Much like Earth, an enhanced atmosphere would: allow larger landed mass of equipment to the surface, shield against most cosmic and solar particle radiation, extend the ability for oxygen extraction, and provide "open air" greenhouses to exist for plant production, just to name a few. These new conditions on Mars would allow human explorers and researchers to study the planet in much greater detail and enable a truly profound understanding of the habitability of this planet. If this can be achieved in a lifetime, the colonization of Mars would not be far away.

Approach: The investigation of a greatly enhanced atmosphere of higher pressure and temperature on Mars can be accomplished through the use of a number of existing simulation tools that reproduce the physics of the processes that model today's Martian climate. A series of simulations can be used to assess how best to largely stop the solar wind stripping of the Martian atmosphere and allow the atmosphere to come to a new equilibrium.

Models hosted at the Coordinated Community Modeling Center (CCMC) are used to simulate a magnetic shield, and an artificial magnetosphere, for Mars by generating a magnetic dipole field at the Mars L1 Lagrange point within an average solar wind environment. The magnetic field will be increased until the resulting magnetotail of the artificial magnetosphere encompasses the entire planet as shown in Figure 1. The magnetic field direction could also maintain an orientation that keeps it parallel with the impinging solar wind interplanetary field thereby significantly reducing mass, momentum, and energy flow into the magnetosphere and thus also damping internal magnetospheric dynamics. This situation then eliminates many of the solar wind erosion processes that occur with the planet's ionosphere and upper atmosphere allowing the Martian atmosphere to grow in pressure and temperature over time.

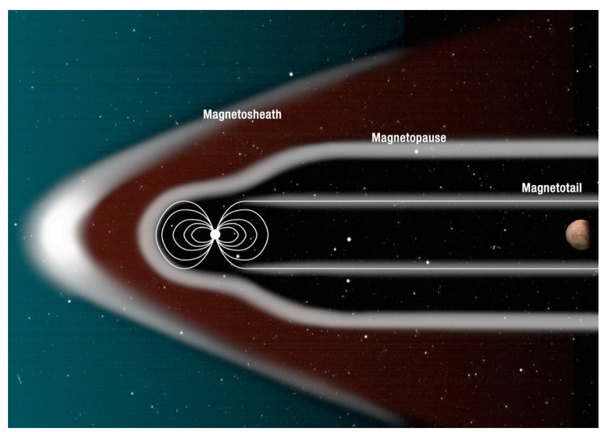

Figure 1: An artificial magnetosphere of sufficient size generated at L1 allows Mars to be well protected by the magnetotail.

This may sound "fanciful" but new research is starting to emerge revealing that a miniature magnetsphere can be used to protect humans and spacecraft.[4] This new research is coming about due to the application of full plasma physics codes and laboratory experiments. In the future it is quite possible that an inflatable structure(s) can generate a magnetic dipole field at a level of perhaps 1 or 2 Tesla (or 10,000 to 20,000 Gauss) as an active shield against the solar wind.[5]

The Mars Climate Modeling Center (MCMC) is used to simulate Mars climate changes by running a variety of "bulk" atmospheric and environmental characteristics for Mars Global Circulation Model (GCM) simulations with increasing CO_2 and other trace gases masses. Currently the MCMC is perfecting the radiative-transfer (RT) module/code to handle increasing atmospheric mass and are getting close to having much tighter energy conservation needed for the modeling of this type. Specific runs are made with global mean surface pressures for 10, 50, 100, 500, and 1000 mbar conditions. It is expected that over these ranges in pressure the average temperature of Mars will increase at each step. The composition of the additional atmosphere is based on MAVEN observations of losses to the solar wind and potentially by new results of trace gases (some of which are greenhouse gases) that may also arise over time from observations by ESA's Trace Gas Orbiter.

Expected Results: It has been determined that an average change in the temperature of Mars of about 4^{o}C will provide enough temperature to melt the CO_2 veneer over the northern polar cap. The resulting enhancement in the atmosphere of this CO_2, a greenhouse gas, will begin the process of melting the water that is trapped in the northern polar cap of Mars. It has been estimated that nearly 1/7th of the ancient ocean of Mars is trapped in the frozen polar cap. Mars may once again become a more Earth-like habitable environment as shown in Figure 2. The results of these simulations will be reviewed and a projection of how long it may take for Mars to become an exciting new planet to study and to live on.

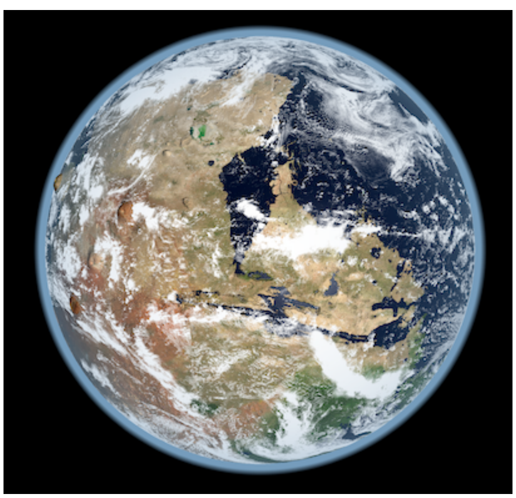

Figure 2: A future Mars protected from the direct solar wind should come to a new equilibrium allowing an extensive atmosphere to support liquid water on its surface.

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ASTRONAUT-DEPLOYABLE GEOPHYSICAL AND ENVIRONMENTAL MONITORING STATIONS.

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Introduction: When the Apollo astronauts landed on the Moon, they deployed a series of science experiments at their landing sites. Combined, these instruments formed the Apollo Lunar Science Experiments Package (ALSEP), which consisted of seismometers, magnetometers, and various instruments to measure the solar wind and charged particles [1]. We expect future astronauts exploring Mars, its moons, asteroids, and the Moon will deploy similar, but more sophisitcated autonomous instrument packages to study and monitor the environment and geophysical properties of the landing site region. Additionally, the longer expected duration of future human missions, relative to Apollo, present the opportunity for astronauts to build up a large *network* of instruments throughout a wide region, enhancing both the scientific return of the instruments and providing advance notice of potentially hazardous events (e.g., martian dust storms) approaching their location. This abstract presents conceptual ideas for future astronaut-deployable Geophysical and Environmental Monitoring Stations (GEMS).

GEMS Concept: Geophysical network science has been rated as high priority for both the Moon and Mars [2]. On Mars, a meteorological network could better study regional scale phenomena such as dust storms and water transport. Seismological networks on both worlds would help study their interiors and localize seismological sources such as quakes or recent impacts. Thus, network science is a driving element in the GEMS concept. Astronauts would be equipped with a substantial number of GEMS units that could be deployed at will during a traverse. Large-scale production of GEMS units would reduce per-unit cost. Over the lifetime of a landed mission (weeks to possibly 1 Mars year), a dense and broad network of GEMS units could be deployed. Such a network would be robust against loss or failure of individual units. Networked monitoring stations have wide applications terrestrially: monitoring severe weather to protect life and property [3], seismic monitoring [4], and conducting targeted scientific studies [5]. A concept GEMS network is shown in Figure 1.

To simplify deployment, which would both foster a more dense network of GEMS units and be safer and simpler for the astronauts, the GEMS units could be carried on the exterior of the astronaut's rover in a "magazine". At set intervals along a traverse, the rover could briefly stop and deploy a GEMS unit with the rover's manipulator arm. After turning on the unit, radioed commands would deploy the solar panels and instruments and perform a communications check. Then the astronauts could proceed upon their traverse and continue to deploy GEMS units without needing to don their suits and perform an extravehicular activity (EVA).

We present a concept drawing of a GEMS unit on Mars in Figure 2. The GEMS unit is box-shaped, with fold down solar panel "wings", a radio antenna, and possibly masts to extend or deploy instrumentation.

Instrumentation: GEMS instrumentation will be tailored to the world that the astronauts will land upon and the scientific goals of the mission. On Mars, meteorological sensors would be included on each GEMS unit. The Rover Environmental Monitoring Station (REMS) instrument [6] onboard the Mars Science Laboratory (Figure 3) represents a useful initial baseline for such a suite of air pressure, wind, and temperature (both ground and air) sensors and they will be largely reflown for both the InSight mission and Mars2020 rover [7]. Sensors to meaure atmospheric optical depth, as will be included on the Mars2020 Mars Environmental Dynamics Analyzer (MEDA) instrument, would also be valuable for scientific and astronaut-safety purposes. For worlds without atmospheres (the Moon and asteroids), meteorological insturments would be replaced with instruments to measure solar wind flux and charged particles. Geophysical instruments, such as seismometers and subsurface heat-flow, would be scientifically valuable on all worlds likely reached by astronauts in the next 35 years.

Conclusion: Human exploration of space will hopefully reach Mars, the Moon, and nearby asteroids in the next 35 years. To perform their scientific studies, a suite of instruments must be designed, built, and tested long before the first mission is launched. Astronaut-deployable GEMS networks would autonomously collect a wealth of data while also enhancing astronaut safety.

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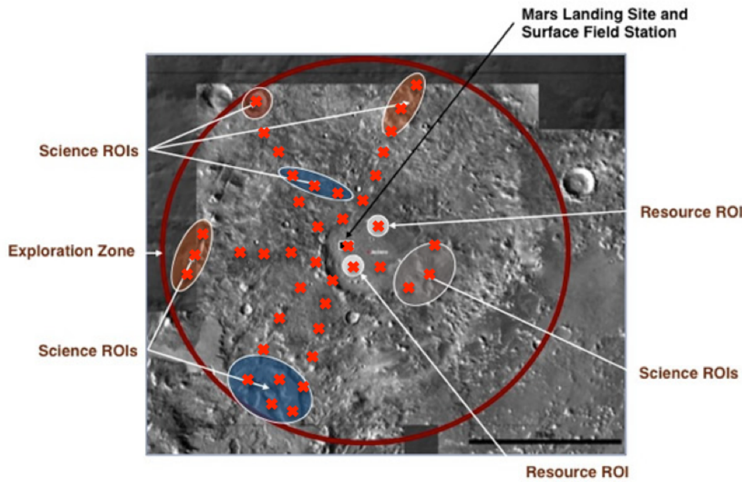
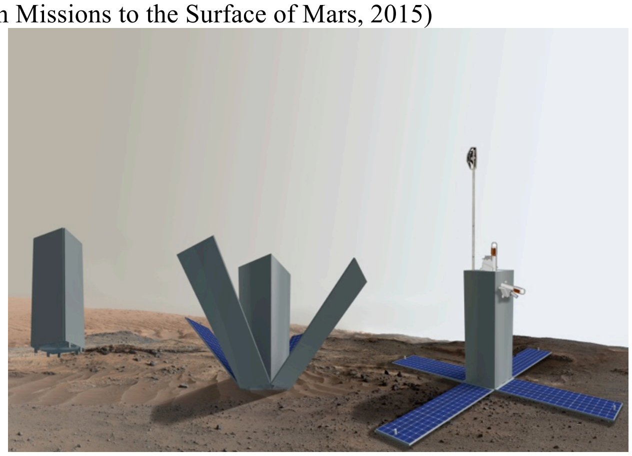
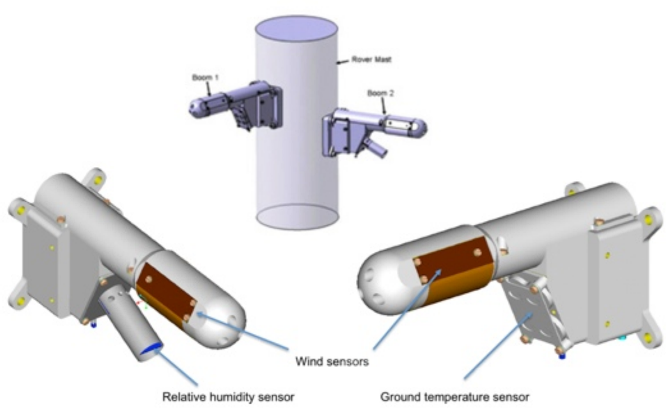


1. GEMS units (red X's) are deployed along astronaut traverse routes to scientific regions of interest (ROIs) and create a wide network in this concept image of a Mars exploration zone (NASA First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars, 2015)



2. Concept image of a GEMS unit unfolding and deploying sensors on the martian surface.



3. The REMS sensor booms, containing temperature (air and ground), humidity, and wind sensors, are attached to the mast of the Curiosity rover [6].

THE NASA REGIONAL PLANETARY IMAGE FACILITY NET OR : A GLOBALLY DISTRIBUTED RESOURCE FOR THE PLANETARY SCIENCE COMMUNITY.

J. J. Hagerty[1], P. Mouginis-Mark[2], P. H. Schultz[3], D. A. Williams[4], and the Directors of the RPIF Network, [1]USGS, Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ email: jhagerty@usgs.gov; [2]Hawaii Institute Geophysics and Planetology, University of Hawaii, Honolulu, HI; [3]Brown University, Providence, RI; [4]School of Earth and Space Exploration, Arizona State University, Tempe, AZ.

Introduction: NASA's Regional Planetary Image Facilities (RPIFs) comprise a network of planetary data and information centers located throughout the United States, in Canada, and overseas. The U.S. locations are currently co-funded by NASA and their host institutions [1]. Each US RPIF is heavily leveraged by significant institutional support (matching NASA dollars more than 1:1). A network of these facilities was established in 1977 to "maintain photographic and digital data as well as mission documentation. Each facility's general holdings contain images and maps of planets and their satellites taken by NASA Solar System exploration spacecraft. These planetary data facilities, which are open to the public, are primary reference centers for browsing, studying, and selecting planetary data including images, maps, supporting documentation, and outreach materials. Experienced staff at each of the facilities can assist scientists, educators, students, media, and the public in obtaining materials for their own use" [2].

The network of RPIFs has expanded to nine U.S. facilities and seven facilities in other countries. The first RPIF to be established outside of the U.S. was in the United Kingdom in 1980, at University College London (UCL), and since then RPIFs have been set up in Canada, France, Germany, Israel, Italy, and Japan. Through its longevity and ability to adapt, the RPIF Network has leveraged its global reach to become a unique resource covering 60 years of international planetary science.

Historically the Network nodes have had an institutional focus, whereby they provided resources to local and regional clients, and communicated with other nodes only when the need arose. Using this methodology, the nodes of the RPIF Network, hereafter referred to as RPIFN, have combined to serve an average of ~65,000 people per year since 2000. However, with the advent of simpler and more wide-ranging forms of data transfer and data sharing, our aim is to allow the nodes to operate together to provide the planetary science community and the public with greater access to 1) archived and derived mission products (e.g., maps, photographs, films, documents, and spatial data infrastructure); 2) mission-enabling documentation and software (e.g., data on previous mission design, development, implementation, and evaluation); 3) science and public research and training support for complex mapping software, and 4) outreach experiences and capabilities and resident expertise in planetary resources. Each node of the Network has unique capabilities and resources that meet one or more of the above criteria; however, by linking the nodes through a collaborative Network, it is now possible to provide a more diverse array of materials to a wider array of users, especially to those in the planetary science community.

Continuing Efforts: The role of the RPIFN is evolving as the volume and complexity of planetary data sets continues to increase. Instead of trying to compete with vast array of materials housed in digital servers (i.e., the PDS, whose goal is to focus on serving more technically oriented NASA-funded users), *the RPIF Network will serve as a valuable resource for specialized knowledge and services that will make it possible to remove the barriers associated with locating, accessing, and exploiting planetary science data, particularly derived data products. The goal of the Network is to provide support and training to a broad audience of planetary data users.*

The RPIF Network nodes will continue to serve as reference and training centers that are needed for preserving and accessing derived products from past, present, and future Solar System exploration missions. In an effort to meet the planetary science community's evolving needs, we aim to achieve the following primary objectives:

1. Maintain and improve the foundation that has been established over the past four decades so as not to lose critical, historical information and to meet the Federal mandate for data discovery and transparency [i.e., 3]. This goal will be aided by a systematic effort to scan and digitize fragile materials as a means of increasing access and preserving the materials.
2. Help users to locate, access, visualize, and exploit planetary science data. In an effort to make this possible, RPIF personnel are being trained in the use of common planetary data sets and processing tools such that they can assist researchers with locating and using planetary data. Many of the facilities have begun to establish Guest User Facilities that allow researchers to use and/or be trained on GIS equipment and software as well as other specialized equipment like SOCET SET/GXP workstations. Another tool that is being used in this effort is the Magic Planet data visualization system from Global Imagination. Each US facility as well as the UK facility, now has one of these globes, which will

make it easier for researchers to visualize and work with global remote sensing data sets.

3. Improve the connection between the Network nodes while also leveraging the unique resources of each node. To achieve this goal, each facility will develop and share searchable databases of their entire collections, enhanced by the development of robust metadata.
4. Communicate more effectively and regularly with the planetary science community in an effort to learn more about the needs of the community and in turn to improve the resources and services provided by the Network.
5. Provide a regional training resource for planetary data for the entire planetary science community, as well as colleges, universities, museums, media, and the general public. The global distribution of the RPIFN nodes makes it possible and feasible to reach and train all of the aforementioned users.
6. Introduce new strategies for visualizing planetary data and products (e.g., 3D printing and virtual reality platforms/experiences).

By achieving these objectives, we will introduce new users to data products from past, current, and new missions. The underlying premise of data needs for users of the RPIFN (whether hard copy or digital) is that research and discovery does not end with each mission, but continues for generations to come. As such, the RPIFN provides the bridge between generations as one phase of exploration ends and another begins.

Over the next several decades the RPIF Network will continue its traditional service as a source of derived data products and expand its reach through new technologies by training users on the importance and applicability of critical data sets required for investigating the workings of the Solar System. New initiatives in data visualization and use will make valuable resources that much more accessible and will provide a mechanism for long term preservation and access as required by the Federal government [i.e., 3]. By leveraging the expertise and resources of the RPIF Network, NASA will be able to make the exciting new discoveries of planetary science more widely available, which will allow the Network to better serve NASA, the planetary science community, and the general public.

For more information, or to request materials, please contact any of the RPIFs listed below. Additional, detailed information can also be found at http://www.lpi.usra.edu/library/RPIF.

RPIFN to : In the coming decades leading to 2050, we expect that NASA (either by itself or in collaboration with international partners) will establish a permanently-crewed base on the Moon, for scientific exploration of the Moon, and in collaboration with the commercial sector) for economic exploitation of lunar resources. Additionally, commercial entities will begin exploration and utilization of resources from Near Earth Asteroids (NEAs), and NASA (with or without international partners) will begin the human exploration, and possible colonization/economic development of Mars. In all cases, various entities conducting this new era of human exploration will require derived data sets from earlier NASA planetary missions, of the surfaces of planetary surfaces to support their activities. We will strive to ensure that the RPIFN is the "go to" source of NASA-derived digital data products of the surfaces of all the terrestrial planets, outer planet satellites, dwarf planets, and small bodies including NEAs, to enable both scientific study and economic utilization of the surface of these objects by both government and non-governmental entities.

We also anticipate that virtual reality technology and experiences will continue to evolve and will potentially become integral tools in exploring and understanding the Solar System. In fact, virtual reality may be the most practical means for allowing future researchers to interact with and analyze data in five dimensions (i.e., x, y, z, time, and wavelength). As such, we envision the RPIFN serving a key role in developing and providing access to virtual reality laboratories (i.e., having lab space at each of the globally distributed RPIFN nodes) where planetary scientists, students, and the public can virtually walk on and interact with other planetary surfaces. 3D printing will also likely be closely tied to virtual reality experiences such that users can print aspects of their virtual experiences for further future evaluation. As such, we will also continue to build and improve upon cutting edge 3D printing capabilities to provide a long lasting and portable tangible aspect to virtual exploration experiences.

Acknowledgements: The U.S. nodes of the RPIF Network are supported by NASA (historically through the Planetary Geology and Geophysics Program) as well as by leveraging funds from host institutions.

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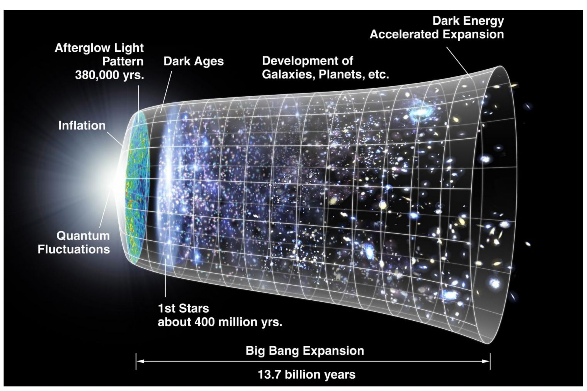
SEARCH FOR LIFE IN THE SOLAR SYSTEM AND BEYOND: A UNIFYING VISION FOR NASA SCIENCE THROUGH 2050. Heidi B. Hammel[1], Matt Mountain[1], and John M. Grunsfeld[2]. [1]AURA, 1331 Pennsylvania Avenue NW, Suite 1475, Washington, DC 20004; [2]NASA, emeritus.

Introduction. The frontiers of science today are intriguing and inspiring; grand discoveries await. We hold, today, a world-view that no generation has possessed before, whether we use it to explore the diverse array of worlds within our Solar System and beyond, to concentrate on the complexities of climate change, or to unravel the intricacies of life itself.

The Endless Frontier. We have arrived at this point in human history in no small part because of the vision set forth in 1946 by Vannevar Bush in "*Science, the Endless Frontier*" [1], and the subsequent commitment made by the United States to the scientific enterprise. As Vannevar Bush wrote, "without scientific progress no amount of achievement in other directions can insure our health, prosperity, and security as a nation in the modern world." His vision continues to resonate today with its prescience.

Because of decades of investment in America's portfolio of fundamental research, we now know the story of our Universe, and our evolution within it, to incredible detail. We know the Universe's age to better than 2%. We have measured the basic constituents of matter to unprecedented precision. We have seen the gravitational signature of two merging black holes with LIGO. And, through genetic analysis, we know that life likely emerged from a common singled-celled ancestor some 3.5 billion years ago.



Our generation revealed the remarkable story of our Universe across 13.7 billion years of cosmic history, from cosmic birth to our living Earth. Initial quantum fluctuations, through the growth of space and time, led to 100 billion galaxies. In one of those galaxies, on one small blue planet circling one of the 200 billion stars within that galaxy, RNA and DNA emerged. After a complex series of events, a species emerged that today looks out into this vast universe with unique tools and asks, "are we alone?"

Mystery Most Profound: Are We Alone? Yet the scientific frontier still holds many secrets, of which perhaps most profound for our species is: can we causally relate the Big Bang to the emergence of RNA and DNA? Can we tell the story of how life emerged, and whether that event was unique?

Today, we suspect that habitable environments may exist in many places within our own Solar System. And within our own galaxy alone, there are more than 200 billion stars with at least 100 billion planets. Yet we still have no way to calculate the probability whether life would emerge on all those worlds and their countless moons, or only one (ours). When the eminent evolutionary biologist E.O. Wilson was asked at a public lecture in 2012 what was "the most important experiment in evolutionary biology," he replied, "the search for extraterrestrial life." [2]

Plurality of Worlds and Plurality of Sciences. By 2050, the search to determine if we are alone within our Universe must take us to the surface of Mars and to the salty ocean under the icy crust of Jupiter's moon Europa. *In situ* explorations of Saturn's moon Titan will offer a glimpse of how the early pre-biotic Earth may have looked: what lurks in its hydrocarbon seas, fed by its methanological weather cycle?

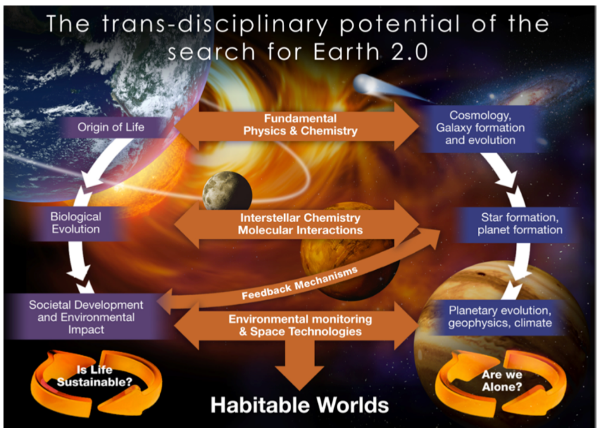
To be comprehensive, our quest for life elsewhere must also include Saturn's moon Enceladus. We must explore Neptune's active moon Triton, the fresh ice floes on the distant double-planet Pluto-Charon, the salty spires on Ceres, and many other places in our Solar System. These explorations are the purview of NASA's Planetary Science Division.

The search for life requires, as well, deep understanding of the influence of our star, the Sun, on our climate and on living ecosystems within our Solar System. It will require the careful assessment of the activity of our Sun and its impact not only now, but on the nascent Earth and other potentially habitable environments. This expertise is found in NASA's Heliophysics Division.

Our search for life elsewhere drives us to the remote sensing of planets around other stars. Just as we study our Sun to learn the story of life here, we will need to carefully assess the affects on habitability of other stellar classes. We must also assess Sun-like stars at other stages of life to assess the impact on the formation and evolution of our habitable environment. Evermore sophisticated telescopes and techniques will permit us to directly detect and evaluate the atmospheres and environments on planets around other stars. This is the realm of NASA's Astrophysics Division.

Cross-Disciplinary Science is Key to Success. As we see, a true search for life elsewhere requires a multi-dimensional space where scientists, technologists, engineers, entrepreneurs and educators will jointly collaborate, explore, and innovate.

Such multi-dimensional exploration is the hallmark of the modern scientific endeavor, whether the effort to combat cancer, or the revolution sought by the Brain Initiative, or the creation of a societal response to climate change.



While this "search for life" endeavor provides a unifying theme across the NASA Science Division, we must acknowledge that this grand challenge is not limited to NASA. True expertise in the fundamentals of life lies in the arenas of biology, biophysics, fundamental chemistry, geodynamics, planetary physics, and many more fields.

The search for life beyond Earth links the central efforts of a manifold of Federal investments in science, including NASA, NSF, NOAA, USGS, DOE Office of Science, and NIH.

This is what a great society can do: we can craft common quests that propel us forward on the path across the endless frontier of science, including the great challenge of the search for life beyond Earth.

Finding life elsewhere defines a frontier that can only be traversed with sophisticated inquiry and unique observations. It requires an investment that only our federal government, in partnership with the international community, can plausibly make. It requires all facets of the NASA portfolio, from science to launch vehicles, to human spaceflight.

Summary. To return to where we started, with Vannevar Bush: "It has been basic United States policy that Government should foster the opening of new frontiers. It opened the seas to clipper ships and furnished land for pioneers. Although these frontiers have more or less disappeared, the frontier of science remains. It is in keeping with the American tradition - one which has made the United States great - that new frontiers shall be made accessible for development by all American citizens."

The search for life beyond the confines of Earth defines a frontier that our generation—for the first time in human history—can cross.

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Exploration Pathways for Europa after initial In Situ Analyses for Biosignatures. K. P. Hand[1], A. E. Murray[2], J. Garvin[3], S. Horst[4], W. Brinkerhoff[3], K. Edgett[5], T. Hoehler[6], M. Russell[1], A. Rhoden[7], A. Yingst[8], C. German[9], B. Schmidt[10], C. Paranicas[11], D. Smith[12], P. Willis[1], A. Hayes[13], B. Ehlmann[1,14], J. Lunine[13], A. Templeton[15], K. Nealson[16], M. Cable[1], K. Craft[11], R. Pappalardo[1], C. Phillips[1], [1]Jet Propulsion Laboratory, Caltech (khand@jpl.nasa.gov, [2]Desert Research Institute & Univerity of NV, Reno, [3]Goddard Space Flight Center, [4]Johns Hopkins University, [5]Malin Space Science Systems, [6]NASA Ames Research Center, [7]Arizona State University, [8]Planetary Science Institute, [9]Woods Hole Oceanographic Institute, [10]Georgia Tech., [11]Applied Physics Laboratory, Johns Hopkins, [12]Massachusetts Institute of Technology, [13]Cornell University, [14]Caltech, [15]CU Boulder, [16]University of Southern California.

Introduction: The 2016 Europa Lander Science Defintion Team has recently completed its report on the science goals, objectives, and investigations to be conducted by a robotic lander on Europa's surface. The highest priority goal is to search for signs of life through in situ analyses of Europa's surface and near-surface material. The second and third goals focus on assessing Europa's habitability, and conducting analyses that will make subsequent missions possible.

Several possible futures exist for the exploration of Europa, contingent on the outcome of of the search for signs of life. Were biosignatures to be found in the surface material, direct access to, and exploration of, Europa's ocean and liquid water environments would be a high priority goal for the astrobiological investigation of our solar system. Europa's ocean would harbor the potential for the study of an extant ecosystem, likely representing a second, independent origin of life in our own solar system. Subsequent exploration would require robotic vehicles and instrumentation capable of accessing the habitable liquid water regions in Europa to enable the study of the ecosystem and organisms. Planetary protection and forward contamination of Europa would be a driving design requirement. Much of this exporation would be targeted along the z-axis, moving into Europa ice and ocean.

Absent any signs of life discovered during the initial landed mission, the question of Europa's habitability and comparative oceanography would be key motivating questions for the future exploration of Europa. Subsequent missions would potentially be designed to enable lateral (x-y plane) exploration to better understand fundamental geological and geophysical process on Europa, and how they modulate exchange of material with Europa's ocean. The definive determination of no life on Europa would be difficult to prove, but a null-result for life on Europa would potentially be as scientifically important as the discovery of life on that world. Both answers have profound implication for understanding life on Earth and our place in the universe.

SUSTAINABLE POLICY SOLUTIONS FOR SPACE SETTLEMENT. J. Haqq-Misra, Blue Marble Space Institute of Science, 1001 4th Ave Suite 3201, Seattle WA 98154, jacob@bmsis.org.

Introduction: Elon Musk's ambitious plan for sending humans to Mars is becoming increasingly technologically feasible. Efforts by SpaceX, Deep Space Industries, Planetary Resources, and other private space corporations now fall in rank with government space agencies such as NASA, ESA, JAXA, IRSO, RFSA, and CNSA. Many of these private and government entities are developing successive plans to visit asteroids or Mars in the coming decades, which are beginning to show prospects for economic gain in addition to scientific return. These recent developments all suggest that Musk's vision of our civilization becoming a 'multiplanetary species' could be realized in the coming century.

Technological advances that will allow humans to settle on another planet or extract resources from planetary bodies must be matched by parallel advances in our civilizational ethics. The 'problem of the commons' articulated by ecologist Garret Hardin [1] and others (e.g. [2]) is at the root of many of our systemic global problems. Hardin argues that solving the population crisis "requires a fundamental extension in morality," while similar arguments can be made about failed efforts to address climate change, poverty, and other sustainability issues on a global scale. The lack of moral progress risks the danger of perpetuating this problem of the commons and other harmful colonial attitudes as our civilization ventures in to space. We need to invest in developing our ethics in tandem with our technology prior to the establishment of space settlements.

Space settlement itself provides a rich source of transformative experiences that hold the potential to radically alter our personal and collective morality. Transformative experiences have guided the development of civilization and led humanity toward new ways of thinking, often by forcing us to confront the nebulous boundary between self and environment [3,4,5]. Transformative events challenge our core preferences and force us to conceptualize new perspectives that would have been otherwise impossible. The first step of a human on Martian soil will carry incalculable transformative value, as will the first arrival of a mining team on a nearby asteroid. Although we cannot predict the mode of transformation that will occur when humans settle on Mars, we can learn from our own history in order to maximize the transformative potential of space settlement.

Indeed, history is rife with examples that show the destructive patterns that emerge from colonialism, and an unabated program of space colonization risks the loss of any transformative potential. International agreements, such as the Outer Space Treaty of 1967, remain silent or ambiguous on issues pertaining to sovereignty and land use for space settlement. The need for new international agreements pertaining to space policy stems from the origin of the Outer Space Treaty in a Cold War era rife with paranoia for military and espionage dominance of low-Earth orbit [6,7]. Contemporary ambitions for human space exploration from private and national agencies are conceivably at odds with international agreements that were drafted in a time before humans had even set foot on the moon.

Rather than repeat colonial patterns of history, I suggest that the goal of space settlement should be to strive after new experiments in civilization that will provide inspiration for new modes of valuation. Here I describe two policy solutions for space settlement: bounded first possession with planetary parks [8] and a sovereign or 'liberated' Mars [9]. I discuss the strengths and weaknesses of these ideas in light of existing international agreements and provide a direction for further research on space settlement policy.

Bounded First Possession with Planetary Parks: The policy for space settlement developed by Bruhns & Haqq-Misra [8] draws upon the first possession principles suggested by [10] and the planetary parks system suggested by Cockell & Horneck [11,12]. A 'bounded first possession with planetary parks' approach to Mars settlement would allow space agencies to make bounded claims on a planetary surface with limited claim to 'exclusive economic zones' based upon first arrival, with inspiration from the successful aspects of the Law of the Seas. A planetary park system would also be established by the global intellectual community to protect select nature reserve and heritage sites, which would be reviewed in a process similar to NASA's decadal survey. This approach would allow for both commercial and national use of space resources while still maintaining the spirit of the Outer Space Treaty that prevents national appropriation of celestial bodies.

Drawing upon successful and unsuccessful examples of cooperative sovereignty [13] from history, we find that international agreements with required equitable sharing and new forms of strong central authority will likely fail when applied to space settlement. (The Moon Treaty of 1979 is an example of one such failed attempt.) This suggests that a 'World Space Agency' model (e.g. [14,15]) may be an inadequate solution for space settlement today. We instead suggest a weak coordinating administrative body dubbed the 'Mars Secretariat' and modeled after the Antarctic Treaty Secretariat that exists today. A Mars Secretariat would provide administrative support and a mode of conflict resolution for national and corporate settlements.

A model of bounded first possession with planetary parks remains technically consistent with the Outer Space Treaty by drawing a distinction between 'appropriation' of celestial bodies (which is forbidden) and 'exclusive economic zones.' But further discussion of this policy in the context of international agreements, including the possibility of amendment of the Outer Space Treaty, needs to be examined in greater detail.

The Sovereign Mars Approach: The idea developed by Haqq-Misra [9] provides a more idealistic policy for Mars settlement that seeks to establish Mars as a sovereign entity prior to the arrival of the first humans. This suggestion to 'liberate Mars' in advance of settlement is effectively a prescription for artificially constructing a nation-state by design. Settlements on Mars will exhibit their own unique populations, territory, and governance, thereby satisfying three of the four conditions for statehood. The sovereign Mars approach suggests that designing Mars as sovereign would retain the greatest transformative potential for space settlement.

Under the provisions of a sovereign Mars, Humans arriving on Mars would embrace a planetary citizenship as martians and relinquish their status as earthlings. Property and other power tied to Earth must also be relinquished, and no entity on Earth may exert any influence on the development of civilization on Mars (aside from the pursuit of mutual scientific endeavors between martians and earthlings). The use of land is determined exclusively by the resident martians, and any objects brought from Earth to Mars become permanent fixtures of the martian civilization. The goal of a sovereign or liberated Mars would be to establish a second instance of civilization that can avoid some of the pitfalls of colonialism from history. This would allow for new experiments in governance, economics, artistic expression, community, culture, spirituality, and other aspects of human life.

The Sovereign Mars model remains consistent with the Outer Space Treaty as written today. Allowing humans to develop Mars as an independent sovereign entity would remain consistent with the Treaty's provision against appropriation as well as the requirement that space be the province of all humankind. However, there is limited historical precedent for abandoning one's national citizenship entirely; further work remains on defining a process by which planetary citizenship can be defined and recognized. Additionally, the success of a sovereign Mars will require tremendous financial foresight by a donor or group willing to invest in the distant future of humanity. Further work should also examine the concept of 'deep altruism' that could allow such a bold endeavor to succeed.

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ACHIEVING VISIONARY PLANETARY SCIENCE GOALS WITH DEEP SPACE CUBESATS.
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Introduction: Success rates and mission lifetimes for Earth orbiting CubeSats have been improving over the last 5-10 years. Instrument payloads are also becoming more sophisticated, enabling novel science investigations from the CubeSat platform. These developments have been made possible through continued investment from NASA, universities and private industry [1,2]. The growing success of CubeSats in Earth orbit has led to additional investments into the development of deep-space interplanetary CubeSat missions (MarCO, Flashlight, Lunar IceCube, NEA-Scout, LunaH-Map, BioSentinal) by NASA SMD and STMD [3,4,5,6,7,8]. The programs under which these missions were selected are currently funding very important developments in new CubeSat technologies for deep-space exploration, including planetary science instrumentation, and continued investments will enable CubeSats to contribute to deep-space planetary science missions well into the 2050's. As with any new technology, deep-space CubeSat components and instrumentation will become more reliable and more capable with time, and like Earth orbiting CubeSats, success rates will improve with continued in-flight testing through increased launch opportunities. This is crucial for the success of future deep-space CubeSat missions.

There are a variety of challenges unique to planetary science CubeSat missions that will be tested for the first time in the near-future and will enable their use as tools of planetary science and exploration in the 2020's and 2030's. There are currently 8 deep-space interplanetary CubeSats scheduled to launch prior to 2020. These will all provide useful data on communications, propulsion, navigation systems, and radiation tolerance, in addition to achieving their science goals. There is significant interest from the planetary science community in sustained deep-space CubeSat programs, With continued support from NASA Science Mission Directorate there are likely to be opportunities to ride along with upcoming New Frontiers or Discovery class missions in the 2020s, 2030s and beyond. With this in mind, it is important to consider the current environment and the future of deep-space planetary science CubeSats, including cost/risk profiles, form factors, and launch opportunities.

CubeSat Philosophy/Vision for Planetary Science in 2020-2050

Launch Opportunities: The Space Launch System (SLS) Exploration Mission-1 (EM-1) launch vehicle, currently scheduled for launch in 2018, is carrying a deployer capable of launching 13 separate deep-space CubeSat missions after Orion separation. For this trend to continue, other launch vehicles should work to accommodate as many CubeSat payloads (in multiple form factors) as possible. More launch opportunities would enable iteration, improvements, and eventually improved reliability with each mission (successful or unsuccessful).

Cost/Risk: CubeSat low costs are driven in part by size but also by higher risk tolerance. The low cost creates a virtuous cycle: more opportunities, more diverse science portfolios, more access for communities not traditionally involved in planetary science. The CubeSat form factor was originally developed and iterated upon at universities, which enabled a lower cost of development and an acceptance of higher risk mission profiles. Maintainaing a similar low cost, high-risk profile for developing and flying deep-space CubeSats would enable continued innovation in a "learn-as-you-fly" approach. These developments will require a commitment to deep-space CubeSat development from the community and its stakeholders. This process is already underway with the first set of deep-space interplanetary CubeSats. Approximate costs for EM-1 CubeSats range from <\$10M to >\$20M, less than a typical single instrument on a larger scale planetary science mission. As established suppliers and providers of CubeSat components, subsystems and instrumentation stabilize, development costs can shrink and overall cost estimates will improve such that by the mid-2020s to 2030s estimating costs for deep-space CubeSat missions will be less speculative.

Rideshare: While the Orion capsule is bound for a lunar flyby, the SLS EM-1 CubeSat deployer is currently destined for heliocentric orbit. For lunar- or asteroid-bound CubeSats, this increases the ΔV requirement and imposes significant trajectory, navigation and design challenges in order to execute the mission with small, low thrust propulsion systems.

In the future, CubeSat mission designers, launch vehicle providers, and the primary mission stakeholders will need to work together to determine how best to accommodate secondary CubeSats on larger planetary science missions. No spacecraft is launch vehicle independent, but the work currently being done on LunaH-Map, Lunar IceCube, Lunar Flashlight and NEA Scout (all destined for lunar orbit or beyond) may lead to more flexibility from future CubeSats on launch vehicle and destination. The trade-off in this case is increased time spent in deep-space, as these missions require significant time to change their velocity in order to be captured at the Moon or to flyby their target. The launch vehicle/primary mission scenario with the lowest ΔV requirement for a secondary CubeSat mission would be to deliver the CubeSat into the desired orbit at the target planetary body. A CubeSat as a secondary mission, however, would ideally pursue a scientific goal that is significantly different from the primary spacecraft. This can impose significant mission design challenges, and will require a propulsive system to either change orbits, flyby or impact/land on the surface.

Enabling Technologies and Approaches: In addition to the maturation of CubeSat subsystems, the miniaturization of scientific instrumentation has been key for making deep-space CubeSats exciting platforms that enable answering planetary science questions. To date, CubeSat scientific instruments have mostly been either focused development efforts for a particular CubeSat mission or ancillary products of miniaturization for mass-constrained landed instruments. Dedicated focus on instrument miniaturization for CubeSat platforms would accelerate the process of creation of more capable instruments.

New propulsion technologies are available that provide sufficient ΔV for, e.g., insertion into elliptical Mars or lunar orbit, opening up new CubeSat mission possibilities for the next decade. Nevertheless, an ideal case for a planetary CubeSat mission is to be delivered into the desired orbit at the target planetary body by a parent craft. A CubeSat could enable certain measurements by the parent craft, e.g. bistatic radar, transmission spectroscopy. A secondary mission could also pursue a scientific goal that is significantly different from the primary spacecraft. This can impose significant mission design challenges, which must be balanced against the science return.

For future deep-space CubeSat missions, communications may be performed between the CubeSat and Earth via the primary spacecraft. This may impose restrictions on operations, and require CubeSats to be more autonomous than the primary spacecraft. Alternatively, continued investments in novel deployable antenna (and solar panels) will open up bodies further from the Earth as viable targets. If the number of planetary missions increases as the proportion of CubeSats grows, investments in ground networks on Earth to receive the signal may be required.

Form Factor: The current 6U standard is likely to become the smallest deep-space planetary science CubeSat form factor. MarCO, a 6U communications CubeSat that will perform a flyby of Mars, requires a relatively large volume for propulsion and a reflector array for direct to Earth communication, leaving little room for a science payload (MarCO is carrying a small camera). LunaH-Map, a 6U CubeSat launching on SLS, requires ~2U for propulsion, and more than 2U for the science payload in order to maximize the surface area of the detector, a neutron spectrometer. For LunaH-Map, a reflector array is not required since communication at lunar distances is possible with relatively small antennas via the DSN. For both MarCO and LunaH-Map, optical remote sensing is not the primary goal, therefore, large apertures do not need to be accommodated and overall spacecraft volume can be small (6U). Cubesats on the order of 12U in size or greater will be better equipped for carrying optical payloads or larger detector arrays.

Summary: Looking to the future, deep-space CubeSat missions may be best served by sticking to their risk-tolerant roots. If costs are kept low and regular launch opportunities can be maintained, high-quality science with CubeSat missions will be common in 2050. The possibilities for planetary exploration enabled by CubeSats are exciting, and mission designs that implement clever, risky methods for achieving high-quality science are well suited for the platform. CubeSats implementing more risk-tolerant mission strategies can enable high-resolution images, radar, spectral or nuclear remote sensing data that will complement data from the primary spacecraft or from previous missions. Furthermore, instrumented CubeSats that serve as penetrators, or soft-landers, onto planetary surfaces could help provide important constraints on orbital measurements, as well as time-resolved measurements of surface properties. Components for deep-space One of the biggest challenges will be to free deep-space CubeSats from parent craft, by independent management of radiation, power, and telecommunitions. Throughout the 2020's – 2050's, CubeSats will help enrich the scientific return from large planetary science missions by providing high-risk, high-reward complementary data to the primary spacecraft mission.

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WAYFARER: SMALL BODY EXPLORATION WITH A COMMON-FORMAT MICROSATELLITE.
W. M. Harris, D. E. Gaylor, and R. Furfaro, University of Arizona.

Introduction: There is a vast population of asteroids and comets with orbits that bring them into the inner Solar System and the vicinity of Earth. These *Near Earth Objects* (NEOs) have diameters of order from 10-10^4 m, and they are compositionally diverse. Their proximity to Earth makes them compelling targets for scientific study, but they are also important by virtue of their potential threat and as a source of resources for future space exploration. Over the past 30-years, spacecraft have experienced close-up encounters (flyby or co-orbital) with 12 asteroids and 6 Jupiter family comets (JFCs), revealing unexpected diversity in their shape, surface, and evolutionary characteristics (Fig. 1). The realization of planetesimals as distinct objects, even within the existing group classifications [1,2], has exposed many generalizations in our understanding of these objects.

Challenges: A logical next step in small body research is to explore the classification space indicated by the diversity identified to date. Such a study would need to adopt a statistical approach similar to that used to characterize comets and asteroids from the ground, and expand the types of objects (e.g. long period comets-LPCs) to those that have yet to be visited with spacecraft. However, the escalation in the rate of encounters implied by this goal is not consistent with the current mission model of custom, high capability, risk-averse spacecraft targeting single objects.

Implementation: In this presentation we describe the *Wayfarer* multi-encounter mission concept. *Wayfarer* incorporates features at the spacecraft and mission design levels that optimize it for low-cost exploration of objects in near-Earth orbital space. These include 1) a common architecture micro-spacecraft bus based on commercial components, 2) a limited suite of sensors that can be packaged for targeted explorations of small bodies, 3) unrestricted launch cadence with orbital storage, 4) flexible mission design (e.g. flyby, multi-target, co-orbit, impact), and 5) low-cost, university-based operations (Figure 2). The NEO/Comet *Wayfarer* implementation can be achieved using existing technology, but it is also intended as a pathfider for multi-spacecraft exploration of targets that are currently beyond the reach of independently operated microsatellites.

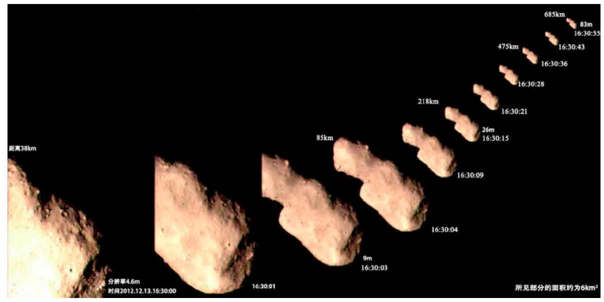

Figure 1. A sequence of images shows the encounter of 4179 Toutatis by the Chang'e spacecraft.

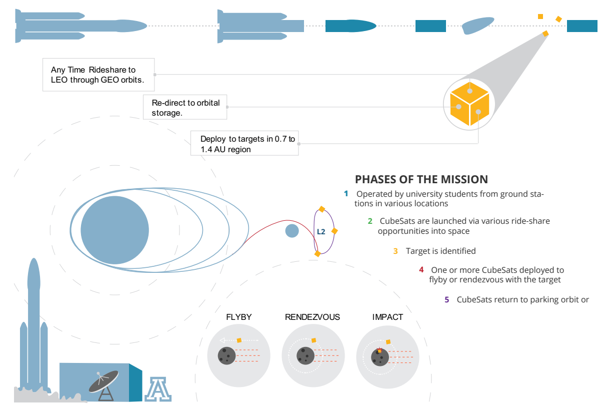

Figure 2. The phases of a *Wayfarer* mission, including luanch, storage, and multi-mission deployment.

SOLAR SYSTEM EXPLORATION WITH THE LARGE ULTRAVIOLET OPTICAL AND INFRARED SURVEYOR (LUVOIR).
W. M. Harris[1], B. E. Schmidt[2], and G. L. Villanueva[3] [1]University of Arizona-Lunar and Planetary Laboratory, [2]ASchool of Earth and Atmospheric Sciences-Georgia Tech, [3]NASA-Goddard Space Flight Center.

Introduction: LUVOIR will be a large aperture UV-Optical-IR space observatory capable of achieving revolutionary science goals highlighted in the NASA 2013 Astrophysics Roadmap "Enduring Quests, Daring Visions" and the recent AURA Report "From Cosmic Birth to Living Earths". The scientific aims of LUVIOR are being developed by the Science and Technology Definition Team (STDT) in the areas of Astrophysics, Exoplanets, Cosmic Origins, and the Solar System. Here we describe the scientific capabilities of a LUVOIR-class facility and their applicability to Solar System study. The Solar System panel of the STDT is assembling science cases that will be incorporated into the LUVOIR study-report to the Astro2020 Decadal Survey.

Observatory and Instruments: The preliminary design of the LUVOIR telescope includes a segmented aperture between 9 and 16 m in diameter with baseline wavelength coverage from 110 to 2500 nm. The facility would operate from an L2 orbit and be fully serviceable. The initial set of instruments includes

1) An optical-near infrared coronagraph.
2) A wide field imager.
3) A mulitp-resolution optical-near infrared spectrograph with multi-field capability.
4) An ultraviolet imager/spectrograph.

Science Development: The solar system science definition team for LUVOIR has been working to develop the science rationale and technical requirements for the proposed mission. This effort is subdivided into 5 areas including

1) The Sun-Planet Connection
2) Atmsopehric Dynamics and Composition
3) Icy Bodies at the Edge of the Solar System
4) Refractory and Active Small Bodies
5) Surfaces.

In this presentation we will describe the major findings of these sub-disciplines, how achieving the most compelling goals is enabled by the LUVOIR facility, and what capabilities must be incorporated.

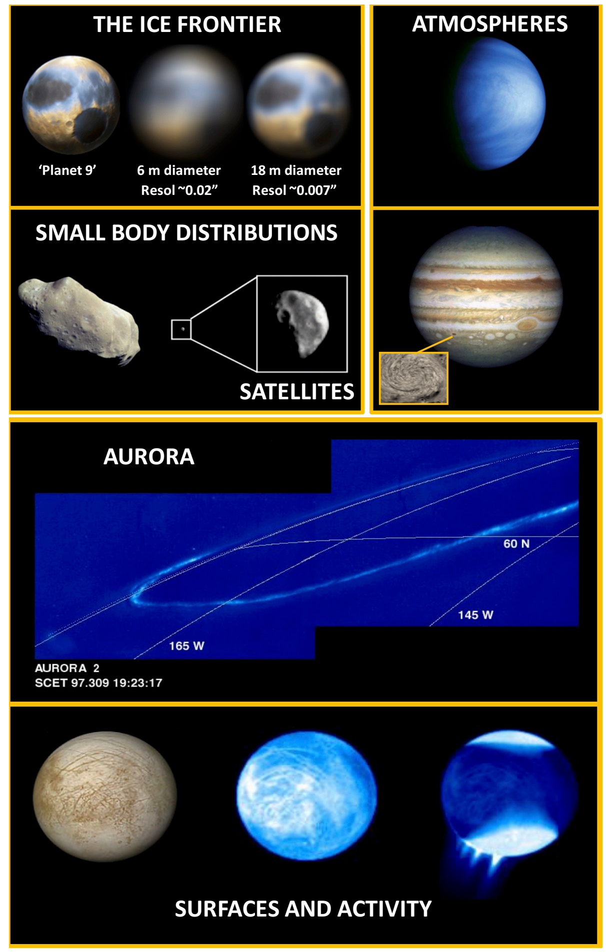

Figure 1. LUVOIR enabled Solar System Science.

PLANETARY HEAT FLOW MAPPING FROM ORBIT. P. O. Hayne[1], M. A. Siegler[2], D. A. Paige[3], T. Reck[1], S. Piqueux[1], [1]NASA – Jet Propulsion Laboratory, California Institute of Technology (Paul.O.Hayne@jpl.nasa.gov), [2]Planetary Science Institute, [3]University of California, Los Angeles

Introduction: Heat flow is a fundamental quantity in planetary science, because it is a signature of a body's formation, interior structure, and dynamics [1]. Primordial materials forming the planets and their satellites produce heat through gravitational accretion and radioactive decay. Heating may be sufficient to initiate convection and interior differentation into a core, mantle, and crust. On Earth, heat flow is spatially variable due to crustal composition, plate tectonics, and volcanism. On the Moon, segregation of radiogenic elements in the crust, particularly the nearside Procellarum terrane, may have also resulted in spatially heterogeneous heat flow [2]. Mars boasts a massive volcanic complex (Tharsis rise) which may overlie a persistent mantle hot spot. However, very few heat flow measurements have been performed to test predictions of planetary formation/evolution models [3].

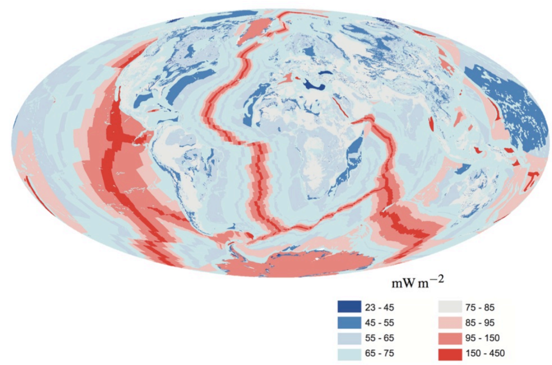

Figure 1: Global heat flow of the Earth, showing variations of ~0.5 W m^{-2} at this scale. These variations are primarily due to plate tectonics driven by mantle convection. Figure from [9].

Potential Advantages of Orbital Heat Flow Mapping. Historically, heat flow has been measured using thermometers placed in the ground at different depths surrounding a material of known conductivity – a technique that has been applied on the Earth, Moon [4], and soon with the InSight mission, Mars [5]. However, this approach requires landing on the surface and drilling to make physical contact with the subsurface, adding significant cost and risk. Furthermore, a distributed network of heat flow probes would be critical to identifying the underlying geophysical mechanisms involved (Fig. 1). If it were possible to detect heat flow from orbit, these measurements (combined with ground-truth from missions like InSight) would pioneer a new way to study the interiors of the planets, at dramatically lower cost.

Background: The possibility of measuring planetary heat flow from orbit was first seriously considered by *Keihm* (1984) [6]. He studied the sensitivity of microwave emission from the Moon to variations in interior heat flow, finding that this technique would yield a marginal detection for the heat flow values measured at the Apollo landing sites, ~15 – 20 mW m^{-2}. However, these equatorial sites are subject to large diurnal surface temperature cycles, which complicate the extraction of the heat flow signature (Fig. 2).

An alternative approach was proposed by *Paige et al.* (2010) [7], using the extremely cold permanently shadowed regions (PSRs) at the lunar poles: in the absence of direct insolation, interior heat flow can be a

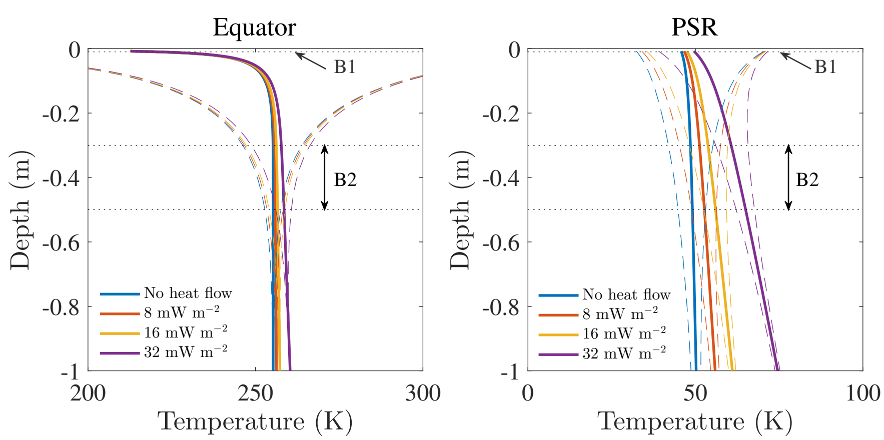

Figure 2: Thermal model [12] results for the Moon showing temperature profiles over one complete diurnal cycle at the equator (left) and in permanent shadow (right). Heat flow is much more easily detectable in the PSRs using the temperature difference between two spectral channels making short-wave ("B1") and long-wave ("B2") radiometric measurements of emission at two different depths. This is because surface temperature variations are much smaller, and thermal conductivity is nearly constant.

significant contribution to the surface energy budget. Using data from the Diviner Lunar Radiometer onboard the Lunar Reconnaissance Orbiter (LRO), the Moon's heat flow at the poles has been constrained using this technique to be < 10 mW m^{-2}. This is much lower than the values for the Apollo sites, likely due to concentrations of radiogenic elements on the lunar nearside [2,8]. Thus, the Diviner measurements reveal a primary feature of the lunar crust and interior evolution, without having touched the surface.

Proposed Technique: We suggest that future missions could map heat flow on solid planetary bodies using a combination of the two techniques described above: 1) microwave radiometry, and 2) targeting low-temperature surfaces using infrared and/or microwave measurements. Next, we outline the advances needed to accomplish this goal by 2050.

Advances Needed in Planetary Science. Knowledge of surface temperature cycles driven by insolation is critical to interpreting the microwave emission spectrum, especially at higher frequencies. Dedicated surface temperature mapping investigations like the one perfomed by Diviner for the Moon would also reveal the presence of PSRs, which can be utilized for bodies where the equatorial energy budget is dominated by insolation. Detailed knowledge of thermal conductivity can also be derived from surface temperature measurements and complementary techniques such as radar.

Advances Needed in Technology. A two-channel radiometer accurate to less than 1 K brightness temperature is needed. Spacing in wavelength between the channels should be maximized to increase the difference in depths measured by the radiometer. *Keihm* (1984) [4] found that wavelengths 15–50 cm were optimal for measuring lunar heat flow near the equator, so an instrument similar to Juno's Microwave Radiometer [10] could be used. Miniaturizing this type of instrument would be limited by the antenna aperture size for the long-wavelength channel and the power consumption and sensitivity of the short-wavelength channel. A low-power CMOS synthesizer could save the system several watts of power. To avoid bulky, power-hungry optical flip mirrors for calibration, a compact waveguide calibration switch can also be applied to the system. These are innovations with a clear technology development path.

A Vision for 2050 and Beyond: Orbital heat flow mapping will be a critical component of future combined surface- and orbital-based geophysical networks. Synergistic heat flow, gravity, and magnetic measurements of the terrestrial planets and icy satellites will provide a clearer picture of planetary interiors. Global heat flow measurements will also constrain the factors behind the onset of plate tectonics, which may be a critical factor in planetary habitability [11]. Mapping heat flow on the icy satellites will reveal recent or ongoing activity, tidal dissipation, and will constrain the depths to subsurface oceans. Mars will also be a compelling target for orbital heat flow mapping, due to its higher expected heat flow than the Moon and a pervasive insulating dust layer. Thus, if successfully demonstrated, the orbital heat flow technique has the potential to provide a fresh new window on planetary interiors.

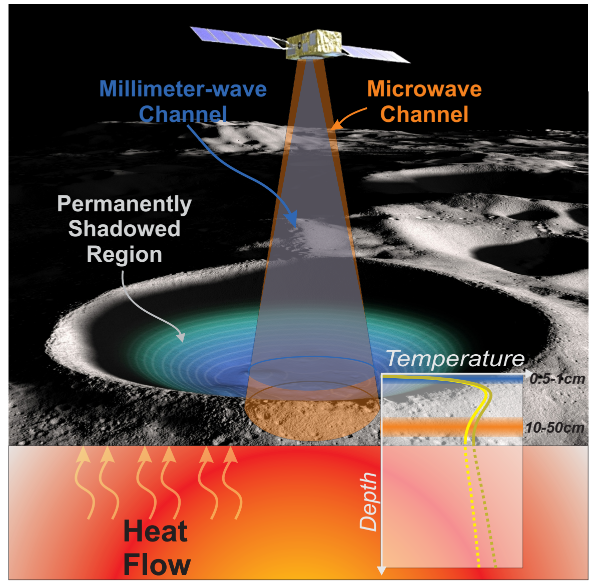

Figure 3: Concept for remote measurement of heat flow using microwave radiometry. Within permanently shadowed regions (PSRs) at the poles of a planet, surface and subsurface temperatures are sensitive to small variations geothermal heat. On some planets, similar sensitivity may be achieved outside of the PSRs.

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Acknowledgement: Part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

2015 NASA ASTROBIOLOGY STRATEGY DOCUMENT AND THE VISION FOR SOLAR SYSTEM EXPLORATION. L.E. Hays[1], M.H. New[2], and M.A. Voytek[2]. [1]Jet Propulsion Laboratory-Caltech, [2]NASA Headquarters.

Introduction: In 2015 the NASA Astrobiology Program released the Strategic Plan [1] to outline the goals of the research program for the next decade. The grass roots process of creating this document took over a year, involved almost 200 scientists from various aspects of the field of Astrobiology, and created an inclusive document that is 257 pages long. This document was designed to be as all-encompassing as the field of Astrobiology itself – so that any scientist who explores a field with broad astrobiological relevance can see their work reflected within the Strategy. Importantly, the structure of the document was not centered around targets (Mars, Europa, exoplanets, etc.), but instead focused on seven major topics of research in the field today.

Major Topics: The seven major topics covered in the Astrobiology Strategy are below:

1. Identifying Abiotic Sources of Organic Compounds

2. Synthesis and Function of Macromolecules in The Origin of Life

3, Early Life and Increasing Complexity

4. Co-Evolution of Life and The Physical Environment

5. Identifying, Exploring, And Characterizing Environments for Habitability and Biosignatures

6. Constructing Habitable Worlds

7. Challenges and Opportunities in Astrobiology

Within each of these topics, there is a discussion of relevant "Areas of Research" and many additionally have a section on "Challenges for the Next Ten Years".

Areas of Research: Some of the "areas of research" are quite broad, and include current and future questions that are being explored within each of the topics. Some of these questions include:

- What is the Role of the Environment in the Production of Organic Molecules? (Topic #1)
- What is the chemistry of macromolecular formation reactions? (Topic #2)
- Dynamics of the Evolution of Life: Intrinsic vs. Extrinsic factors (Topic #3)
- How Does Our Ignorance about Microbial Life on Earth Hinder Our Understanding of the Limits of Life? (Topic #4),
- "How Can We Identify Habitable Environments and Search for Life within the Solar System?" (Topic #5)
- "What are the Processes on Other Types of Planets That Could Create Habitable Niches?" (Topic #6).

Although these "areas of research" questions include activities that are ongoing and in the near-future, they are wide-ranging enough to help set the stage for long-term research goals for these interconnected topics within astrobiology, some that will take technological innovations, improvements in information and data processing or exploration of other bodies in our solar system that will unfold over the next few decades.

Challenges for the Next Ten Years: In addition to longer-ranging and more broad areas discussed above, four chapters independently call out some of the major goals for the next ten years of research. Although these are more limited in time scale and scope, they provide specific targets for the medium range astrobiology research.

The Topic 1 challenges are identified as:

- How do environments drive organic molecule production?
- Were meteorites and comets relevant to organic inventories on prebiotic Earth? Were all molecules required for the emergence of life on Earth generated endogenously, or were some necessarily provided from exogenous sources?
- What were the sources of the molecules that became the building blocks of life?
- What compounds derived from abiotic synthesis are characteristic of their sources?

The Topic 2 challenges are identified as:

- Investigate possible evolutionary paths from earliest macromolecular assemblies and polymers to contemporary DNA/RNA/protein-dominated life. Modern methods of analysis must be employed to evaluate and extend current and proposed models.
- Structures of modern biomolecules at all levels, from the primary to the tertiary, when viewed in their phylogenetic context, can inform us about biopolymer history.
- Separation of template and daughter molecules in the absence of evolved enzymes such as DNA or RNA polymerase remains a challenge.

The Topic 4 challenges are identified as:

- Investigate possible evolutionary paths from How do the different worlds of the past, present, and future Earth inform our understanding of exoplanets?

- How can we better understand the constraints on the timing and tempo of surface evolution and processes?
- What is the fidelity of proxies of biology and environment over long and complex geologic histories?
- How can biological data and geologic data be integrated through evolutionary time?
- How can we develop new approaches or modifications of current approaches to enrich and ultimately isolate organisms currently known only by their DNA sequences?
- What are the methodological challenges coordinating and synthesizing in silico data?

The Topic 6 challenges are identified as:

- Understanding how each of habitable states on Earth was maintained and the processes that governed the transitions into succeeding states provides opportunities for understanding habitable states on other planets.
- Understanding the processes that move complex systems between states is important for developing and testing hypotheses about complex cause and effect relationships (e.g., the timing of the oxygenation of the atmosphere and the evolution of oxygen production).
- Inquiries into epochs and duration of change in planetary cycles are important because the chemical systems that preceded the emergence of life needed time to form.

Relevance to Workshop Goals: Three of the Planetary Science Vision 2050 workshop goals, Origins, Workings and Life could be addressed by sections within the Astrobiology Strategy. Origins, defined as "understanding formation and evolution of solar systems (including exoplanetary systems)" should include topics addressed in the Strategy such as how early processes contribute to habitable environments throughout the solar system and other stellar systems (from Topic #6) and how these formation mechanisms deliver different compounds important to life to forming planets (from Topic #1). Workings, defined as "understanding how the processes in our solar system operate, interact, and evolve" should be related to astrobiological topics such as how the presence of life on planetary surfaces affects surface processes and how the two evolve together (from Topic #3 and Topic #4 in the Strategy). Finally, the goal relating to Life, defined as "improve our understanding of the origin and evolution of life, including Earth analogs, to guide our search for life elsewhere" is essentially parallel with the overarching goal of Astrobiology as a science. Questions about origin of chemical processes and then early life are covered in Topics #1 and #2 and partly #3. Research relating to the evolution of life is discussed in detail in Topics #3 and #4. Habitable environments throughout the solar system and beyond and their analogs are covered in Topic #5. Finally, Topic #6 expands on this idea further to entire habitable worlds and what their characteristics may be.

The detailed information in the Astrobiology Strategy, compiled by, and with ideas from, a large number of scientists with diverse research backgrounds and perspectives represents the goals of this community and the long-term vision of Astrobiology science.

Summary: The Strategy is a recently completed document that represents the long-term scientific goals of the broad and interdisciplinary Astrobiology community. This paper will focus on highlighting the areas of overlap between the suggested key research directions highlighted in the Astrobiology Strategy and the stated goals of Origins, Workings and Life of the Planetary Science Vision (PSV) 2050 Workshop.

Reference:

[1] Hays L. E. (editor-in-chief) *2015 NASA Astrobiology Strategy* (*https://astrobiology.nasa.gov/uploads/filer_public/01/28/01283266-e401-4dcb-8e05-3918b21edb79/nasa_astrobiology_strategy_2015_151008.pdf*)

Exploration of Planetary Crusts: A Human/Robotic Exploration Design Reference Campaign to the Lunar Orientale Basin.

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By the year 2050 we need to be working on fundamental scientific problems in an integrated fashion, utilizing a broad strategy for the systematic exploration of the solar system using wide ranges of technology and accomplishing our fundamental goals through international cooperation. For example, Microsymposium 56, "The Crust of the Moon: Insights Into Early Planetary Processes", (http://www.planetary.brown.edu/html_pages/micro56.htm) identified a series of outstanding problems for future international human/robotic exploration of the Moon centered on: 1. Crustal geometry/physical structure; 2. Crustal Chemistry/mineralogy/petrology; 3. Exogenic crustal modification by impacts; 4. Chronology of crustal formation/evolution. Furthermore, the nature of mantle uplift and the possibility of sampling mantle in the uplifted material as well as determining the nature of basin impact melt processes (differentiated or undifferentiated) is critically important. Direct dating of impact melt and placing Orientale in the firm context of lunar chronology is also achievable.

In response we are formulating a human/robotic exploration design reference campaign to the 930 km Orientale impact basin (1,2), the most well preserved basin on the Moon, that provides insight into all aspects of these fundamental questions. Our design reference mission is a model for the exploration of the planets in the 2050 time frame, and combines robotic exploration geophysics traverses operated radially from the basin interior, together with human exploration missions to the key sites that will provide data to address these questions. We outline six human exploration mission landing site targets using the HALO Mission Architecture concept and capabilities: 1) Base of the Cordillera ring/Montes Rook Formation; 2) Base of the Outer Rook ring/Lacus Veris maria; 3) Inner Rook peak-ring massifs/Maunder Formation impact melt rough facies 1; 4) Maunder Formation impact melt sheet smooth facies; 5) Central melt sheet craters/Mare Orientale/Kopff crater; and 6) Maunder crater interior/ejecta. Our strategy for human/robotic exploration optimization centers on six themes and is totally flexible to the important new results of significant discoveries that will be made in the next few decades:

I) Precursor (What do we need to know before we send humans?);

II) Context (What are the robotic mission requirements for final landing site selection and regional context for landing site results?);

III) Infrastructure/Operations (What specific robotic capabilities are required to optimize human scientific exploration performance?);

IV) Interpolation (How do we use robotic missions to interpolate between human traverses?);

V) Extrapolation (How do we use robotic missions to extrapolate beyond the human exploration radius?);

VI) Progeny (What targeted robotic successor missions might be sent to the region to follow up on discoveries during exploration and from post-campaign analysis?).

We use the targeted human exploration sites to illustrate how human exploration, complemented and assisted by robotic exploration, can provide insights into early planetary processes by exploring and characterizing the crust of the Moon. Our architecture provides insight into human/robotic exploration strategies for other lunar regions and other destinations on other planetary bodies.

This international design reference mission approach will assist in identifying the key technologies, including laboratory, remote sensing and in situ that will be necessary to accomplish these fundamental and broad scientific goals in the 2050 time frame. It will also serve to form the partnerships and identify the opportunities and obstacles to international synergism. Human-Robotic partnerships in science and engineering synergism (SES), such as that exemplified by the

NASA Solar System Exploration Virtual Institute (SSERVI), are absolutely essential to formulating and achieving these goals.

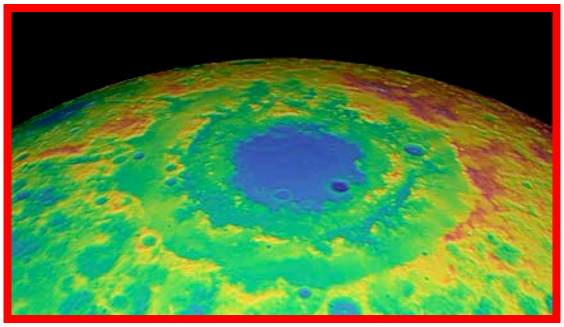

Fig. 1. Perspective view of the topography of the Orientale Basin. LRO LOLA data.

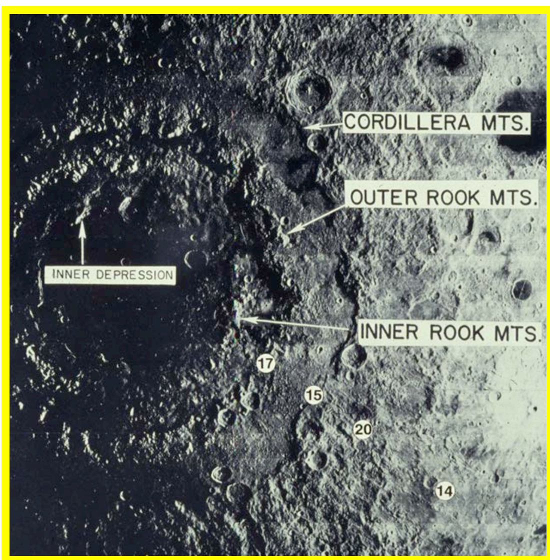

Fig. 2. The Orientale Basin from Lunar Orbiter, showing the rings and the Apollo and Luna equivalent landing site locations for the Orientale Basin.

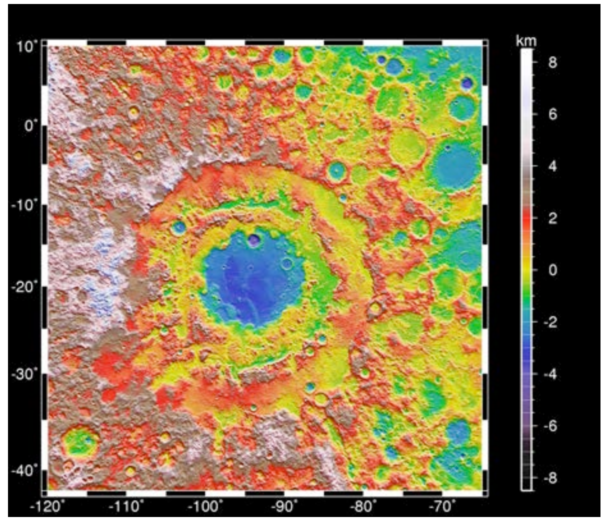

Fig. 3. LRO LOLA Topography of the Orientale Basin.

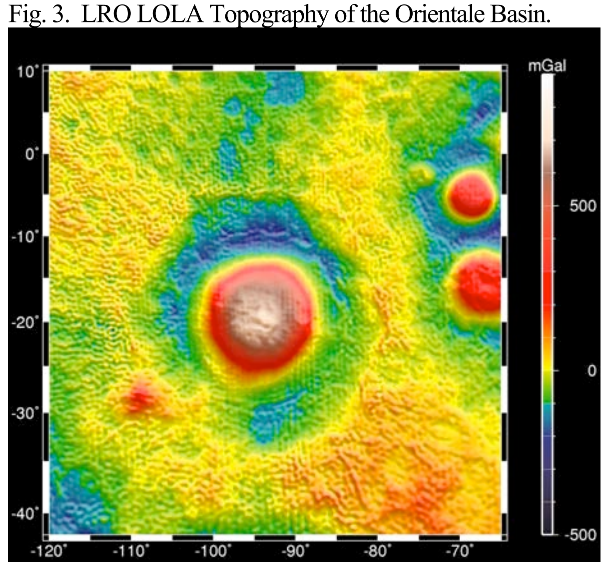

Fig. 4. GRAIL Bouguer gravity map of Orientale Basin.

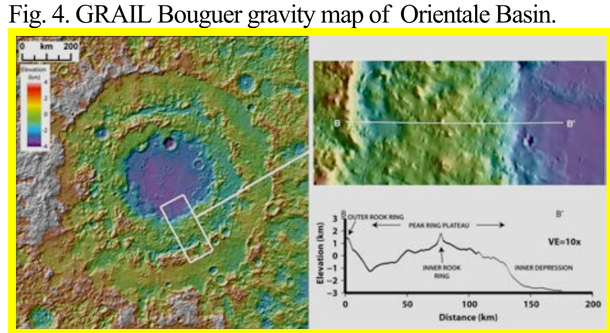

Fig. 5. Exploration Region of Interest 3 (ROI-3) for the origin of Inner Rock Mountains and Maunder Formation impact melt.

References: (1) Zuber, Maria T. et al, (2016) Gravity field of the Orientale basin from the Gravity Recovery and Interior Laboratory Mission. *Science*, 354, 438-441DOI: 10.1126/ science.aag0519. (2) Johnson, B. et al. (2016) Formation of the Orientale multiring basin, *Science*, 354, 441-444, DOI: 10.1126/science.aag0518.

ROADMAPS TO OCEAN WORLDS. A. R. Hendrix[1], T. A. Hurford[2], the ROW Team. [1]Planetary Science Institute, Tucson, AZ (arh@psi.edu), [2]NASA Goddard Space Flight Center, Greenbelt, MD (terry.a.hurford@nasa.gov).

Introduction: The House Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2016 directed NASA to create an Ocean Worlds Exploration Program whose "primary goal is to discover extant life…" To support this initiative, NASA's Outer Planets Assessment Group (OPAG) formed the Roadmaps to Ocean Worlds (ROW) to lay the scientific groundwork for such a program, and as input to the Decadal mid-term review and the next full survey. OPAG gave ROW the following charter:

• Identify and prioritize science objectives for Ocean Worlds (tied to the 2013 Decadal Survey) over the nest several decades

• Design roadmap(s) to explore these worlds to address science objectives (including mission sequences, considering a sustained exploration effort)

• Assess where each Ocean World fits into the overall roadmap

• Summarize broad mission concepts (considering mission dependencies and international cooperation)

• Recommend technology development and detailed mission studies in support of the next decadal survey

The ROW team is producing two documents: 1) Goals, Objectives, Investigations for Ocean Worlds and 2) Ocean Worlds Missions Scenarios, Roadmaps & Technologies; here we highlight the goals and investigations.

Definition of an Ocean World: For the purposes of ROW, and to bound the extent of a future Ocean Worlds program, we define an "ocean world" as a body with a current liquid ocean (not necessarily global). All bodies in our solar system that plausibly can have or are known to have an ocean will be considered as part of this document. The Earth is a well-studied ocean world that can be used as a reference ("ground truth") and point of comparison.

Philosophy and Overarching Goal: There are several – if not many – ocean worlds or candidate ocean worlds in our solar system, targets for future NASA missions in the quest to understand the distribution and origin of life in the solar system. In considering ocean worlds, there are several with confirmed oceans, several candidates that exhibit hints of potential oceans, and worlds that may theoretically harbor oceans but about which not enough is currently known. As a philosophy, the ROW team deems it critical to consider all of these worlds in order to understand the origin and development of oceans and life in different worlds: does life originate and take hold in some ocean worlds and not others and, if so, why? Thus, the ROW team supports the creation of a program that studies the full spectrum of ocean worlds; if only one or two ocean worlds are explored and life is discovered (or not), we won't fully understand the distribution of life, its origin and variability, or the repeatability of its occurrences in the solar system.

We have considered that Enceladus, Europa, Titan, Ganymede and Callisto have known subsurface oceans, as determined from measurements by the Galileo and Cassini spacecraft. These are *confirmed* ocean worlds. Europa and Enceladus stand out as ocean worlds with evidence for communication between the ocean and the surface. Titan, Ganymede and Callisto's subsurface oceans are expected to be covered by a relatively thick ice shell, making exchange processes with the surface more difficult, and with no obvious surface evidence of the oceans.

Although Titan possesses a large subsurface ocean, it also has an abundant supply of a wide range of organic species and surface liquids, which are readily accessible and could harbor more exotic forms of life. Furthermore, Titan may have transient surface liquid water such as impact melt pools and fresh cryovolcanic flows in contact with both solid and liquid surface organics. These environments present unique and important locations for investigating prebiotic chemistry, and potentially, the first steps towards life.

Bodies such as Triton, Pluto, Ceres and Dione are considered to be *candidate* ocean worlds based on hints from limited spacecraft observations. For other bodies, such as some Uranian moons, our knowledge is limited and the presence of an ocean is uncertain but they are deemed *credible possibilities*.

The ROW team decided on an overarching goal for the roadmaps: **Identify ocean worlds, evaluate their habitability, and search for life**. This overarching goal has four underlying sub-goals, described here:

Goal I: Identify ocean worlds in the solar system.

I. A. Is there a sufficient energy source to support a persistent ocean?

A.1 Is there remnant radiogenic heating?

A.2 Is there or has there been significant tidal heating?

I. B. Are signatures of ongoing geologic activity (or current liquids) detected?

B.1 Do signatures of geologic activity indicate the possible presence of a subsurface ocean? (surface hotspots, plumes, crater-free areas, volcanoes, tectonics)

B.2 Does the body exhibit tidal and/or rotational evidence indicating the presence of a sub-surface ocean?

B.3 Does the gravity and topography of the body indicate the presence of a sub-surface ocean?

B.4 Are temporal changes observed at the body that would indicate the presence of a sub-surface ocean?
B.5 Is there an atmosphere or exosphere that could be linked with the presence of a sub-surface ocean?
B.6 Does the electromagnetic response of the body indicate the presence of a sub-surface ocean?
B.7 Can the surface composition be linked with the presence of a sub-surface ocean?
B.8 Is the signature of a surface liquid observed (e.g. specular reflection)?

I. C. How do materials behave under conditions relevant to any particular target body?
C.1 What are the phase relations of materials composing ocean worlds at relevant pressures and temperatures?
C.2 What is the composition and chemical behavior of materials composing ocean worlds?
C.3 What are the rheological mechanisms by which material deforms under conditions relevant to ocean worlds?
C.4 How does energy attenuation/dissipation occur under conditions relevant to ocean worlds?
C.5 What are the thermophysical properties of material under conditions relevant to ocean worlds?

Goal II: Characterize the ocean of each ocean world.
II.A Characterize the physical properties of the ocean and outer ice shell
A.1 What is the thickness, composition, and porosity of the ice shell (crust) and how do these properties vary spatially and /or temporally?

A.2 What is the thickness, salinity, density and composition of the ocean? How do these properties vary spatially and /or temporally?
A.3 What are the drivers for, and pattern of, fluid motion within the ocean.

II. B. Characterize the ocean interfaces
B.1 Characterize the seafloor, including the high-pressure ocean – silicate interaction
B.2 Characterize the ice-ocean interface

Goal III: Characterize the habitability of each ocean world.
III.A. What is the availability (type and magnitude/flux) of energy sources suitable for life, how does it vary throughout the ocean and time, and what processes control that distribution?

A.1 What environments possess redox disequilibria, in what forms, in what magnitude, how rapidly dissipated by abiotic reactions, and how rapidly replenished by local processes?
A.2 (Where) is electromagnetic radiation available? In what wavelengths and intensity?

III.B. What is the availability (chemical form and abundance) of the biogenic elements, how does it vary throughout the ocean and time, and what processes control that distribution?
B.1 What is the inventory of organic compounds, what are their sources and sinks, and what is their stability with respect to the local environment?
B.2 What is the abundance and chemical form of nitrogen, oxygen, phosphorus, sulfur, and inorganic carbon, what are their sources and sinks, and are there processes of irreversible loss or sequestration relative to the liquid environment?

Goal IV: Understand how life might exist at each ocean world and search for life
IV.A. What are the potential biomarkers in each habitable niche? (determine what we're looking for)
A.1 What can we learn about life on ocean worlds from studying life on Earth?
A.2 What niches for life are possible on ocean worlds?
A.3 What can we learn about life by understanding the history of ocean worlds from their formation to the present?
A.4 What should be our target indicators? (Life Detection Ladder)
A.5 How do we distinguish extant from extinct life in environments in which life might develop, and which timescales (e.g., for metabolism, reproduction, dormancy) matter?

IV.B. How to search for and analyze data in different environments?
B.1 How can we look for life on an ocean world remotely (from orbit or during a flyby)?
B.2 How can we look for life on an ocean world in situ (landed, underwater, plume) investigations?
B.3 How can we look for life on an ocean world with sample return science?
B.4 Which science operational strategies should be used to detect life on ocean worlds?

ROW is focused on the search for signs of extant life and characterizing the potential habitability of ocean worlds. The goals outlined here offer a vision of ocean world-related planetary science beginning over the next 3 decades. Key to accomplishing these goals are technological advances, for instance *in situ* life detection and sampling methods, power sources and energy storage systems suitable for cryogenic environments, autonomous systems for e.g. pin-point landing on Titan (different from Europa and Enceladus) and aerial or landed mobility, subsurface ice acquisition/handling, plume capture, planetary protection technologies and ice sample return with cryogenic preservation. Technologies also need to be developed for survival and operation of both electronic and mechanical systems in the ocean world environments.

UV IMAGING SPECTROSCOPY: THE 2050 VISION.
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Introduction: Ultraviolet (UV) imaging spectroscopy has proven to be an invaluable technique for planetary science studies, and in the last decades has demonstrated its diverse potential for planetary science discoveries. We encourage the community to support use of this technique as we continue on our journeys in the solar system to 2050, even to targets not traditionally thought of as being sources of UV signals. It is also critical that UV-related technologies are advanced and laboratory studies are encouraged, to continue furthering the scientific results of these instruments at other planetary bodies.

A number of UV instruments have flown or are flying on spacecraft (e.g. Hubble Space Telescope (HST), Lunar Reconnaissance Orbiter (LRO), Cassini, Rosetta), and more will do so in coming years. These UV instruments are enabling significant new findings regarding surfaces (in addition to atmospheres -- the traditional use of the UV regime). For instance, recent UV results (e.g. from asteroids and the Moon) that this is a rich spectral range for studying Solar System small bodies. An example is shown in Fig. 1.

New insights in the last decade: UV spectroscopy has been used since the earliest space missions for atmospheric and auroral studies (e.g. [2][3][4][5][6][7][8][9]). The advantages of UV imaging spectroscopy for detecting and investigating plumes and thin atmospheres (e.g. at Enceladus, Io, Europa) via emissions and occultations (gas absorptions) have been made obvious in recent years (e.g. [10][11][12]). UV spectroscopy for studying cometary emissions is also well-established (e.g. [13]). The lunar exosphere was studied in the UV in the Apollo 17 mission [14] and study continues with the LRO/LAMP investigation (e.g. [15]). MAVEN/IUVS at Mars is a prime example that improved instrumentation can still result in substantial discoveries even ~50 years after the first interplanetary UV instruments.

Insights from UV imaging spectroscopy of solar system surfaces have been gained largely in the last 1-2 decades, including studies of surface composition, space weathering effects (e.g. radiolytic products) and volatiles on asteroids (e.g. [1][16][17][18][19]), the Moon [20][21][22], comet nuclei [23] and icy satellites (e.g. [24][25][26][27][28][29][30]). The UV is sensitive to some species, minor contaminants and grain sizes often not detetcted in other spectral regimes. ***Here we highlight recent UV results on solid surfaces as examples***.

Diagnostic carbon-related spectral features. Carbon compounds are ubiquitous in the solar system but are challenging to study using remote sensing due to the mostly bland spectral nature of these species in the traditional visible-near infrared regime. In contrast, carbonaceous species are spectrally active in the UV but have largely not been considered for studies of solar system surfaces. Hendrix et al. [31] compiled existing UV data of carbon compounds -- well-studied in contemplation of the interstellar medium (ISM) extinction -- to review trends in UV spectral behavior. Thermal and/or irradiation processing of carbon species results in the loss of H and ultimately graphitization. Graphitization produces distinct spectral features in the UV, as shown in Fig. 2. We have suggested that a graphitized carbon is important at Ceres [1] and small grains of such a species could be responsible for the UV "bump" in reflectance seen there near 1600 Å (Fig. 1). The presence or lack of such a feature at carbonaceous bodies throughout the solar system could be an important indicator of exposure age. Polycyclic aromatic hydrocarbons (PAHs) also exhibit widely varying and diagnostic UV-visible spectral shapes (e.g. [32][33]).

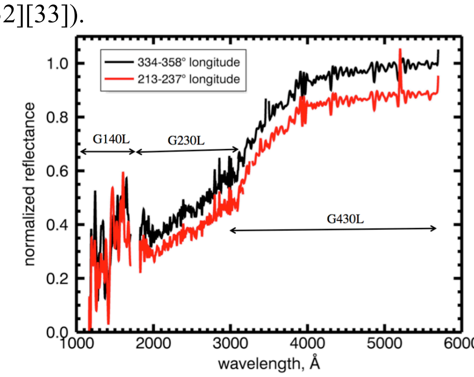

Figure 1. Ceres: composite normalized reflectance spectra derived by combining data from the three gratings (G140L, G230L, G430L) from two hemispheres on Ceres. From [1].

Lunar Hydration. Though the UV signature of H_2O is known to exist in polar permanently-shadowed regions (PSRs) (e.g. [20][34]), at lower latitudes, hydration is present but is less well-understood. The Lyman Alpha Mapping Project (LAMP) onboard LRO senses a strong water absorption edge in the far-UV (near 165 nm; Fig. 3), indicating hydration on the lunar dayside [21]. Hendrix et al. [21] found a relationship between the UV spectral slope and time of day, with spectral slopes consistent with increased hydration earlier and later in the day, and at higher latitudes. Near noon, the spectral slopes were most consistent with lower amounts – or no – hydration. More recent results [35] show a distinct difference in UV slope vs. time of day around local noon, exhibiting a sudden loss of the UV-sensed hydration approaching noon, and a slower re-accumulation of the hydration effect in the afternoon. Such results are in work but have implications for the sources and migration of hydrating species on/in the lunar regolith.

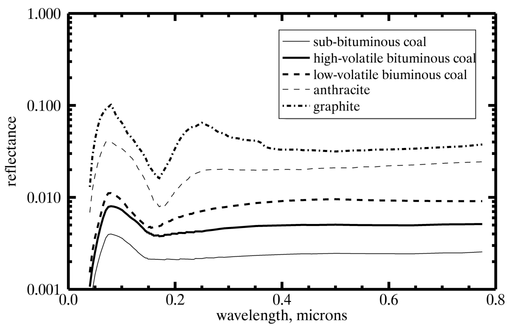

Figure 2. Coals with increasing graphitization, showing that the absorption feature near 200 nm becomes stronger and narrower and shifted to the red; after [36]; spectra are offset.

Lab Work & Advances in Technologies needed: As planetary science advances toward 2050, advancements in UV-related technologies (detectors, gratings, electronics miniaturization) are needed to advance to the next step. Weak signals at outer solar system targets (e.g. KBOs, Trojan asteroids, moons of Uranus and Neptune), for instance, will require utilization of more sensitive detectors to fully take advantage of the UV-diagnostic spectral clues. We also suggest that orbital missions are not the only place for UV instrumentation – landers and rovers can also benefit from this technology, for *in situ* studies.

Furthermore, UV lab studies (e.g. reflectance spectra of candidate species and mixtures) are critically needed to support and interpret the acquired spacecraft data, down to wavelengths as short as ~100 nm (or shorter). Some of the only existing far-UV lab data were made decades ago [37] of terrestrial, lunar, meteoritic powders, and frosts (including H_2O, CO_2, SO_2, and NH_3); their results suggest that extending the spectral range of lab measurements from the more traditional visible-NIR (VNIR) into the far-UV (100-200 nm) reveals significant diagnostic compositional information. UV lab measurements have particular challenges, but as evidenced by the newly identified carbon features, numerous discoveries can be anticipated in the next 30 years.

Summary: The UV is an exciting spectral regime in which to study solar system targets, including surfaces. UV imaging spectroscopy is already a critical component of planetary science in the areas of atmospheres, aurorae, plumes and surfaces, and with development of new technologies that will enable even more powerful imaging spectrometers, we expect to further improve discovery rate in the UV. We encourage the community to recognize the contributions in these areas and the potential for new important discoveries as NASA formulates its Planetary Science Vision for the next 3 decades, and to include advances in UV technologies in NASA plans. The potential is great!

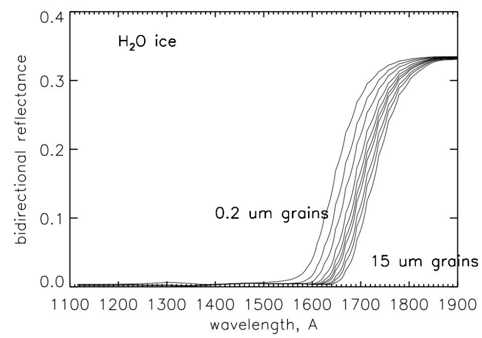

Figure 3. The UV reflectance spectrum of water ice of varying grain sizes; models from Hendrix and Hansen (2008).

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A VISION FOR ICE GIANT EXPLORATION. M. Hofstadter[1], A. Simon[2], S. Atreya[3], D. Banfield[4], J. Fortney[5], A. Hayes[4], M. Hedman[6], G. Hospodarsky[7], K. Mandt[8], A. Masters[9], M. Showalter[10], K. Soderlund[11], D. Turrini[12], E. P. Turtle[13], J. Elliott[1], and K. Reh[1], [1]Jet Propulsion Laboratory/Caltech (4800 Oak Grove Drive, Pasadena, CA 91109 mark.hofstadter@jpl.nasa.gov), [2]Goddard Space Flight Center, [3]University of Michigan Ann Arbor, [4]Cornell University, [5]University of California Santa Cruz, [6]University of Idaho, [7]University of Iowa, [8]Southwest Research Institute, [9]Imperial College London UK, [10]SETI Institute, [11]University of Texas Austin, [12]Institue for Space Astrophysics and Planetology Rome Italy, [13]Johns Hopkins Applied Physics Lab.

From Voyager to a Vision for 2050: NASA and ESA have just completed a study of candidate missions to Uranus and Neptune, the so-called ice giant planets. It is a "Pre-Decadal Survey Study," meant to inform the next Planetary Science Decadal Survey about opportunities for missions launching in the 2020's and early 2030's. There have been no space flight missions to the ice giants since the Voyager 2 flybys of Uranus in 1986 and Neptune in 1989. This paper presents some conclusions of that study (hereafter referred to as The Study), and how the results feed into a vision for where planetary science can be in 2050. Reaching that vision will require investments in technology and ground-based science in the 2020's, flight during the 2030's along with continued technological development of both ground- and space-based capabilities, and data analysis and additional flights in the 2040's.

We first discuss why exploring the ice giants is important. We then summarize the science objectives identified by The Study, and our vision of the science goals for 2050. We then review some of the technologies needed to make this vision a reality.

The Importance of Ice Giants: The ice giants Uranus and Neptune, and their rings, satellites, and magnetospheres, are dynamic systems that challenge our understanding of the origins and workings of planets. The current state of knowledge of these systems along with exploration priorities and strategies were summarized in the 2011 Planetary Science Decadal Survey [1] and later workshops [2]. Results of The Study are consistent with those works.

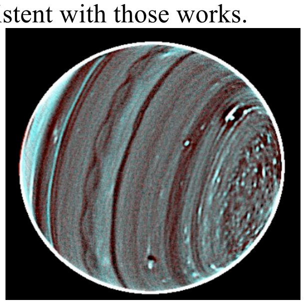

Fig. 1: Ground-based image of Uranus [3], showing zonal banding, unusual cloud features over the North Pole (right), a high-altitude haze over the South Pole (left), and atmospheric waves creating scalloped clouds near the Equator.

The ice giants are distinctly different planets from the more familiar gas giants (Jupiter and Saturn) and the terrestrial planets. The terrestrial planets are, by mass, almost entirely made up of "rock", the most refractory elements. Conversely, the gas giants are composed almost entirely of the most volatile elements, hydrogen and helium. Uranus and Neptune contain some rock and gas, but about 2/3 of their mass is species such as water and methane [4], species referred to as "ices". We have not yet carried out a detailed exploration of either ice giant system, leaving significant holes in our understanding of planetary formation and evolution and the history of our solar system. This gap also affects our understanding of exoplanets; the majority of planets discovered around other stars are thought to be ice giants [5], and they are far more abundant in our galaxy than one would think based on our own solar system. The 2011 Decadal Survey [1] recognized the importance of Uranus and Neptune, and called for exploration of an ice giant system with a Flagship mission. Budget realities have pushed that goal into the decades covered by the Visions 2050 workshop. A program of ice giant exploration is central to achieving goals related to the Origins, Workings, and Life themes identified for this workshop.

Science Goals: This section discusses how the concrete objectives of an ice giant mission launched around 2030 feed into visionary goals for 2050.

The 2016 Pre-Decadal Study. At the time of this writing, the final report for NASA's just completed ice-giant study is being assembled. The results will be available in early 2017 at

http://www.lpi.usra.edu/icegiants/mission_study/.

The highest-priority science objectives identified by The Study target the internal structure and bulk composition (including noble gases and isotopic ratios) of the ice giants. These are the fundamental properties that define what an ice giant is, and constrain models of their formation and evolution. The Study science team identifies 10 additional objectives, all given equal priority, to advance our understanding of the magnetic fields and magnetospheres, satellites, rings, and atmospheric dynamics of the ice giants (see the study report for details and references). These objectives include:

- Understanding the flow of energy and mass from the solar wind into the magnetospheres and upper atmospheres of these planets, utilizing the unique geometries created by their complex magnetic fields which can open and close to the solar wind on 16-hour time scales,
- Determining the geology, composition, and internal structure of Uranus' major satellites, such as the tortured surface of Miranda (Fig. 2), and of Neptune's captured Kuiper Belt Object, Triton,
- Exploring the narrow, dense rings of Uranus and the clumpy rings of Neptune, each displaying features not seen in the broad rings of Saturn or the tenuous rings of Jupiter,
- Exploring the chaotic gravitational interplay of the rings and small moons of Uranus,
- Exploring the nature and driving forces of atmospheric dynamics, Uranus being the only giant planet whose atmospheric energy balance is dominated by sunlight, while Neptune's is dominated–more so than any other giant planet–by the release of internal heat.

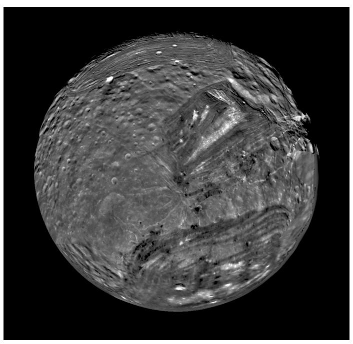

Fig. 2: Miranda, as seen by Voyager 2.

The Study concludes that Uranus and Neptune are equally valuable and that each is compelling as a scientific target. While equal, however, they are not equivalent. Each planet teaches us different things, and there is tremendous value in visiting both Uranus and Neptune.

Goals for 2050. The science objectives just described feed into higher-level goals for 2050.

Specific to the "Origins" theme of this workshop, one science goal is to collect measurements to definitively determine whether planetary migration has occurred. The ice giants have potentially migrated the farthest radially [6], and may contain the most obvious clues in their compositions or in the compositions of their satellites. Another Origins goal is to understand ice-giant formation well enough to be able to reliably infer the composition and structure of exoplanets using only knowledge of their mass, radius, and perhaps the abundance of trace species in their upper atmospheres. This will allow us to explore the formation and evolution of individual exoplanetary systems.

Regarding the "Workings" theme, exploration of the ice giants is a crucial piece for understanding atmospheric dynamics and the processes that drive them; deep interior dynamics and how they generate magnetic fields; the physics of cataclysmic, stochastic processes such as those that resulted in Uranus' tilt and the expulsion or destruction (presumably by Triton) of Neptune's native large satellites; and mass and energy transport from the solar wind, through a magnetosphere, and into upper atmospheres. The diverse surface geology of the satellites provide information about how cratering, tectonic and cryovolcanic processes can operate at low temperatures, and the dynamical interactions between rings, moons and the planet can place constraints on the lifetime of tightly-packed rings and dynamical systems, and even the internal structures of the planets.

Finally, regarding the "Life" theme of this workshop, we note that each giant planet in our solar system is a potential host of a habitable ocean world, and Uranus and Neptune may contain unique niches for life in their icy satellites and possibly within the extensive oceans thought to exist within the planets themselves.

Enabling Technologies: Addressing these science priorities will require technological advances as well as investments in Earth-based observations, modeling, and infrastructure. Technolgies discussed in the course of The Study include extremely deep atmospheric probes (to 100's of kbar pressures), multiple long-lived platforms in hydrogen atmospheres, constellations of satellites in the outer solar system, and icy-satellite landers whose design is robust enough to operate in an environment not known at launch. Communication facilities capable of handling large data volumes from the outer solar system are important. Another key component will be rapid and inexpensive access to the outer solar system. Waiting decades for the opportunity to apply the knowledge gained from current discoveries hinders progress and innovation.

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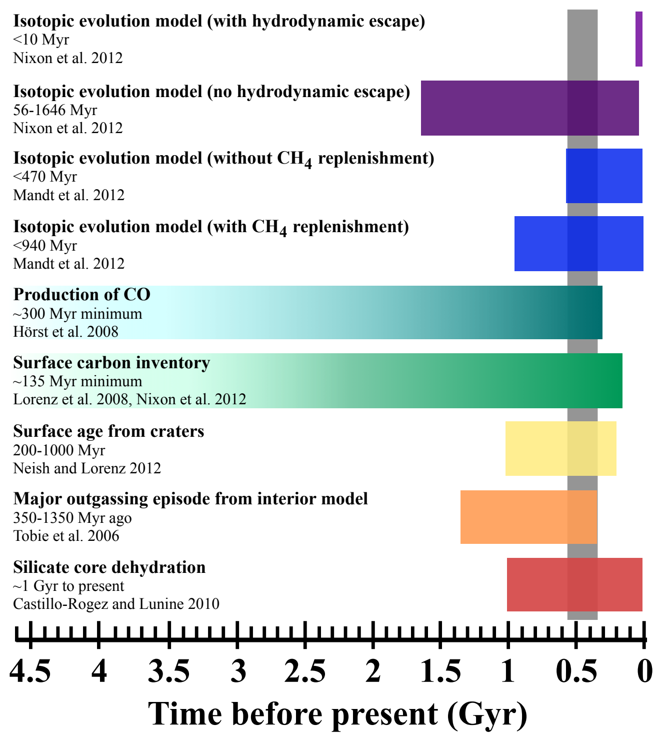
TITAN'S ATMOSPHERE AND CLIMATE: UNANSWERED QUESTIONS S.M Hörst[1], [1]Johns Hopkins University, sarah.horst@jhu.edu

Introduction: Titan is unique in our solar system: it is the only moon with a substantial atmosphere, the only other thick N_2 atmosphere besides that of Earth, the site of extraordinarily complex atmospheric chemistry that far surpasses any other solar system atmosphere, and the only other solar system body that currently possesses stable liquid on its surface. Titan's mildly reducing atmosphere is favorable for organic haze formation and the presence of some oxygen bearing molecules suggests that molecules of prebiotic interest may form in its atmosphere. The combination of liquid and organics means that Titan may be the ideal place in the solar system to test ideas about habitability, prebiotic chemistry, and the ubiquity and diversity of life in the Universe.

Since the Voyager era, we, as a community, have made significant progress in understanding Titan's atmosphere and climate; we have transformed Titan from an enigmatic moon into a dynamic world. This transformation required the persistent and sustained effort of an international, multidisciplinary community that leveraged ground and space based observing, spacecraft measurements, laboratory experiments, and models in pursuit of one overarching goal: to understand Titan as a world. In the process, we have pushed our understanding of terrestrial processes like fluvial and aeolian erosion into completely new phase space allowing us to begin to determine the underlying fundamental physics and chemistry that drive a number of planetary processes. We unveiled a beautiful world that holds so many pieces to the puzzle of how planets form and evolve. We revealed atmospheric organic chemistry that is so complex we are forced to rethink our ideas about how atmospheres work.

Unanswered questions: As with any wildly successful mission, we enter the post-Cassini-Huygens era with new questions, in addition to some long standing questions that continue to evade our understanding. These questions include [1]:

1. What are the very heavy ions in the ionosphere, how do they form, and what are the implications for complexity of prebiotic chemistry?
2. What is the connection between the plumes of Enceladus and Titan's atmosphere?
3. What is the composition of the haze and how does it vary spatially and temporally?
4. How do the organic compounds produced in the atmosphere evolve once reaching the surface?
5. What are the dynamics of Titan's troposphere and how does that affect the evolution of the surface?
6. How variable is Titan's weather from year to year and how variable is the climate over longer timescales?
7. How old is Titan's current atmosphere?



Constraints on the age of Titan's atmosphere from various measurements and models [1]

8. What happened on Titan 300-500 Myrs ago?
9. Is Titan's atmosphere cyclic and if so, what are the implications for habitability?
10. Where is the origin of Titan's methane and what is the fate of the photochemically produced ethane?
11. What is controlling Titan's H_2 profile and potential spatial variations?
12. What is the composition of the surface and on what scales is it spatially variable?
13. What is the composition of the dune particles and how are they produced?
14. Does cryovolcanism occur on Titan?

Answering many of these questions definitively will require future missions, but in all cases there are necessary technology and laboratory needs, discussed below, before we can

Technology investments: One particularly vexing challenge for studying Titan is the need for analysis of extremely chemically complex samples at cryogenic temperatures while minimizing the possibility of sample chemical alteration during acquisition and analysis. This challenge is not unique to Titan and many of the technology challenges that must be overcome to truly explore and understand Titan are also present for exploration of other Ocean Worlds such as Europa and Enceladus. In particular, there is a need for:

1. Sample acquisition systems that minimize chemical alteration of samples (in particular that minimize and/or eliminate heating and contamination of samples)
2. Cryogenically capable sample handling systems
3. Analytical techniques that measure chemical composition and structure for a large range of concentrations (from major to trace constituents), are capable of discerning between and identifying species of the same nominal mass (isobars), and can do so for solids, liquids, and gases
4. For Titan in particular, solutions to 1-3 must minimize power requirements due to the limited energy available on Titan's surface.

Need for dedicated laboratory facilities: Many of our outstanding questions about Titan stem in part from a lack of laboratory measurements of material properties, reaction rates, etc. at relevant temperatures. Titan's complex atmospheric chemistry combined with cryogenic temperatures results in the production of materials that can be challenging to handle safely and in a scientifically rigorous way in Earth laboratories. This presents an additional challenge for developing and testing sampling and sample handling systems and raising the TRL of instruments (the need for which is discussed above). NASA should invest in maintaining laboratories capable of these types of investigations, fund them at stable levels necessary to produce information required by the scientific community and support of flight development, and ensure that students have access to such facilities to ensure that future generations receive necessary training and experience (whether at a university, institute, or at a NASA center).

Equity and Inclusion in Planetary Science: Our mission teams, mission leadership, and full professors do not reflect the demographics of our field [2-4] and the demographics of our field do not reflect the demographics of the US population [4]. This is unacceptable and hinders our ability to attract, train, and retain the scientists and engineers required for the most innovative, creative, and visionary thinking, which is required to solve the challenges we face. Despite numerous studies demonstrating the barriers faced by minoritized groups (see e.g., [5,6]), our institutions remain slow to respond to these issues or in some cases even acknowledge that they exist. For example, at the same rate of change over the past ~20 years, our field will not reach gender parity until nearly 2050. Any vision for Planetary Science in the next 3 decades must acknowledge the existing barriers to equity and inclusion and actively work to dismantle them. The abstract submitted by Rathbun et al. for this workshop includes a much more detailed discussion of these issues and presents a number of suggested starting points.

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DATA ORGANIZATION AND ACCESSIBILITY FOR SMALL SOLAR SYSTEM BODIES IN THE ERA OF LARGE SURVEYS.
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Background: In the field of small solar system body science, we are currently in an era where we have access to large data sets, and are looking forward to even larger data sets in the future. Many of these large data sets (e.g., catalogs of albedos, diameters, taxonomic classifications, spin vectors, and so on) are available for community use via the Small Body Node of NASA's Planetary Data System (PDS), although other data sets, including those from the Catalina Sky Survey and Pan-STARRS1 survey, are either archived elsewhere or not (yet) publicly available. Even those data available through the PDS are distributed across multiple standalone data sets with only limited functionality for querying multiple data sets simultaneously. This lack of coordinated access to multiple disparate data sets means that substantial additional effort is required on the part of researchers to take full advantage of the broad range of efforts that our community has engaged in over the years to better understand small body populations in our solar system.

Current and Future Large Surveys: The Large Synoptic Survey Telescope (LSST) is expected to revolutionize small body science, increasing the known populations of minor planets and comets by an order of magnitude or more, and acquiring tens of millions of observations of both new and currently known objects. While the exact details of the LSST's Moving Object Processing System (LSST-MOPS) are not yet finalized, its main product will likely be a catalog of individual object detections with calibrated astrometry, photometry, and morphological parameters (e.g., point-spread function widths), and basic metadata such as object designations, orbital elements, observation dates and times, and image quality parameters. This will be accompanied by an alert system for notifying members of the community about observations of objects meeting specified criteria.

While the LSST moving object detection catalog will undoubtedly become an extraordinary resource for a wide range of small body science, it will also be insufficient for actually performing much of that science without significant additional effort. For example, some scientists may be interested in retrieving only those data acquired when an object was within a certain heliocentric distance range or at a particular orbital position or meets other geometric, photometric, or morphological criteria. Other scientists may be interested in selecting data for all asteroids that have certain orbital characteristics and/or physical properties, rather than having a list of specified targets.

Meanwhile, multiple other surveys are currently in operation or are being planned or proposed, including the Catalina Sky Survey, Pan-STARRS, Gaia, the Asteroid Terrestrial-Impact Last Alert System (ATLAS), the Dark Energy Survey, the Zwicky Transient Factory (ZTF, successor to the Palomar Transient Factory survey), and the Near-Earth Object Camera (NEOCam) mission, among many others. Efforts are also underway to extract the vast amount of asteroid data that have been serendipitously obtained over decades of conventional telescope observations of non-solar system targets, much of which currently sits untapped in public archives. Maximizing the amount of science that can be achieved will rely heavily on our future ability to draw on all of these disparate data sources and also connect them with the appropriate metadata (e.g., heliocentric and geocentric distances, phase angles, true anomalies, etc.) needed to properly interpret them. Effective management and synthesis of current and future data streams will also help to maximize the reconnaissance value of these data for future scientific and commercial missions to small bodies,

Proposed Work: With so many large and disparate data sets currently available that are relevant to small body science, and many more to come — the largest being the LSST moving object catalog — we foresee an urgent need for far greater sophistication in the way that we organize and access these data. We are currently in the early stages of an effort to develop tools for producing higher-level SSSB-specific data products from LSST data than will be produced by the baseline LSST and LSST-MOPS pipelines. We also seek to design a database infrastructure and user interface to organize and provide access to those data products and relevant metadata to facilitate scientific usage of LSST data by the broader solar system community. This effort additionally includes plans for cross-linking LSST detection data to external or mirrored data sources such as albedo or taxonomy catalogs, asteroid family lists, or lightcurve databases to provide added physical context. The overall system would ultimately be aimed at allowing users to retrieve data for objects that simultaneously meet a multitude of observational, physical, and dynamical conditions, thus streamlining the process by which focused scientific investigations of particular types of objects observed under particular conditions can be conducted. We expect that, ultimately, this system could then be expanded to incorporate data and derived products from many of the other current, planned, or proposed survey efforts mentioned above to increase their collective value and impact even more.

Until now, the solar system community has been reasonably successful conducting scientific investigations of survey data on an ad-hoc, individual basis. However, the flood of data that awaits us in the future will require a substantially different approach on our part as a community if we hope to make the most of our current and future investments in survey efforts in pursuit of our scientific, exploratory, and hazard mitigation goals. Given the imminent arrival of this new era in data volume, we argue that the time for careful consideration of how to manage and leverage current and future data streams, and development of the tools to do so, is now.

IN SITU VISUALIZATION OF HIDDEN LIFE FORMS WITH PHASE SENSITIVE X-RAY MICRO- AND NANO-IMAGING.
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Introduction: Unraveling mysteries of the formation of the solar system and the origin of life will require in situ access to nanoscale worlds of the solar system. There are two basic reasons for that: (1) The fundamental building blocks of the solar system, including small primitive volatile organics and ice grains, are most likely at the submicron and/or nanoscale in size, and (2) organisms could be prevalent across our solar system and beyond but predominantly present in small forms of life hidden on other worlds such as ocean worlds. The next ~ 30 years of planetary exploration will provide the opportunity to revolutionize our fundamental understanding of the solar system and life, including answering one of the most profound questions facing humanity: Is there life elsewhere in the universe? To make that happen, however, we have to develop new instruments now that will enable extant life on other worlds of the solar system to be directly detected and physically visualized. In this presentation, we will explore the potential of phase sensitive X-ray micro- and nano-imaging to in situ visualize and analyze the morphology and structures of organisms in 2-D and 3-D detail.

Phase sensitive X-ray imaging: Phase contrast or phase sensitive X-ray imaging, which incorporates phase contrast into otherwise absorption X-ray imaging, enables the hidden, intact microscopic structures, textures, and morphologies of heterogeneous materials, including lifeless material and living things, to be visualized in a detailed manner otherwise unobtainable. The interaction of X-rays with matter can be described by a complex index of refraction n, $n=1-\delta-i\beta$, where δ and β are the refraction (phase shift) and absorption terms, respectively. In other words, both refraction and absorption occur as X-rays pass through an object. Conventional hard X-ray radiography and tomography imaging relies on only photoelectric absorption (the β) and hence has poor image sensitivity to low-density objects or components (e.g., water and organic matter) in heterogeneous materials. This causes the difficulty of spatially mapping/distinguishing organic matter, lower-density minerals and those with similar density, and organisms potentially preserved in pristine or less irradiated ice samples of icy moons (e.g., Europa and Enceladus). Phase contrast X-ray imaging, on the other hand, utilizes X-ray refraction (the δ), which occurs at the interfaces that define various structures of interest (e.g., grains, pores, organisms and internal structures), and it translates structure-induced phase modulations into intensity variations through wave propagation, resulting in edge or interface enhancement (Fig. 1). Moreover, for hard X-rays travelling through low-density material such as organic matter, the phase shift term δ is dominant, on the order of 10^{-6} compared with 10^{-8}-10^{-9} for the absorption term β. In other words, the phase-shift cross section can be several orders of magnitude greater than the absorption cross section. This is the basis reason why phase contrast X-ray imaging enables such delicate internal structures to be visualized in both lifeless and life-containing or living solid samples that may be difficult to resolve otherwise.

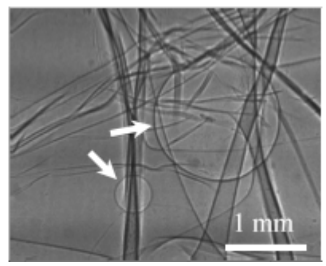

Fig.1. Phase sensitive X-ray microradiography image revealing polymeric foam structure and water droplets (arrowed) trapped in the foam through phase contrast. Strong black/white phase contrast forms at the water-air interface and foam edges.

Phase sensitive X-ray imaging for planetary science: Significant progress has recently been made in X-ray imaging both technologically and scientifically. For example, exploiting phase contrast X-ray nanotomography has allowed intact pores, carbonaceous material, medium-, and high-density grains in bulk interplanetary dust particles (IDPs) to be visualized and analyzed morphologically, texturally, and microstructurally in 3-D ~ 10 nm detail [1]. These include Fe/Fe-rich minerals, amorphous silicates, and low-density sub-μm refractory grains (e.g., Fig. 2). The tiny distinct refractory hollow grain (Fig. 2) is virtually transparent to 10 keV photons used. But the strong phase contrast effects at the interfaces have not only made this intact, ancient grain visible but also have revealed surprisingly morphological and textural details. Likewise, exploiting phase contrast X-ray microtomography has enabled us to noninvasively uncover the morphological, textural, and structural details of organisms, cellular polymers, and porous carbon composites. Both morphological and structural details would be crucial for providing unambiguous evidence of extant life on ocean worlds. As seen below, organism-containing ice samples would be ideally suited to phase sensitive X-ray imaging.

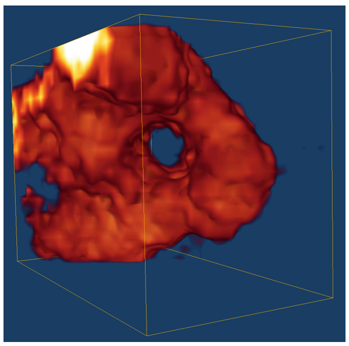

Fig. 2. Phase contrast X-ray nanotomography image of a low-density sub-μm refractory hollow grain uncovered noninvasively in an intact IDP [ref. 1]. Rendered volume: 270×330×435 nm^3.

Compelling evidence of the presence of a global, active salty-liquid-water ocean between a rocky core and an icy crust on Europa and Enceladus has made them two of the most plausible places that could harbor extant life in the solar system beyond Earth [2-9]. Ocean material may well have been brought to the water ice crust though various geological processes and preserved in pristine ice at depths of ~ 10 cm below the surface of Europa. This provides the opportunity for lander missions to geologically-young, less irradiated surface areas to directly search for and detect extant life (e.g., small organisms). Organisms embedded in the ice matrix are well suited to phase sensitive X-ray radiography and tomography. This case is conceptually similar to imaging the water droplets trapped in the polymeric foam (Fig. 1), a crystal immersed in liquid [10], or an organism surrounded by air (not shown here). The millimeter-centimeter thick water ice matrix will only produce negligible or weak background contrast in high-energy X-ray images. For example, the attenuation path length, the distance into the material where the intensity of X-rays falls to 1/e of its initial value, is 33.6 mm for 30 keV photons passing through water ice. In situ phase sensitive X-ray radiography and tomography would make individual organisms in the ice matrix conspicuous both morphologically and structurally because of the extreme sensitivity to the interfaces that define their internal structures as well as to their edges or peripheries. In a case where an ice sample of Europa contains organisms and other materials such as NaCl or halite crystals [11], strong phase contrast effects at various interfaces, including at the NaCl-water interface, would make morphologically distinct crystals and organisms stand out from the ice matrix. In many cases, a few high-resolution phase sensitive X-ray radiography images of the bulk ice sample would probably suffice to enable organisms to be recognized morphologically and structurally, providing a simple, fast yet powerful way to noninvasively uncover morphological and structural evidence of life. In addition, the levels of details to be revealed in situ would enable meaningful comparisons of small life forms on different worlds morphologically, structurally, and compositionally, when combined with composition analysis. The investigation would provide insights into the formation and evolution of life and local environments. The new imaging technique could be equally utilized to search for life on Mars. It would also enable pristine icy comet samples to be structurally visualized to in situ uncover a primitive microscopic world of the early solar system.

Summary: Recent advances in X-ray imaging both technologically and scientifically have opened up the opportunity to address science questions that might be inconceivable previously. With its extreme sensitivity, high resolution, and great flexibility, phase sensitive X-ray microscope imaging will enable intact organisms preserved in bulk ice samples to be visualized and analyzed morphologically and structurally in 2-D and 3-D detail. Developing in situ phase sensitive X-ray imaging at the micro- and nano-scale would create a powerful new X-ray eye to uncover the hidden microscopic world of "extraterrestrial life" in our solar system and gain new insight into the origin of life.

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LUNAR VOLATILES AS A RESOURCE FOR SCIENCE AND EXPLORATION. D. M. Hurley[1], the LEAG Executive Committee[a]; [1]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD (dana.hurley@jhuapl.edu).

Introduction: Our knowledge of volatiles on the Moon has made significant progress in that last decade. However, many unanswered questions remain that will guide the work on Lunar Volatiles for years to come. In the general path of planetary exploration that proceeds from flyby to orbit, to land, to rove, to return samples, Lunar Volatiles research is in the "orbit" stage. Interestingly, general research on the Moon has been through all of those stages in the 1960s and 1970s, even including human exploration, without addressing lunar volatiles. The progress made postdates those efforts, enabled by orbiters, varying instrumentation, and technology advances for analyzing returned samples.

Volatiles on the Moon have both scientific and exploration significance. For exploration, water represents a valuable resource that can be mined for production of propellant and life support. Most visions of sustained operations in space beyond low Earth orbit include exploiting resources on the Moon to reduce the cost of planetary exploration. The in situ resource utilization (ISRU) of lunar water will require a combination of science, engineering, policy, and business development.

For science, lunar volatiles offer a window into the past inventory of volatiles in the Inner Solar System, including volatiles retained by the Moon during its formation, fluxes of exogenous volatiles over billions of years as well as the present day [1-3]. The Moon's environment is representative of many other airless bodies in the Solar System where the surfaces are highly activated. Weathering by ion bombardment, photons, and meteoroid impacts distorts the mineralogical and electronic structure of the surface [4]. Interactions between gases and the surface play an important role in volatile distribution and retention [5]. The Moon's relative ease of accessibility enables investigation of these processes in situ more readily than its more distant cousins. In addition, the extremely cold, persistently shadowed regions (PSR) at the lunar poles are an interesting laboratory for prebiotic chemistry. Many of the building blocks for life are potentially retained in the PSRs where they are exposed to cosmic rays, meteoroid impacts, and potentially electric discharges [6]. These stimuli can slowly synthesize complex molecules over the long lifetime of volatiles in the PSRs [7].

Vision: In 2050, the proposed Moon Village [8] will be at some stage of implementation. Therefore, the Moon will host a combination of activities from a diverse set of nations and commercial groups. Lunar volatiles will be in regular use for exploration efforts. Commercial entities will be harvesting the volatiles and improving production strategy. The Moon will be a testing ground for ISRU efforts on asteroids and Mars.

Scientifically, much work will have been done to understand the sources, sinks, age, and redistribution of volatiles on the Moon. Ongoing work will use the Moon as a baseline for comparison of volatiles on other airless bodies such as Mercury, asteroids, and the Martian moons. Scientific work will focus on interactions between volatiles and external drivers especially in PSRs, where the cold temperatures retain the more volatile compounds.

Pathway and Vision: Multiple documents already exist containing suggestions for the roadmap for lunar research including the Scientific Context for the Exploration of the Moon (SCEM) report [9], the Lunar Exploration Roadmap (LER) [10], including the implementation strategy that explores and utilizes lunar volatile resources [11], the Volatiles Strategic Action Team (VSAT) report [12], and the ISECG Global Exploration Roadmap [13]. Here we highlight some aspects that will enable scientific progress and exploration goals, and also reflect the LEAG LER implementation plan [11].

2020s: Lunar remote sensing can still provide a wealth of information on lunar volatiles: monitoring sources, sinks; mapping distributions; determining composition and physical form; and quantifying abundances. Cubesat and Smallsat opportunities provide a low-cost method to perform targeted investigations of single pieces of the system. A dedicated long-lived volatiles orbiter mission could make significant progress at understanding the hydrological cycle on the Moon.

Many questions are, however, better answered by an in situ investigation. Landed missions to the surface of the Moon both inside and outside of the PSRs are required to provide ground truth to the remote sensing investigations and provide in situ subsurface data. Landed packages can inform on the composition of volatiles, the physical form, the abundance and the distribution. They can monitor ongoing processes. With commercial entities planning lunar landers, these investigations can be included as rideshares. Multiple dedicated missions offer efficient means to assess lunar volatiles in situ. These should address scientific and exploration objectives, which largely overlap in the early stages. Inclusion of ISRU demonstration packages is a necessary step toward regular production of resources from lunar volatiles.

2030s: The landed exploration with mobility will lead to understanding the magnitude, accessibility, form, and extractability of volatile deposits. This in turn will lead to sample return, where the most sophisticated instrumentation is available to conduct the analysis. Cryogenic sample return of lunar volatiles from inside and outside of the PSRs will validate and extend the results from remote sensing and in situ analysis (see also [14]).

As humans become part of activities near and on the Moon, they can assist in furthering both science and exploration objectives. Their contributions may include tele-operation of landed craft, instrument deployment, production plant set-up and maintenance, and sample acquisition. ISRU will begin. Operations will develop on the Moon of increasing magnitude. The methods will be ported for potential demonstration on Mars and asteroids.

Investigations of comparable bodies including Mercury and asteroids will progress. A mission impacting into PSRs at Mercury will provide important constraints on the volatiles there. In situ analysis on asteroids will provide detailed analogous data for relating processes on the Moon and asteroids.

2040s: Asteroid and Martian ISRU operations expand and enable further exploration. Landed missions on Mercury investigate sources, composition, and distribution of volatiles on Mercury. The overall understanding of volatile inventories of the Inner Solar System becomes more detailed in terms of relative importance of sources through space and time, roles of external drivers to alter the composition and distribution, radiation-induced and surface-catalyzed molecular synthesis.

Critical Issues: While science and exploration have many aligned objectives, consideration must be made that they do not inhibit one another. For example, large-scale operations on the lunar surface will introduce volatiles into the lunar environment that can migrate to the PSRs. Scientific analysis should precede major utilization efforts to maintain the scientific integrity of the region. Fortunately, the scientific analysis enables the eventual utilization by providing the necessary prospecting and characterization to design the extraction technique.

The PSRs, however, are an extremely challenging environment. From an operational perspective, the low temperature and lack of solar power complicate the engineering and design of systems, particularly with respect to power. Some lunar PSR not only lack sunlight, but Earth visibility as well, requiring communications via an orbiter. The lack of high-resolution images increases the uncertainty in surface operations.

Multiple nations are presently planning and conducting lunar programs. Coordination of those activities through ISECG or a similar organization can maximize the return for each participating nation, reduce reproduction of effort, and provide an array of resources for all involved. Policy for international cooperation and for private/public coordination is a critical component to development of lunar volatiles.

Conclusion: Lunar volatiles are important to both exploration and science. They retain a record of the volatile history of the Moon and the inner solar systems and can provide insight into the evolution of the Sun. From an exploration perspective they can significantly reduce the cost of spaceflight by providing water for both life support and fuel (as well as other volatiles) by reducing the amount of mass launched from the Earth. Lunar volatiles will not be understood by orbital data alone, in situ surface and subsurface samples and data will be required for scientific and exploration objectives.

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THE VENUS AND MARS PILOTED INTERPLANETARY ROUNDTRIP EXPEDITIONS: SCIENCE OPPORTUNITIES OF THE NEXT HUMAN SPACEFLIGHT AGE.
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Introduction: Venus science missions are detailed in the current NASA Decadal Survey [1] and ESA's Cosmic Vision [2]. NASA's Discovery and New Frontiers programs, and the ESA's M-class solicitations regularly include small and medium-size Venus mission proposals on multi-year year cycles. The Venera D mission – a joint effort between NASA, Russia, and others [3], is being explored as well. However, opportunities for Venus exploration, especially for large, high-capability missions are few and far between. A class of opportunities for multiple significant Venus planetary science missions exists on the human pathway to Mars over the next decades.

Age of EMPIRE: Venus flybys and even orbital missions have been part of plans for human space exploration since the early days of space flight. The earliest documented Venus human flyby proposal dates back to 1956, with a launch opportunity in 1971 [4] (Fig 1). In the ensuing decades, multiple NASA studies explored in detail various multiple piloted planetary mission scenarios, some of which included Venus flybys, or dual-planet missions [5-7, others]. The series of studies was included EMPIRE (Early Manned Planetary-Interplanetary Roundtrip Expeditions), and meant to leverage nuclear rockets and Apollo-era hardware into ever more ambitious human space endeavors.

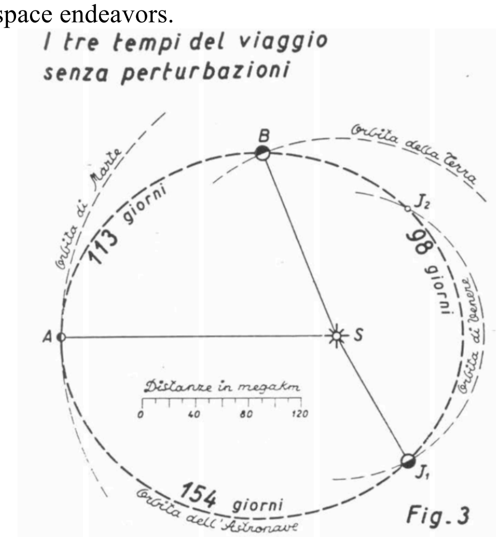

Fig. 1. First proposed piloted Venus-Mars flyby trajectory [4].

Early proposals proved to be technically, economically, and/or politically unfeasible or unworkable over time. For example, in addition to basic long-term human life support, long-term radiation exposure and inner solar system heat hazards could not be addressed in detail 50 years ago. Nevertheless, a number of human piloted Venus flyby and rendezvous mission studies were undertaken and completed through the 1960's and early 1970's and Venus flyby components of Mars missions have persisted through the decades.

Venus to Mars Today: In the current NASA plan for human exploration of Mars, as expressed in the amended Design Reference Architecture (DRA) 5.0 [8-10], Venus flybys remain as valid choices in the latest documented plans for the human path to Mars using current and imminent technological capability such as the Space Launch System (SLS) [11].

Venus flyby scenarios currently under consideration are for "opposition" type missions to Mars (Fig. 2) in which the spacecraft swings by Venus on the outward or return leg to Mars, and mission durations at Mars are from 20 to 100 days in length [10]. These shorter Mars-stay missions, as opposed to 550 to 730-day stay-at Mars "conjunction" class missions occupy an enticing sweet-spot among candidate Mars rendezvous missions, combining weeks to months at Mars with shorter total mission duration and lower total mission ΔV (Fig. 2).

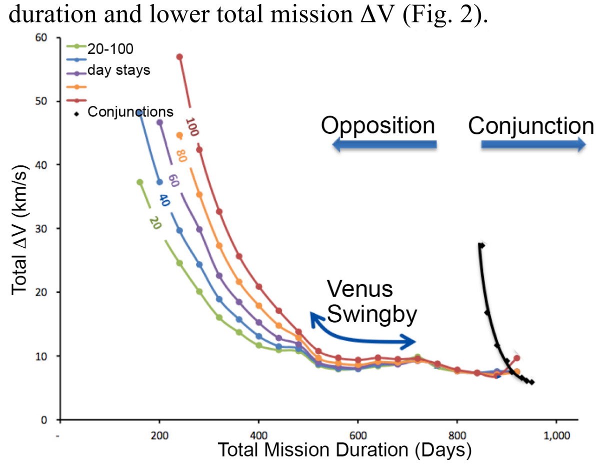

Figure 2. Example round trip ΔV as a function of total mission duration. See [10] for bounding assimptions. The "Venus Swingby" region delineates a subset of mission types that minimize both total duration and ΔV.

From the beginning, Venus flyby missions were not viewed merely as an opportunity for getting to Mars more easily, or with lower cost and risk, but also as a science opportunity. Venus flyby plans have included language for "dropping off" of science payloads and science observations during the flyby. The same would be true in the modern conception of a piloted Venus flyby, and for unpiloted support or infrastructure missions en route to Mars. Both the planetary and human space flight communities would benefit from consideration specific science opportunities of the different options.

A New EMPIRE: Most current concepts of SLS-launched missions to Mars include 4-10 rocket launches, and each SLS launch has the capability of bringing up secondary payloads (of as yet unconstrained mass and other specifications). Even human Mars missions that do not include a Venus flyby component still provide orbital staging opportunities for planetary missions. The DRA describes SLS secondary accommodations for multiple comsat or equivalent secondary payloads per SLS launch. These payloads present opportunities for solar system targets, including Venus. However, on Earth-Venus-Mars-Earth (EVME) or Earth-Mars-Venus-Earth (EMVE), Venus probes in particular would be logical secondary payload choices. Venus flyby orbits would create enabling opportunities for one or more significant probes to be dropped for insertion to Venus orbit or descent into the atmosphere and/or to the surface. The EVME mission might be most practical for larger Venus-destined payloads carried with the crew, since the jettisoning of Venus-bound payloads would reduce total mass for spacecraft maneuvers for the rest of the mission.

What kind of missions might be enabled by a piloted flyby of Venus? Having a crew en route, during, and after flyby enables several mission architectures, including, but not limited to:

- "Very Large Venus Probes": This concept would include large, potentially modular probes or constellations launched in pieces and assembled or otherwise enabled by crew en route to Venus. Mission concepts could include cubesat, smallsat, or larger multiple satellite constellations [12], or large probes brought into space in pieces in multiple SLS launches with final assembly en route to Venus.
- "Human-In-The-Loop Probes". These missions would capitalize on the minimization of light-speed delay in communication between a crew flying by Venus and a payload inserted into Venus's atmosphere or surface to enable real-time decision-making and reaction to events [13]. Crew may actively guide human-in-the-loop probes in the Venus environment during the days or weeks around closest approach using real-time telemetry. These mission concepts include guide-able aerial platforms [14,15] to surface rovers [16]. Human decision-making could assist in terminal guidance for pinpoint landing selection, fast evaluation and sample selection, initial roving destination and guidance for mobile platforms, and possibly other functions.
- "Grab and Go Sample Return" Fast sample-grab-and-return from the Venus atmosphere, rendezvousing with the departing spacecraft instead of transiting to Earth [17].

The Opportunity: While Venus flyby opportunities on the path of human exploration of Mars are currently in the books, they do not have high mind-share in the human spaceflight community. Issues, technical challenges, and risks of temperature and radiation exposure in the <1 AU environment, and protection of crew and equipment are examined in the current DRA and its supplements, but Venus flybys are not at the forefront of thinking or plans.

Another concern about any pathway to Mars is the repeatability of the architecture. Risk and cost are reduced if a mission profile can be repeated multiple times. EVME and EMVE present two similar Mars mission profiles that are still different from each other as well as from direct-to-Mars trajectories. The question remains whether the potential costs and benefits to human spaceflight and scientific exploration balance out in favor of a Venus component. Venus flybys en route do, however, create multiple additional opportunities for Mars flyby and Mars rendezvous missions. Analysis of opportunities for the current decade (2015-2025) [18], find five Mars flyby and six Mars short-stay (weeks to months) opportunities with Venus flybys either outbound or inbound, all with reasonable total mission durations and ΔV. In addition, Earth-Venus-Earth (EVE) flyby missions were identified. Low ΔV EVE launch opportunities are more frequent than are Earth-to-Mars (19-month cadence vs. 26 month) [19], and could be utilized as early, reduced-risk, long-duration piloted missions on the path to Mars, i.e., a "shakedown" dress-rehearsal mission prior to the longer-duration first human expedition to Mars.

Repeating Venus planetary science opportunities presented by EVE, EVME and EMVE missions are significant and, in an era of renewed interest in and ambition for going to Mars, a timely opportunity that could span decades.

Looking to 2050, the Venus science community has the opportunity at this time to voice active support not just for human-crewed missions, but human exploration of Mars in particular (*and* Venus) in the next several decades, for the additional payload opportunities it creates. Furthermore, the Venus community has a stake in advocating for *how* we get to Mars as well. Making the case that the best path may include both planets is an idea whose time has come around again.

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MARS EXPLORATION 2050: HUMAN AND ROBOTIC EXPLORATION INTERTWINED. B. M. Jakosky, Univ. of Colorado (LASP, U. of Colorado, 3665 Discovery Dr., Boulder, CO 80303, bruce.jakosky@lasp.colorado.edu).

Introduction: Space exploration over the next thirty years is likely to include increased human involvement and to have increased collaboration between human and robotic missions. One of the options being discussed for human missions is Mars. Why Mars? "People in space" has always been about reaching beyond our grasp and exploring the unknown, and a target such as Mars is simultaneously very difficult and very doable. In addition, Mars allows us to explore profound and fundamental scientific questions – how do planets form and evolve, what factors control the evolution of planets and of climate, and is there life beyond the Earth.

The Science Is Important: Mars exploration brings together most aspects of our scientific goals in exploring the solar system. It gets at our understanding of planetary formation, interior/thermal history, climate evolution, interaction with the Sun and the solar wind, and, of course, the origin and evolution of life. Combining these questions at one object has made Mars a central focus in exploring our solar system. It is the place that best combines a reasonable likelihood of having (or having had) life with relatively straightforward accessibility by spacecraft.

The question of whether Mars has life might be answered in part by the ESA/Russian Trace Gas Orbiter, by *in situ* analysis, or by sample return in the next decade. However, a simple yes or no will not fully address the questions. If life exists, what is its distribution around the planet, its history, its relationship to the planet's geologic and climate history, and does it represent an independent origin from that on Earth? If life never existed, what is it about the Martian environment or its history that precluded its origin or existence?

Human Mars Missions Are Doable. The first human mission is not likely to be a full-up multi-year exploration of the surface. Such a mission would involve too many technical challenges and the stringing together of too many new developments. Rather, we can build toward that with a flyby or orbital mission using technology we have at hand today. This approach is analogous to the Apollo missions to the Moon – test out technologies in Earth orbit, then in lunar orbit, lunar flyby, full-up test in Earth orbit and lunar orbit, then land on the Moon. Taking this approach at Mars, we would start with a human flyby or orbital mission; we have the technical capability today to develop this mission. Taking this approach would allow us to start development today of a mission that could fly in 10-15 years, making it soon enough as to be real rather than infinitely far into the future. This mission also gives us time to develop the hardware for a later mission that would take people to the surface and back up, first for a quick sortie and then for a longer stay. A full-up program might take several decades to carry out fully, but would have short-term objectives that by themselves are important.

Human And Robotic Exploration Are Compatible: Many planetary scientists see the human exploration program as the enemy of "real" science. It's not an either/or – cancelling the human program, for example, would not result in that money going into the robotic program. Rather, the human and robotic programs are not only compatabile with each other, they are intimately intertwined – each plays on the successes of the other, and both work toward a common goal.

A decision to continue the human program or to send people to Mars will not be made on the basis of the science that will come out of it. That decision will be based on national pride, a desire to explore the unknown, and the challenge of doing human missions. If people are going to Mars, however, we should work to integrate science into these missions from the beginning. Robotic missions will inform the science to be carried out by human missions, can provide the context in which humans will explore, and can provide key information that will significantly help develop human missions have a higher level of robustness.

Science can be carried out by human missions, often in greater depth and more quickly than can be done robotically. While astronauts in orbit can target areas of the surface, control rovers more easily than from Earth, or explore Phobos or Deimos in person, the real value of having people there will be seen once they are on the surface – *in situ* exploration is dramatically enhanced when carried out directly by people.

Conclusions: We have the ability today to credibly plan and carry out a human mission to Mars. If Mars is the goal, we should do it by sending people to Mars and not by a decades-long diversion to somewhere else in the solar system. We have the capability to begin a Mars program today that has near-term, high-value objectives.

THE LONG RANGE FUTURE OF THE SCIENTIFIC EXPLORATION OF MARS. Mars Exploration Program Analysis Group (MEPAG) Executive Committee: J. Johnson[1], D. Beaty[2], B. Bussey[3], P. Christensen[4], V. Hamilton[5], S. Hubbard[6], M. Meyer[3], G. Ori[7], L. Pratt[8], R. Zurek[2], S. Diniega[2], L. Hays[2], [1]John Hopkins University, Applied Physics Laboratory, Laurel, MD 20723 (Jeffrey.R.Johnson@jhuapl.edu), [2]Mars Program Office, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 (David.W.Beaty@jpl.nasa.gov), [3]NASA HQ, [4]Arizona State University, [5]Southwest Research Institute, [6]Stanford University, [7]IRSPS (Italy), [8]Indiana University.

Introduction: Current planning for the scientific exploration of Mars is organized around three broad scientific goals [1]: *(I)* Determine whether Mars has ever supported life; *(II)* Understand the processes and history of climate on Mars; *(III)* Understand the origin and evolution of Mars as a geological system. In addition, MEPAG carries a fourth, implementation-oriented goal, which is *(IV)* Prepare for human exploration.

The vision of what the Mars Exploration Program (MEP) would or could look like in 2050 is dependent on what happens in each of the above goal areas, modified by the potential for "disruptive" discoveries, based on ongoing as well as upcoming missions (such as NASA's 2020 Mars rover, ESA's ExoMars missions, and ISRO's next Mars mission). There are many pathways and contingencies, none of which can be described completely here. For the purpose of this document we assume basic engineering success for potential future missions (including Mars Sample Return (MSR)), that the international public remains interested in Mars exploration, and that by 2050 humans have successfully landed on the martian surface. Although implementation is not discussed here, the potential future science investigations may be most effectively pursued under international collaborations and/or utilizing "commercial" payload space, and are generally helped with a robust, concerted NASA Mars Exploration Program.

Possible scientific lines of in uiry after 1 :

Goal I (Life). The search for evidence that life existed on Mars in the past (whether or not it also exists today) would be dominated by the *MSR campaign*. Evidence of ancient microbial life is likely difficult to observe without samples in terrestrial laboratories. The result of these analyses would provide the single most important scientific disruption to consider in future planning (discussed below). The search for modern life is focused on the high-precision *measurement of trace gases* in the martian atmosphere, which could generate evidence of one or more refugia that could potentially be followed up by other missions. In addition, there are various hypothesis-driven proposals for specific tests of extant life in various martian environments. A discovery in this area would also be highly disruptive.

Goal II (Climate). Our current strategy involves ongoing *orbital monitoring of atmospheric dynamics* (including the transfer of mass and energy to/from the polar ice caps), atmosphere-surface interactions, and developing an understanding of extreme weather events (causes, magnitudes, predictability). By 2050, as long as orbital and landed assets capable of monitoring the martian weather have been adequately replenished so as to extend the temporal baseline and increase temporal and spatial coverage, we expect that sufficient data sets and predictive algorithms will exist for support of site characterization and human exploration.

Goal III (Geology). Martian geology is complicated by significant spatial and temporal variations in composition, mineralogy, hydrology, and landform evolution. In order to understand Mars as a global geological system, multiple landings in multiple geologic provinces are required, with sufficient high-resolution orbital data for characterizing the geologic context of in situ measurements. (This is no different than trying to interpret the geology of the Earth from a small handful of landings.) Importantly, MSR would provide answers for at least one site in the context of new information on the precise ages and ranges of geochemical and hydrological environments experienced by the samples.

Goal IV (Prep. for Human Explor.). The risk of sending a human mission to the martian surface can be significantly reduced by acquiring certain specific data sets [2]. This allows the mission to be designed to a narrower set of constraints, rather than to the total width of the uncertainty envelope. Whether a data set is required depends on the magnitude of the risk reduction that can be achieved, and the cost of engineering against the adverse consequences (which changes as our understanding of risk and risk tolerance evolves).

Primary pathways into the future: For purposes of the planning associated with this workshop, we assume that MSR has been completed, and the samples have been analyzed initially, by 2030-2035. We postulate that the results from these samples will constitute a Branch point in our long-range planning, that revolves around the following question: *Do the samples contain either permissive or definitive evidence of martian life?* This Branch point has implications for observations in situ and orbital investigations, and for human exploration plans. We also note that there are other types of observations that respond to objectives and priorities that are independent of the life question – some of those parallel science tracks are discussed below (within Branch #3).

Branch 1: MSR discovers life: *If MSR were to deliver evidence of ancient life in the sample suite, our scientific objectives would immediately diversify from "find the life" to "characterize the life", "how did it originate", "does it persist to the present", "how do we begin interacting with it", etc.* These types of big questions are not currently in the MEPAG Goals Document [1] nor within the MEP design because the motivation for them does not currently exist.

What would the MEP look like in this kind of environment? How would this change our science objectives and priorities within all areas of Mars science, not just the life-focused questions (i.e., Goal I within the MEPAG Goals Document [1])? In particular, one imagines that the need to characterize life and learn of its origin and evolution would require treating the exploration of the geologic and climatological context of any lifeforms and their habitat as a high priority.

The implications of this Branch for the human exploration of Mars are complicated. Even though MSR is designed as a test for ancient biosignatures, the positive discovery of past life would increase the possibility that life exists there today, with concomitant ramifications for planetary protection strategies. Thus, such a powerful discovery could trigger a delay in human exploration to first allow additional robotic investigation -- the first interaction of humans with another life form would need to be planned carefully.

Branch : MSR does not discover life: *What does the MEP future look like if MSR comes up empty on the life question?* Given the single sampling site currently planned for Mars 2020, how does the strategy for life detection evolve, if it continues to be a goal? It could focus on more of "survey"-type studies for past habitable environments exposed at the surface. Or it could focus more on drilling to access the subsurface, which may have been a better candidate both for habitability and preservation. In that realm the results from the ExoMars rover will influence future efforts for near-subsurface investigations.

Certainly investigations of Mars aside from the life question would increase the priority of non-MSR-dependent science. In achieving those investigations of the past and present environment, the generated information could continue to advance our understanding of the limitations on where life does develop.

An interesting implication of this Branch is that it would ease (but not eliminate) the planetary protection concerns related to the human exploration of Mars. This may have the effect of enabling and accelerating sending humans to the martian surface.

Branch : Science Enabled by Strategies that are Not Dependent on MSR: What is the future of the sectors of Mars science that are independent of the sample return studies? *Many geologic and climate focused science questions (i.e., elements Goals II and III within the MEPAG Goals Document [1]) have priorities that would remain high whether or not examined in the context of life.* For example, understanding the Martian climate over the planet's history adds to our understanding of climate cycles and interactions, and to models of atmospheric processes and components, many of which are relevant to human exploration studies. Determining how the formation and evolution of the lithosphere is revealed in the geologic record through analyses of surface mineralogy, impact history, seismology, and volatile evolution in both polar and equatorial regions improves our understanding of Mars as a geologic system and its place in the Solar System. Such studies are relevant for advancing studies of terrestrial environments as well as for the larger-scale study of planetary atmospheres (i.e., comparative climatology). Other important investigations include Mars seismological science or identification of construction materials and in situ resources for human exploration.

Although these scientific objectives have value independent of the life question, a key issue for discussion is the stability of the MEP in an environment geared dominantly towards non-life questions . In this instance, the "survey"-type study may also be a way to understand more about Mars as a system and could involve interdisciplinary research that could be key to long-term stability.

Breakdown into larger Thrusts. The above analysis naturally lends itself to the breakdown of the next several decades into four partially overlapping thrusts that will be described more fully at the workshop: *(1)* The MSR Thrust. We assume that the samples can be delivered to Earth and analyzed by about 2030-2035. *(2)* The pre-human-driven exploration Thrust. This is likely to overlap MSR, and the overall timeline will be driven by the timing of humans to the martian surface. *(3)* The non-MSR science Thrust, that runs in parallel. *(4)* The human exploration Thrust.

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DEPLOYABLE PROPULSION PO ER AND COMMUNICATIONS SYSTEMS FOR SOLAR SYSTEM EXPLORATION. L. Johnson,[1] J. Carr,[1] and D. Boyd,[1] NASA George C. Marshall Space Flight Center, ED04, Huntsville, AL 35812, les.johnson@nasa.gov.

Introduction: NASA is developing thin-film based, deployable propulsion, power, and communication systems for small spacecraft that could provide a revolutionary new capability allowing small spacecraft exploration of the solar system. By leveraging recent advancements in thin films, photovoltaics, and miniaturized electronics, new mission-level capabilities will be enabled aboard lower-cost small spacecraft instead of their more expensive, traditional counterparts, enabling a new generation of frequent, inexpensive deep space missions. Specifically, thin-film technologies are allowing the development and use of solar sails for propulsion, small, lightweight photovoltaics for power, and omnidirectional antennas for communication.

Solar Sails: Like their name implies, solar sails 'sail' by reflecting sunlight from a large, lightweight reflective material that resembles the sails of 17th and 18th century ships and modern sloops. Instead of wind, the sail and the ship derive their thrust by reflecting solar photons. This continuous photon pressure provides propellantless thrust, allowing for very high ΔV maneuvers on long-duration, deep space exploration. Since reflected light produces thrust, solar sails require no onboard propellant. Solar sail technology has been discussed in the literature for quite some time, but it wasn't until 2010 that sails were proven to work in space.[1]

Studies show that sails of various sizes can propel small spacecraft to multiple destinations in the inner solar system, many of which are otherwise unreachable (from a propulsion point of view) – including asteroids, comets, planets and moons. In some cases, the benefits of a solar sail are in launch window flexibility – providing additional opportunities for space launch.

The Near Earth Asteroid (NEA) Scout reconnaissance mission will demonstrate solar sail propulsion on a 6U CubeSat interplanetary spacecraft and lay the groundwork for their future use in deep space science and exploration missions.[2] The NEA Scout mission, funded by NASA's Advanced Exploration Systems Program and managed by NASA Marshall Space Flight Center (MSFC), will use the solar sail as its primary propulsion system, allowing it to survey and image one or more NEA's of interest for possible future human exploration. A full-scale engineering model of the solar sail can be seen in Figure 1. NEA Scout uses a 6U cubesat (to be provided by NASA's Jet Propulsion Laboratory), an 86 m^2 solar sail, and will weigh less than 12 kilograms. NEA Scout will be launched on the first flight of the Space Launch System in 2018.

Figure 1. 86 square meter test sail deployed horizontally during a test at NASA MSFC. A half-scale sail hangs vertically in the background.

Deployable Power Systems: Thin-film photovoltaics are revolutionizing the terrestrial power generation market and have been found to be suitable for medium-term use in the space environment. When mounted on the thin-film substrate, these photovoltaics can be packaged into very small volumes and used to generate significant power for small spacecraft.

The use of thin-film based solar arrays for spacecraft applications has long been recognized as an advantageous power generation option. Thinner materials yield a mass savings, equating to lighter launch loads and/or more payload allocation. Perhaps more importantly for the small spacecraft community, their mechanical flexibility lends itself well to stowage and deployment schemes.

This allows an improvement to both specific power (W/kg) as well as stowed power density (W/m3), enabling higher power generation for small spacecraft. Though several larger scale thin-film or partial thin-film arrays are in development, sub-kilowatt thin-film arrays remain scarce. The Marshall Space Flight Center (MSFC) Lightweight Integrated Solar Array and anTenna (LISA-T) seeks to fill this void, both increasing as well as simplifying small spacecraft power generation.[3]

LISA-T marries the most recent advances in the solar sail and photovoltaics community to create a fully thin-film array. Two configurations are currently under development: (i) the omnidirectional (non-pointed) and

(ii) the planar (pointed). The former stows into a single CubeSat U, while the latter into 1/2U. The omnidirectional array is based on a three-dimensional shape such that no matter how the craft is orientated, power will be generated. This relaxes the need for pointing and greatly simplifies power generation.

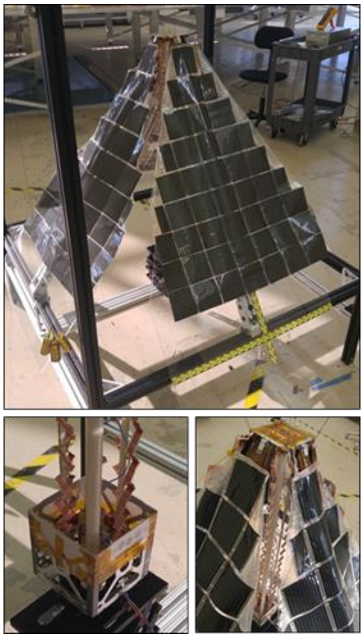

Figure 2. Deployed LISA-T omnidirectional configuration prototype. The complete, deployed power system and antenna were stowed in ½ U.

Power levels up to 125W peak beginning of life are currently achievable in this configuration. The planar array is based on a traditional flat configuration. Though it requires solar pointing, it maximizes solar cell use and the array parametrics. Power levels up to 300W are currently achievable in this configuration. Options for leveraging both a high performance (~28% efficient @ ~$250/W) triple junction thin-film solar cell as well as a low cost (~10% efficient @ ~$15/W) single junction are being developed for both configurations. Stowage efficiencies approaching 400kW/m3 with specific powers approaching 250W/kg are currently achievable

Work to date has brought both configurations to Technology Readiness Level (TRL) 6. NASA's Space Technology Mission Directorate if funding a flight demonstration study of the LISA-T with a Mission Concept Review (MCR) planned for later in 2017.

Deployable Antennas: Embedded antennas are being developed that can be adhered to thin-film substrates to provide lightweight, omnidirectional UHF and X-band coverage, increasing bandwidth or effective communication ranges for small spacecraft.

Non-pointed missions benefit from antenna system designs with customizable radiation patterns. Antenna arrays provide opportunities for custom radiation patterns, overall gain increases, diversity reception, directional interference cancelling or steering, and incoming signal direction determination. The created surface area of these deployable propulsion and power systems creates new opportunities for the inclusion and positioning of multiple lightweight deployable antennas. LISA-T integrates lightweight axial mode helical antennas into the deployable power system. These lightweight antennas are flexible for stowage and can be positioned on either the center point of a panel package or on the panels themselves. Antennas on the panels can be placed on either side of the panel as desired.

Custom lightweight helical antennas have been created for S band and X band communications. Simulations show both S band and X band helical antennas to have a main beam gain greater than 10db. By placing multiple antennas in various positions on the structure, desired coverage patterns or phased array implementations can be achieved.

In addition to S and X bands, integrated UHF dipole antennas with a simulated gain of 1.6db have also been developed. These dipole antennas can be integrated into the panel between or beside solar cell elements. Further details on the antenna development are published elsewhere.

Benefits: Considered individually, each of the innovations described above are enabling for the emerging use of smaller spacecraft for solar system science and exploration. Taken together, they may enable a host of new deep space destinations to be reached by a generation of spacecraft smaller and more capable than ever before.

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PROPULSION AND PO ER USING ELECTRODYNAMICS. L. Johnson,[1] L. Habash Krause,[1] B. Wiegamnn,[1] S. Bilén,[2] and B. Gilchrist,[3] [1]NASA George C. Marshall Space Flight Center, Huntsville, AL 35812, les.johnson@nasa.gov, [2]The Pennsylvania State University, [3]The University of Michigan

Introduction: In order to advance our capabilities in space exploration within our solar system over the next several decades, it is necessary to a) understand our science and exploration priorities, b) determine operational requirements, c) assess gaps in technologies necessary to fulfill those requirements, and d) perform the necessary research and development to fill those gaps. This is often not a linear process, but an iterative one in which "leap-frog" progress is often the result. With the combined efforts of scientific and technical experts from a broad scope of relevant disciplines, it is possible to develop a comprehensive vision for the pathway to advanced space exploration over the next 35 years. This paper provides potential solutions for two of the most common necessities in space exploration: propulsion and power. In particular, we discuss two forms of electrodynamic propulsion and power, namely electrodynamic tethers and electric sails, as science-enabling technologies for planetary research.

Electrodynamic Tethers EDTs : EDT propulsion generates Lorentz force thrust through the interaction between current driven along a conducting tether and a planetary magnetic field, using the planet itself as reaction mass rather than the expelled propellant. In general, three key principles govern EDT operation [1]: 1) the conductor has an intrinsic electromotive force (*emf*) generated along it due to the orbital motion of the tether (**v**) across the magnetic field (**B**); 2) the conductor provides a low-resistance, current ( ) conducting path connecting different regions of the ionosphere; and 3) access to external electron and ion currents is confined to specific locations, such as the endpoint when the conductor is insulated, or collected along a length of bare tether [2].

Current flows through the tether when a connection is made between the tether's endpoints and the surrounding ionospheric plasma, which can be accomplished via passive or active means. In the passive case, the voltages and currents in the overall system distribute themselves in a self-consistent manner, which can require the endpoints to charge to high levels in order to attract enough current. Active means generally employ an electron generator of some type, such as an electron gun or hollow cathode plasma contactor (HCPC). Future tether systems may employ field emitter array cathodes (FEACs), but much work remains before FEACs are practicable for EDT systems. With either connection method, current flows through the tether as shown in Figure 1. In the EDT propulsion case, current flows down the tether because a high voltage source has overcome the motion-induced $\mathbf{v} \times \mathbf{B}$ electric field in the tether. After electrons are collected at the lower satellite, they are conducted through the tether to the upper satellite where they are ejected. Current closure occurs in the ionosphere, thus making the overall circuit complete. The resulting $\times \mathbf{B}$ force is in a direction such as to pull the tether. Thrust levels are highly dependent on current flow and typically less than 1 N.

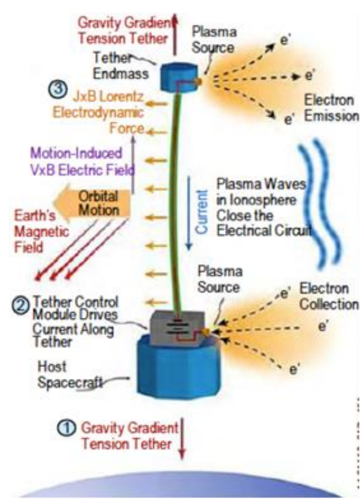

Figure 1. The essential physics of EDT propulsion. An EDT system generates thrust using interaction between current driven along a tether and the magnetic field of the planet it orbits, enabling propulsion without expelling propellant. (Concept art courtesy of Tethers Unlimited.)

The drag, or de-boost, case does not require the high voltage source and, as such, is often referred to as the self-powered mode. In this case the current flows up the tether, resulting in a $\times \mathbf{B}$ drag force. This configuration also allows for energy-harvesting, in which the tether current may be driven through other electrical loads (e.g., resistors, flywheels, batteries)[3].

Electrodyamic tether propulsion and power generation can work around any planetary body with a magnetosphere and has been studied for operation at both Jupiter and Saturn [4]. A modest-sized tether operating at Jupiter could provide tens to hundreds of kilowatts of power and produce thrust sufficient for relatively high delta-V maneuvering.

The technology has benefitted from extensive testing in Earth orbit where tethers ranging from a few meters to tens of kilometers have been successfully deployed and operated [5].

Electric Sails E Sails : The E-Sail will enable scientific spacecraft to obtain propulsive thrust using the momentum of the hypersonic solar wind to provide propulsion throughout the solar system. Consistent with the concept of a "sail", no propellant is needed as electrostatic interactions capture a small amount of thrust from the solar wind that can, over a period of months, accelerate a spacecraft to enormous speeds—on the order of 100–150 km/s (~ 20–30 AU/yr).

The basic principle on which the E-Sail operates is the exchange of momentum between an "electric sail" and the solar wind, which continually flows radially away from the sun at speeds ranging from 300 to 700 km/s. The "sail" consists of an array of long, charged wires that extend radially outward 10 to 30 km from a slowly rotating spacecraft (see Figure 2). Momentum is transferred from the solar wind to the array through the deflection of the positively charged solar wind protons by a high voltage potential applied to the wires.

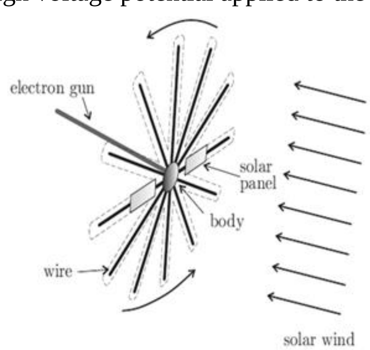

Figure 2. An Electric Sail obtains thrust by reflecting solar wind protons.

The thrust generated by an E-Sail is proportional to the "area" of the sail, which is given by the product of the total length of the wires and the effective wire diameter. Although the wire is approximately 0.1 mm in diameter, its effective diameter is determined by the distance the applied electric potential penetrates into space around the wire (on the order of 10 m at 1 AU). As a result, the effective area over which protons are repelled is proportional to the size of the region of electric potential, or the plasma sheath region, that surrounds the wires of the array.

A large sheath is, therefore, beneficial to the generation of thrust. However, this benefit must be balanced with the additional fact that electron collection is proportional to sheath size. Electrons collected by the wire array must be injected back into the solar wind in order to maintain the potential on the wires—which requires power. The primary power requirement for E-Sail operation is, therefore, also proportional to sheath size.

Size of the sheath is determined by the applied potential and how effectively the charged particles of the solar wind shield the electric potential. This shielding effect is proportional to electron density, so that as the solar wind density decreases with distance from the Sun as $1/R^2$, the shielding effect weakens and the sheath grows proportionately. This increases the effective area of the sail and partially compensates for the $1/R^2$ decrease in solar wind proton density (and, therefore, the force per unit area). As a result, the thrust produced by an E-Sail only decreases as $1/R^{7/6}$ with distance from the Sun, while solar sail thrust decreases as $1/R^2$, thus providing a distinct advantage for the E-Sail. A solar sail mission stops accelerating at distances > 5AU the E-Sail missions will continue to accelerate the spacecraft to distances of ~15 AU

The TRL of E-Sail systems is admitdely low, but this is only at the full system level. Almost all of the subsystems required for an E-Sail system to operate have been demonstrated in space. What is lacking is a system-level, integrated demonstration.

Benefits: E-Sail propulsion will enable trips to Pluto in ~6 years, Jupiter flybys in 24 to 30 months, and trips to the Heliopause region of the solar system in 10 to 12 years. EDTs can provide propulsion without fuel and generate significant power operating within planetary magnetospheres, augmenting the performance of deep space missions and enable high-power operation without the addition of nuclear power at outer solar system bodies.

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UNDERSTANDING THE ELECTROMAGNETIC ENVIRONMENT AND ITS RELATIONSHIP TO LIFE IN THE COSMOS AND THE EVOLUTION OF THE BIOSPHERE.

C. C. Jones

Introduction: Much work has been done to understand the chemical and material conditions necessary to support life, but as yet little has been done to adequately understand the electromagnetic requirements of life, nor has there been enough study of the changing electromagnetic characteristics of the biosphere as life evolved .

Life and the Sun: Life on Earth has evolved in the context of a very specific electromagnetic environment, largely shaped by the interaction of our Sun, the geomagnetic field, and galactic and intergalactic phenomena, with that environment itself changing and being shaped by the further evolution of life. For example, our star, the Sun, has a very specific black-body radiation frequency curve as a function of its temperature, with its peak frequency being in the region we consider the visible part of the EM spectrum. This specific peak likely accounts for the reason why plant life adapted its photosynthetic capability to absorb light that lies in that range, to maximize available energy. Also noteworthy in this regard is the evolution of key sense capabilities by animal life, specifically humans, to this range of the electromagnetic spectrum. This frequency peak and distribution will differ for different stars of different temperature, and consequently planets which orbit those stars will be exposed to different relative quantities of varying parts of the electromagnetic spectrum. What does this mean for life that may travel to these regions, or conversely for life which has evolved in these differing regions of the cosmos?

Evolution and the Atmosphere: Furthermore, life on earth evolved structures of the biosphere, namely the various layers of the atmosphere, which regulate what radiation makes it to the surface. For example, not only are certain types of cosmic rays transformed through their interaction with the atmosphere, but the atmosphere has a chemical composition, as in the case of ozone, such that destructive UV radiation from the sun is absorbed before reaching the surface. Given the coherence of size between UV waves and This is very specific to Earth's particular atmospheric composition and is an evolutionary phenomenon attributable to the "oxygen revolution".

Electromagnetic Environment: Keeping with the theme of the atmosphere, due to the presence of the ionosphere, the Earth maintains a constant environment of extremely low frequency (ELF) radiation, known as Schumann Resonance, whose peak frequencies, as standing waves, are a function of the size of Earth's radius(with modification due to damping effects). The energy for these ELF waves is driven by the ongoing lightning events around the globe, and occurs predominantly and primarily in cloud systems over densely vegetated regions of land. This leads to the hypothesis that consistent lightning events, and consequently the Schumann Resonance, are an evolutionary effect of life moving onto land. There is also evidence that the more highly evolved mammalian brain maintains consistent background ELF activity in the Schumann range, as measured by EEG, which may be an adaptive trait, whereas the reptilian brain is more chaotic with no distinct baseline frequencies.

Conclusion: Currently there are many more questions than answers concerning the relationship of electromagnetism to the processes of life. There is none the less strong evidence to suggest that life does not operate independent or irrespective of its electromagnetic environment, and in fact there may be an evolutionary dynamic between the two that is worthy of further investigation.

Additional Information: If you have any questions or comments contact the author at: creighton-jones141@gmail.com

Chemical reactions impacting the potential of Planetary habitability.

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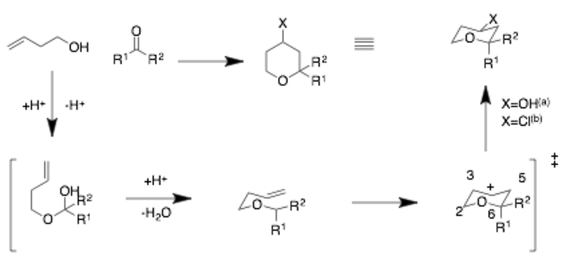
Introduction: Chemical processes on the emerging worlds are important and interesting. Complex molecules are constantly formed from the pre-existing simpler molecules. Complex organic molecules such as Polyhydroxylated compounds (polyols) such as sugars, sugar alcohols and sugar acids are considered to be the precursors of nucleic acids of life- DNA, RNA and cell membranes. Formation of complex molecules on planetary surfaces has been postulated by many path ways. Meteoric amino acids have been extensively studied.

On early planetary surfaces where the Ph is usually acidic, the reactions of smaller aldehydes and allylic alcohols can lead to the formation of complex pyranose molecules. Understanding the acid catalyzed Prins type cyclization and cleavage reaction pathways can give an answer to the key pathways involved in the formation of Precursors of amino acids, Nucleic acids, DNA and RNA.



Scheme 1: Mechanism of the synthesis of THP rings by Prins reaction(a) When H_2SO_4 was used. (b) When HCl was used.

Discussion: The enantiomeric composition of abiotically produced amino acids is racemic, in contrast to the homochirality (almost exclusively L-enantiomers) found in biological systems on Earth. A few meteoritic amino acids, most notably isovaline, have been found to exhibit an L-enantiomeric excess.(see reviews and references therein: Ref [1] Aponte 2016, [2] Elsila et al., 2016).

The formation of Amino acids, the key building blocks of life might have been a two step process. 1) Acid catalyzed cyclization reaction, resulting in the formation of substituted pyran moiety and 2) ring opening / cleavage of pyran ring resulting in selective chiral prebiotic precursor molecule. The Prins type Cyclization acid catalyzed reaction and formation of tetrahydropyran derivatives in the context of evolving planetary surfaces has never been explored . On early planetary surfaces where the pH is usually acidic.

On Mars the phoenix lander detected minerals that indicated ~ neutral pH in the soil (but there are supposed to be some acidic areas). However, on Earth there are acidic environments -even today- that are analogs of likely locally acidic environments billions of years ago. Recently Mars ice deposit[4] and "warm and wet" early Mars climate scenario[5] have been reported.

So there were probably a lot of local environments good for acidic chemistry, where the reactions of smaller aldehydes and allylic alcohols can lead to the formation of complex pyranose molecules.

Understanding the Prins reaction pathway[3] at various temperatures and under conditions similar to that of icy moons can give an answer to the key pathways involved in the formation of Precursors of Nucleic acids, DNA and RNA.

Summary: Exploring the formation of acid catalyzed cyclization reaction products under warm-wet/ wet-cold/cold-dry/ dry-hot cycles on planetary conditions is paramount reaction to improve our understanding of the origin and evolution of life . This concept to understand the formation and cleavage of cyclic ethers like substituted pyran, piperidine, thiopyrans under conditions including UV irradiation can hold a key to guide our search for life elsewhere.

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OUR SOLAR SYSTEM : ADVANCING THE SCIENCE TECHNOLOGY AND SOCIETAL RELEVANCE OF PLANETARY EXPLORATION THROUGH PUBLIC PARTICIPATION. A. P. Kaminski[1], C. D. Bowman[2], L. E. Buquo[3], P. G. Conrad[4], R. M. Davis[5], S. Domagal-Goldman[6], Z. T. Pirtle[7], N. G. Skytland[8], G. J. Tahu[9], and M. L. Thaller[10], M. A. Viotti[11], [1]NASA Headquarters (300 E Street, SW, Washington, DC 20546; amy.p.kaminski@nasa.gov), [2]Raytheon Corporation/NASA Jet Propulsion Laboratory (300 N. Lake Ave., 11th Floor, Pasadena, CA 91101; catherine.d.bowman@jpl.nasa.gov), [3]NASA Headquarters (300 E Street, SW, Washington, DC 20546; lynn.buquo-1@nasa.gov), [4]NASA Goddard Space Flight Center (8800 Greenbelt Road, Greenbelt, MD 20771; pamela.g.conrad@nasa.gov), [5]NASA Headquarters (300 E Street, SW, Washington, DC 20546; richard.m.davis@nasa.gov), [6]NASA Goddard Space Flight Center (8800 Greenbelt Road, Greenbelt, MD 20771; shawn.goldman@nasa.gov), [7]NASA Headquarters (300 E Street, SW, Washington, DC 20546; zpirtle@nasa.gov), [8]NASA Headquarters (2101 NASA Parkway, Houston, TX 77058; nicholas.g.skytland@nasa.gov), [9]NASA Headquarters (300 E Street, SW, Washington, DC 20546; george.tahu@nasa.gov), [10]NASA Headquarters (300 E Street, SW, Washington, DC 20546; michelle.thaller@nasa.gov), [11]NASA Jet Propulsion Laboratory (4800 Oak Grove Drive, Pasadena, CA 91109-8099; michelle.a.viotti@jpl.nasa.gov).

Most solar system exploration achievements to date have involved a relatively small set of entities in establishing science goals and objectives; designing, developing, and operating investigations; and collecting and analyzing the resulting data. Participants have typically included scientists, engineers, and program managers from NASA and other national space agencies, academia, and private companies collaborating through mechanisms including contracts, cooperative agreements, peer-reviewed grants, and memoranda of understanding. It is through the joint efforts of these entities that humanity has witnessed spacecraft reaching all of the planets and regularly receives newfound knowledge about the solar system. The continued leadership of these experts remains vital to addressing outstanding scientific questions and technological needs in planetary exploration.

At the same time, technoscientific organizations and experts across fields ranging from the health sciences to zoology increasingly recognize that they can advance research and development by tapping creative ideas and contributions from a wider base of participants. Technoscientific professionals are welcoming members of the public to aid in formulating scientific investigations, collecting and analyzing data, making discoveries, developing data applications and technologies, and solving complex problems. Citizen science and crowdsourcing projects, prize competitions, data hackathons, and public deliberations are all becoming more broadly accepted modes of defining, accelerating, and maximizing research and development activities as professional researchers and engineers strive with limited resources to attain observations over geographically disperse regions, process enormous volumes of data, optimize technical solutions, or ensure their work is commensurate with societal needs and values. Such projects are ever more feasible today due to the ability to interact with huge numbers of people worldwide through the ubiquity of the internet, social media, collaboration platforms, and smartphones. In addition to their scientific and technical value, these projects can help educate and empower participating members of the public to engage with scientific issues and processes.

There is a growing trend toward using these participatory approaches in planetary science. NASA's space telescopes and planetary exploration spacecraft provide powerful capabilities for understanding the solar system through the enormous volumes of data they produce daily. Crowdsourcing is enabling researchers to accelerate significantly the time required to analyze images or data returned from missions when computer algorithms are not sufficient to detect patterns of interest and human judgment is required. For example, the Stardust@home project welcomes participants to search online microscope images for interstellar dust particles trapped in the aerogel collectors of the Stardust spacecraft, which returned to Earth in 2006. Similarly, hundreds of thousands of people worldwide have taken part in searches of imagery taken by NASA's spacecraft, such as through the project Planet Four, which invites participants to identify windswept terrains on Mars.

Participatory activities are serving planetary science in still other ways. The JunoCam project has invited amateur astronomers worldwide to participate in the Juno mission by uploading their images of Jupiter, discussing features of interest and helping with planning what images will be taken by the Juno spacecraft currently in orbit at Jupiter, and aiding in processing the images once acquired. Working with outside partners, NASA has run open hackathons to encourage the public to mine NASA data to create applications. The agency's prize competitions have yielded ideas for scientific payloads to optimize the use of mass on Mars-bound spacecraft, software algorithms to improve the ability to detect hard-to-spot features in planetary imagery, and Mars maps designed to aid human explorers. NASA has also funded the development of Cubesats and new tools to support public access to spacecraft imagery while also conducting forums to solicit public views concerning plans to detect and mitigate asteroid hazards.

Collectively, these projects have extended the planetary exploration community's ability to gather, process, and maximize the use of research data; to assemble ideas and prototypes of technologies to support future exploration; and to gauge public reactions to potential program directions. All the while they have exposed many thousands of people to planetary exploration achievements as well as the risks and challenges of this endeavor.

We suggest that broadening participation by using these and other methods will prove all the more valuable and plausible for enhancing the science, technology, and societal relevance of planetary exploration over the next few decades. While it is difficult to predict how the economic, political, and technological landscape will evolve, the planetary science community will almost certainly continue to maintain greater ambitions than are possible to fulfill given technical and financial constraints. Concomitantly, a treasure trove of archival data will await innovative approaches to unlocking the mysteries contained within. Planetary science will face new opportunities and challenges as more international organizations and commercial entities take up Mars, lunar, and other solar system exploration efforts of their own; these developments could lead both to a surge of public interest in studying the planets as well as to questions about whether those traditionally involved can or should maintain claim to the vast amount of resources typically committed for these activities. At the same time, an increasingly networked world will expand the ability to engage millions more people in the complex work of planetary exploration.

In sum, the combination of these "demand" and "supply" side factors argue strongly for articulating not only a scientific vision for planetary exploration through 2050 but also a vision of who could and should participate in the development and execution of that vision. We will offer a set of ideas for how the planetary science community can work together to expand the participant base of those substantively involved in this endeavor. We draw here on the results of a workshop NASA conducted in September 2016 that brought together a subset of Mars community members, NASA program officials, and individuals with experience developing projects that engage the public in research and technology development to contemplate how NASA and the Mars community could leverage public ingenuity and interest to advance the science, technology, and societal relevance of Mars exploration. Many of the promising participatory visions, opportunities, and partnerships and potential steps toward realization that the workshop participants identified are broadly relevant and could be applied across planetary science.

ADVANCED SPACE ROBOTICS AND SOLAR ELECTRIC PROPULSION: ENABLING TECHNOLOGIES FOR FUTURE PLANETARY EXPLORATION. M. Kaplan and A. Tadros, SSL MDA Holdings, Inc., San Francisco, CA, michael.kaplan@sslmda.com and alfred.tadros@sslmda.com.

Introduction: Obtaining answers to question posed by planetary scientists over the next several decades will require the ability to travel further while exploring and gathering data in more remote locations of our solar system. Scientific investigations will require much more complex instrumentation, often operating in extreme environments. To meet these challenges, timely investments need to be made in developing and demonstrating several key technologies. Among these technologies are **solar electric propulsion** and **space robotics**. This abstract will explore the potential needs for and likely benefits derived from investments in these two critical technologies.

Advanced Solar Electric Propulsion (SEP): SEP technology can provide significantly higher ΔV when compared with most other propulsion technologies. Use of SEP can reduce mission life cycle costs by minimizing transit times to planetary destinations by using of constant thrust trajectories Additionally once in orbit around a destination body, most missions can benefit from the ability to change orbits, as well as to travel to additional destinations. Current examples of electric propulsion thruster technology are illustrated in Figure 1 below.

Comparison of Electric Propulsion Thrusters from 4.5–12 kW

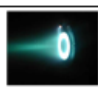
Thruster	 Aerojet XR5	 Fakel SPT-140	 Busek 12k
Power (kW)	4.5	4.5	12.5
ISP (sec)	2000	1750	2500
Throughput (MN-s)	8.7	8.2	50.0
Thrust (N)	0.26	0.29	0.64

Figure 1. Comparison of Current Electric Thruster Technology

To more fully take advantage of the potential of SEP, advances needed include increases in power levels to provide even greater ΔV as well as developing systems capable of operating in both cryogenic and extremely high radiation environment that can be present in the outer regions of the solar system. Larger amounts of power, from either larger solar arrays or space nuclear power, coupled with advances in SEP power levels could provide significant increases in ΔV. It's important to point out that the benefits of advanced SEP are not constrained only to outer planet exploration. For example, large ΔV SEP could also enable a new class of multi-asteroid mission, capable of exploring dozens of objects.

Advanced Space Robotics: Future planetary science missions will require much more sophisticated robotics that could enable much more complex investigations. We know that as missions get more complex, failures can occur. Advanced robotic systems that are capable of autonomously making repairs in space could be a huge forward, making the difference between mission success and failure. The same advanced space robotics technology could also be capable of completing assembly/deployments in space, potentially lowering launch costs. Figure 2 below illustrates a concept that we have developed to finalize spacecraft assembly on orbit under DARPA sponsorship.

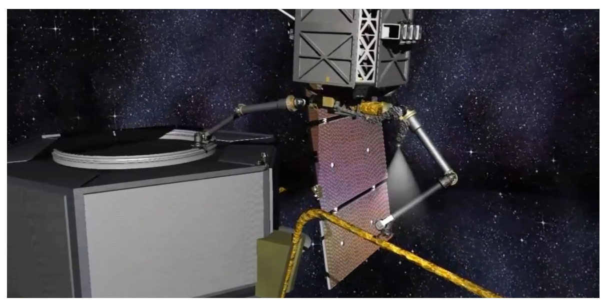


Figure 2. Notional rendering of robotic assembly in space

An added benefit could be that various elements of a spacecraft could be re-arranged during different phases of a mission, potentially reducing or even eliminating mission operations constraints to enhance scientific return. Having this technology in hand should result in the development of new spacecraft architectures to more fully leverage advanced space robotics. Investments are needed in the development of ever more sophisticated space robotics that possess increased levels of autonomy as well as the ability to work collaboratively with multiple systems. Additionally, these advanced space robotics systems will need to operate in extremely challenging environments that are present. These range from the surface of Venus (extremely high temperatures and pressures in a highly corrosive atmosphere) to the surface of Europa (cryogenic temperatures in a high radiation environment.)

Advanced SEP and Space Robotics Roadmaps: To pursue robust exploration of the solar system, roadmaps are needed for both SEP and space robotics. These roadmaps should be developed and then aligned with a future planetary mission roadmap. This could provide NASA with the ability to make timely technology development and demonstration investments to enable scientifically powerful and exciting future missions.

World Leadership in SEP and Space Robotics: SSL MDA Holdings Inc. is the world's most experienced SEP spacecraft and space robotics provider. We understand all the key technological issues regarding these technologies as well as how to incorporate these systems into successful, affordable space missions.

Unparalleled Experience in SEP Spacecraft. Our Space Systems Loral (SSL) division is the world leader in operational SEP systems; 25 of our 82 satellites operating in geostationary orbit feature Hall-effect thruster based solar electric propulsion that, combined, have greater than 60,000 hours of on-orbit Hall-effect thruster and Power Processing Unit (PPU) operation and greater than 100 years of satellite operational life. In addition, 14 more satellites with Hall-effect thruster based solar electric propulsion are currently in production. SSL sees continuing SEP advancement as a key to continual commercial success. Finally, SSL has a long and productive history working with NASA Glenn on communications and electric propulsion technologies, including conducting EP testing at GRC facilities.

Leadership in Space Robotics. Our MDA division has built most U.S. space robotic systems, including the Space Shuttle and International Space Station robotics and all the manipulators that have successfully operated in the dusty Martian environment. We understand how to seamlessly design the interfaces and operate a robotic payload which reduces integration risk. To address potential future collaborative robotic - human mission aspects of the design, we know how to leverage our 35+ years of experience working with NASA JSC to design crew- safe space robotics for the ISS and Shuttle for future planetary science missions. Recent examples of our leadership in advanced space robotics technologies include recent awards for NASA GSFC's Restore-L mission (both robotics and spacecraft bus), DARPA's Phoenix robotics technology program, DARPA's Dragonfly space robotics demonstration NASA STMD's NASA's Tipping Point initiative to advance the goals for robotic and human exploration of the solar system through the development of critical space technologies. Restore-L is a GSFC led mission to service NASA's Landsat 7 spacecraft in orbit.

As a world leader in both critical technologies, we look forward to participating in this extremely important Workshop so that we might contribute our experience and expertise in helping to make this Workshop a success.

GRAVITY SCIENCE IN THE YEAR 2050. J. T. Keane[1], [1]University of Arizona, Tucson, AZ, USA (jkeane@lpl.arizona.edu)

Introduction: Measurements of moments of inertia, gravity, and topography are some of the most powerful probes for investigating the interior structure of solar system objects. Remote measurements of these geophysical quantities have revolutionized our understanding of the formation and evolution of almost every object in the solar system. In this abstract, I summarize the present state of gravity science in the solar system, and current gaps in our knowledge that could be addressed by robotic missions in the coming decades.

The Current State of Planetary Gravity Science: Fig. 1 summarizes the resolution of published gravity fields for all solid solar system objects for which a gravity field has been measured. Here, I focus only on objects for which higher-order gravity fields have been measured (spherical harmonic degree l=2 and above).

The Moon is a clear example where our understanding of the object has been substantially shaped by gravity science. The earliest gravity field measurements from the Apollo spacecraft, subsatellites, and Lunar Orbiters, revealed a gravity field vastly different than the Earth's. The Moon's gravity field was lumpy, with several large mass concentrations ("mascons") significantly perturbing the orbits of spacecraft [1]. When spacecraft returned to lunar orbit in the 1990s and 2000s, gravity and topography enabled the first detailed studies of the gigantic South Pole-Aitken impact basin on the lunar farside (the largest confirmed impact basin in the inner solar system) [2]. After Clementine, Lunar Prospector, and Kaguya, the gravity field of the Moon was known to l~150 (resolution ~ 100 km). This all changed in 2012 with the successful Gravity Recovery and Interior Laboratory (GRAIL) mission [3]. The dual

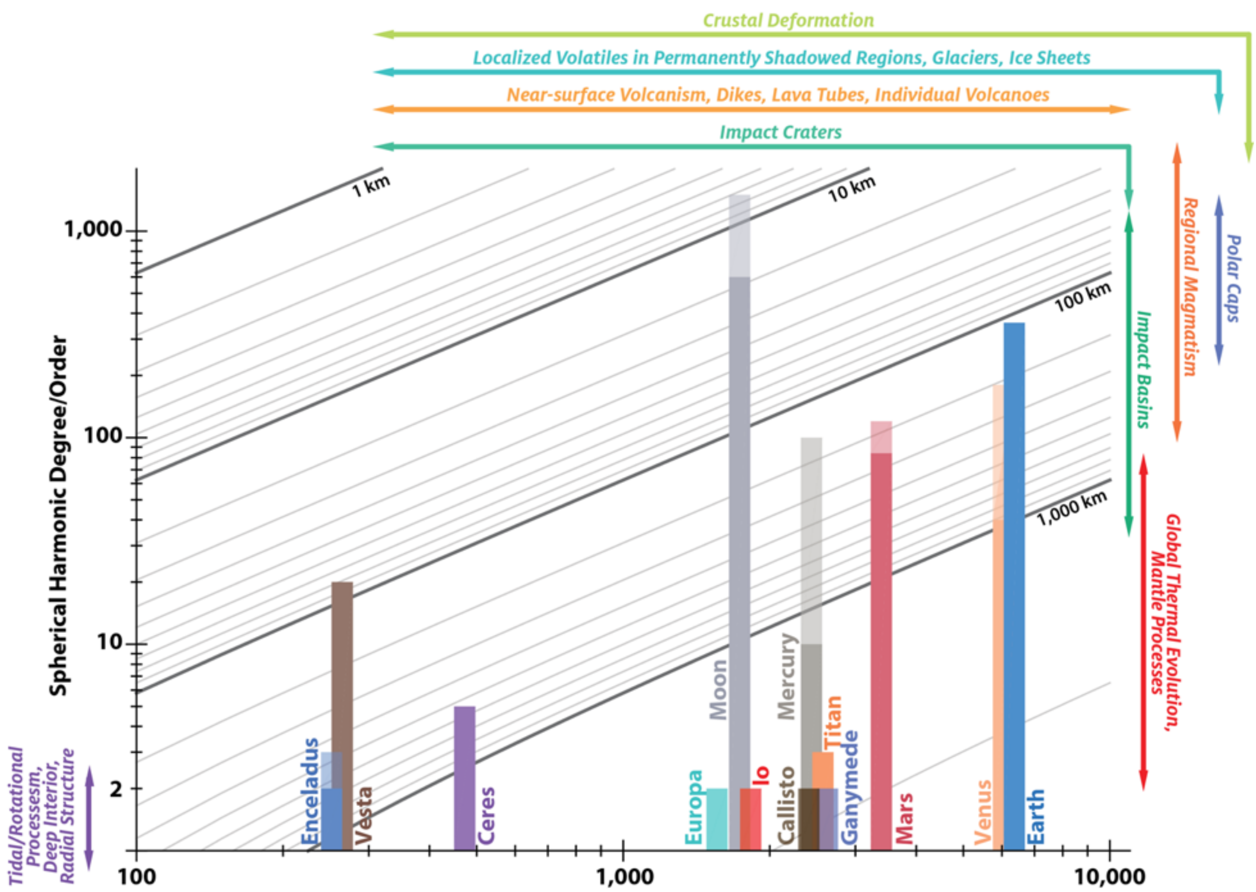


Figure 1. The resolution of all published gravity datasets for solar system objects. Colored arrows on the margins of the plot indicate what geologice features can be probed as a function of spatial/spectral resolution.

spacecraft GRAIL mission used spacecraft-to-spacecraft ranging, and a low orbital altitude (at times <10 km) to provide unprecedented high quality, global gravity measurements. In fact, the Moon now has the most well characterized gravity field of any object in the solar system (*l*=1500, resolution ~ 10 km; Fig. 2). Coupled with comparably high resolution topography data (from LRO/LOLA), GRAIL has provided insight into a variety of geologic processes—from the formation of impact basins [4-5], the early thermal evolution of the Moon [6], volcanic processes [7], and the presence of a liquid outer core [8].

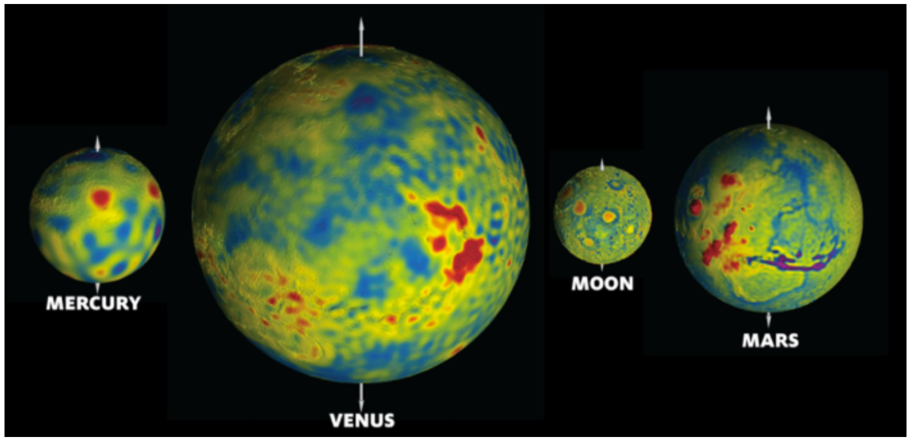


Figure 2. *The gravity fields of Mercury, Venus, the Moon, and Mars. The differences between the gravity fields of each world is due both to differences in geology (e.g. volcanism on Venus verse impacts on the Moon), and resolution of the gravity field. In this visualization, Mercury's gravity field is expanded to l=10; Venus to l=80; the Moon to l=600; and Mars to l=100.*

Our present-day knowledge of the gravity fields of the Earth, Venus, and Mars (Fig. 2) are comparable to our mid-1990's understanding of the Moon's gravity field. While future missions (or renewed analyses of exisitng spacecraft data) may further improve the resolution of the gravity fields of these planets, they will almost certainly never reach the caliber of the GRAIL gravity field—simply because the presence of an atmosphere prohibits a low-altitude gravity science campaign. Nonetheless, gravity-focused missions to Venus in particular may be able to monitor atmospheric dynamics in a way similar to what has been done for the Earth with the Gravity Recovery and Climate Experiment (GRACE) and Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) [9].

Mercury (Fig. 2), Vesta, and Ceres, all have similarly low resolution gravity fields, comparable to the state of knowledge of the Moon in the 1960's, and thus only provide insight into the longest-wavelength structures on these worlds.

The quality of measured gravity fields drops off precipitously in the outer solar system. Degree-2 gravity fields have been measured for only a handful of moons of Jupiter and Saturn, and even then often rely on significant assumptions; for example, assuming a fixed ratio between degree-2 spherical harmonics [10]. If we continue our analogy with lunar gravity science, the current state of knowledge of the gravity fields of icy satellites are comparable to the Moon circa the year 1800! (The Moon's degree-2 gravity field was inferred by eye and telescopic observations of the Moon's libration and orbital motion.)

A Vision for Planetary Geophysics in the Year 2050: The icy satellites are the single largest gap in our current understanding of planetary gravity fields. A dedicated geophysics mission (consisting perhaps of a gravity science package and laser altimeter or stereo camera) would revolutionize our understanding of icy worlds. Furthermore, a high resolution gravity field of an icy satellite would provide a unique counterpoint to the high resolution gravity field of the Moon, and enable a variety of comparative planetology studies. For example, we only recently believe we understand how multi-ring basins form on the Moon [5, 11], and plausibly the other terrestrial planets by extension. Perhaps the best test for the numerical modelers would be to predict how such impact basins would form on icy worlds, where the rheology is substantially different. Like GRAIL, an icy world geophysics mission would perhaps be best suited for a low-cost (Discovery class) mission, in tandem, or subsequent to a more traditional remote sensing spacecraft.

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IO: THE VOLCANIC WORLD THAT WILL TELL US HOW OCEAN WORLDS WORK (AND A MISSION CONCEPT TO GET US THERE). J. T. Keane[1], P. Becerra[1], K. Basu[2], B. Davis[3], V. Fox[4], L. Hays[5], J. Herman[6], C. Holstein-Rathlou[7], A. Hughes[8], E. Marcucci[9], E. Mendez Ramos[3], A. Nelessen[3], M. Neveu[10], N. Parrish[6], A. Scheinberg[11], J. S. Wrobel[12]. [1]University of Arizona, Tucson, AZ, USA (jkeane@lpl.arizona.edu); [2]Pennsylvania State University, University Park, PA, USA; [3]Georgia Institute of Technology, Atlanta, GA, USA; [4]Washington University, Saint Louis, MO, USA; [5]Jet Propulsion Laboratory, Pasadena, CA, USA; [6]University of Colorado, Boulder, CO, USA; [7]Boston University, Boston, MA, USA; [8]Embry-Riddle Aeronautical University, Daytona Beach, FL, USA; [9]University of Alaska, Fairbanks, AK, USA; [10]Arizona State University, Tempe, AZ, USA; [11]Massachusetts Institute of Technology , Cambridge, MA, USA; [12]JW Research & Design, LLC., Boulder, CO, USA.

Introduction: Jupiter's moon Io is the ideal target to study extreme tidal heating and volcanism, two major processes that shape the formation and evolution of planetary bodies. The dramatic magnitude of these processes on Io make it far easier to study these processes on Io than any other icy world. Because of this, the 2011 Planetary Decadal Survey [1] identified an Io Observer as a high-priority New Frontiers class mission for the 2013-2022 decade. In response to the 2009 New Frontiers Announcement of Opportunity, we drafted a mission concept for such an Io observer mission, named Argus (after the mythical watchman of Io) (Fig. 1). This concept mission was developed by the students of the August 2014 session of NASA's Planetary Science Summer School (PSSS), together with the Jet Propulsion Laboratory's Team X.

Figure 1. Argus mission logo

Key Themes: The Argus concept mission was designed around 4 key themes. (1) Tidal heating may extend the habitable zone for planets and satellites. (2) Active lava flows on Io resemble early, ultramafic volcanism on Earth. (3) Io's active volcanism creates a wealth of interaction with Jupiter and its magnetosphere system. (4) Better knowledge of Io's composition improves our understanding of planetary accretion and solar system formation as a whole.

Instruments: To address these themes, a suite of seven instruments was designed.

IGNITERS: Io Global Nighttime Temperatures Radiometer – Millimeter radiometer and spectrometer (a la Rosetta MIRO) that measures surface heat flow and plume/atmospheric chemistry.

IGLOO: Io Global Optical Observer – NUV-NIR camera for regional color imaging (a la Galileo SSI), and providing insight into Ionian volcanism, tectonics, and surface properties.

IoLA: Io Laser Altimeter – High precision laser altimeter, optimized for fast flybys, that measures global shape and local topographic features, revealing geophysical processes.

IoNIS: Io Near-Infrared Spectrometer – NIR spectrometer (a la Cassini VIMS) for mapping mineral composition patterns that reflect geological processes that shape the surface.

IoFLEX: Io Field Line Experiment – Magnetometer (a la MAVEN MAG) for measuring currents arising from Io's magma and constraining models of the Io dynamo and upper mantle circulation.

IoPEX: Io Plasma Experiment – Measures the Io plasma torus dynamics to help discriminate between above/below-surface sources of magnetic fluctuations.

A final science experiment possible from the high-gain antenna is *IRAGE: Io RAdio Gravity Experiment*, which determines the internal mass structure of Io, and looks at the effects of tides. The observation strategy (Fig. 2) was designed to maximize data collection to address our science goals and test key hypotheses chosen to interrogate the Io environment.

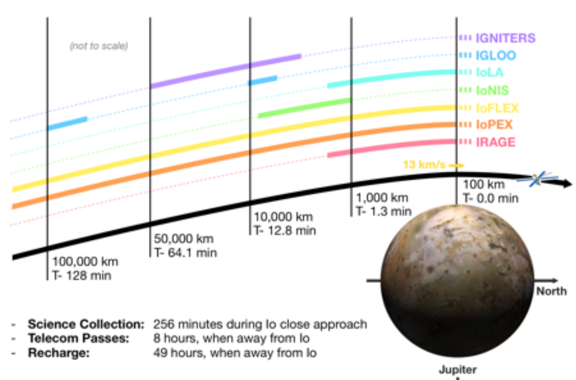

Figure 2. Argus observational strategy

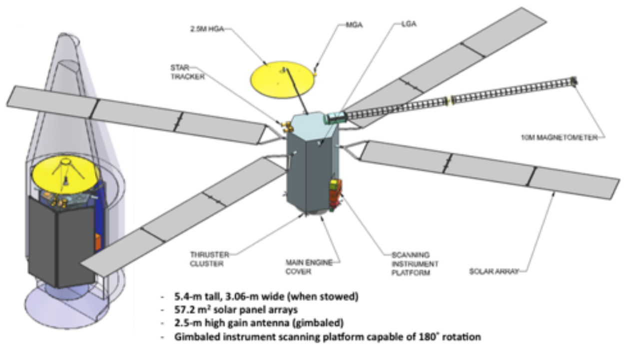

Figure 3. Spacecraft designed to fit into the nose of an Atlas 421 rocket. Solar power was chosen over MMRTGs.

Mission Design: Argus would be launched on an Atlas 421 rocket (Fig. 3) and use three planetary gravity assists (Venus, Earth, Earth) to reach Io. In an inclined (i = 31°), eccentric Jovian orbit (Fig. 4), Argus would make 10 flybys of Io with a closest approach of 100 km. Flybys take place between 7:30-19:30 local time, covering 100-260°W (anti-Jovian hemisphere) (Fig. 5) with a velocity of 13 km/s.

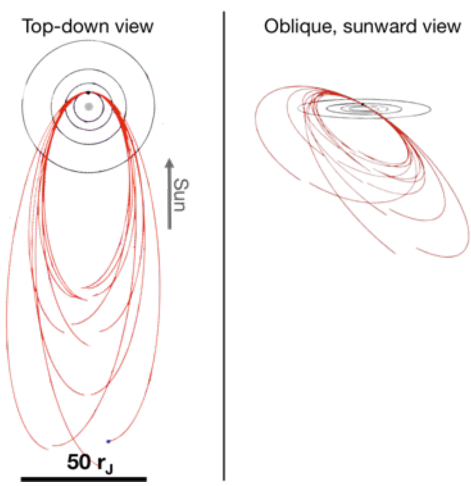

Figure 4. Argus' orbit about Jupiter.

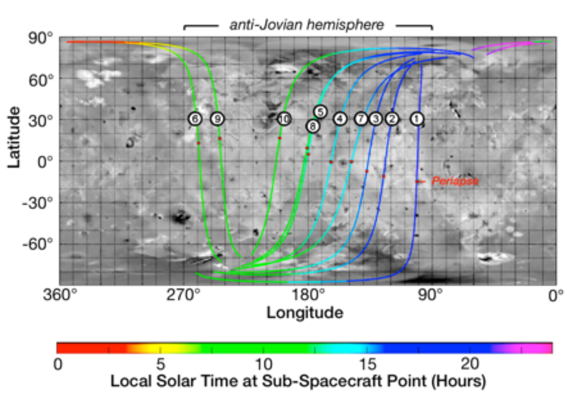

Figure 5. Ground tracks will cover the anti-Jovian hemisphere and a variety of Io true anomalies.

Key Challenges: During this design concept, we were faced with two main challenges: (1) the intense radiation environment around Io and (2) a trade between solar and Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) power sources.

Io orbits through the Jupiter plasma torus, the harshest radiation environment around any planet. Therefore, instruments and the spacecraft need to have mitigation strategies, similar to other missions – Galileo, Juno, and Europa Clipper. To mitigate this risk, we implemented a 500 mil aluminum radiation vault for the electronic components, spot shielding for other components outside the vault, and additional cost allocation for radiation hardening of instruments. Additionally, the high inclination orbit 31° orbit (Fig. 4) balances radiation exposure with science objectives.

The August PSSS session specifically examined power systems. Solar panels have a lower cost and mass, but are sensitive to radiation. Solar panels also dictate an instrument platform because of Sun- vs. Io-pointing requirements, and introduce instrument pointing problems, due to panel flexure. MMRTGs have a steady power output and waste heat can be repurposed, although they are significantly more expensive and higher mass. After comparing these two options, solar panels where chosen as they reduced cost by a factor of four.

Cost & Schedule: Following the 2009 New Frontiers Announcement of Opportunity, the mission was designed to fit under a cost cap of FY15$ 1 billion, with an additional $46 million for the use of a mid-range launch vehicle (Atlas 421). The mission cost is $867 million for the development phases A through D (5 years) and $143 million for the operation phases E and F (6.5-year cruise + 2.5 years at Jupiter), for a total of FY15$ 1.01 billion.

Final Thoughts: The Argus Io Observer Concept Mission was designed during the August 2014 session of the JPL Planetary Science Summer School. Tidal heating and strong volcanism are prime processes for shaping planet evolution. Study of these processes is best done at Io.

Acknowledgements: We thank the organizers of the JPL PSSS for making it possible for us to carry out this concept study, in particular Charles Budney, Karl Mitchell, Leslie Lowes, Jessica Parker, as well as Bill Smythe and many JPL scientists and engineers who contributed their insight to this study.

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SOLAR SYSTEM RESOURCE ASSESSMENT IN 2050. L. Keszthelyi[1], D. Trilling[2], J. Hagerty[1], N. Moskovitz[3] and M. Milazzo[1], [1]USGS Astrogeology Science Center, Flagstaff, AZ 86001, [2]Northern Arizona University, Flagstaff, AZ 86001, [3]Lowell Observatory, Flagstaff, AZ 86001.

Introduction: In 2015 the United States Geological Survey began a feasibility study for assessing natural resources in asteroids [1]. By 2050, we expect that such assessments will be a key "customer" of data collected by NASA planetary science missions. Here we (1) provide our rationale for expecting this need, (2) describe how such data would be used in USGS resource assessments, and (3) provide some specific mid-term activities that would lay the groundwork for robust resource assessments across the solar system in 2050.

Rationale for Solar System Resource Assessment: The long-term goal of the United States space program is establishing a human presence on Mars. This goal has been remarkably stable for decades, unfazed by changes in administration, geopolitical situations, economic conditions, and generations of the American public. One can debate the merit of this goal, but this core of our Nation's space policy can be expected to persist past 2050. Planetary science will thrive best if it is able to demonstrate its relevance to transforming humans into a true space-faring species.

Several major challenges must be overcome before there are human bootprints on Mars. The most problematic obstacle may be the price tag, a large fraction of which comes from hauling material out of Earth's gravity well. Obtaining key resources (e.g., water and metals) in the space between Earth and Mars could dramatically reduce the costs of a trip to Mars. A sustained human presence on Mars is only practical if local resources can be utilized. The most obvious way to obtain such resources is to mine near-Earth objects (NEOs) and the shallow subsurface of Mars (and perhaps the Moon). Enabling such mining will almost certainly be a key component of the US space program in 2050.

Before such mining can be prudently undertaken, unbiased, quantitative and reliable assessments of key resources will be needed. Creating such assessments is the Congressionally mandated responsibility of the United States Geological Survey. The "Organic Act" of 1879 established the USGS with a few specific obligations, including "the classification of public lands and examination of the geologic structure, mineral resources, and products…" In 1962, Congress extended those examinations to "beyond the borders of the United States."

In 2015, USGS management recognized that this phrase extends the USGS legal obligation to space. At this time Congress has not provided funding specifically to assess extra-terrestrial resources. Nevertheless, the USGS Mineral Resources Program decided that it was prudent to fund a small feasibility study to examine if existing terrestrial methods can be applied to asteroids. This effort has demonstrated that the USGS resource assessment methodology can be readily applied to asteroids. Furthermore, even this crude feasibility study is sufficient to robustly conclude that the NEO population could sustain at least a million-fold increase in the 2016 level of human activity in space for a million years – if the technology to extract the resources were to exist.

Given this potential to enable human activity in deep space, we expect that Congress will have directed the USGS by 2050 to provide resource assessments of the NEOs, likely landing sites on Mars, and perhaps the Moon. Before describing the kinds of data most desired for these future assessments, it is useful to briefly review the USGS methodology for resource assessments.

The USGS Resource Assessment Methodology: The USGS minerals, energy, and water resource assessments are all designed to produce unbiased and reliable results in a format readily understood by decision makers who are not technical experts in the field [2]. Here we adopt the terminology used in mineral assessments, but the concepts are similar for all resources. This methodology is often called the "three-part" model because it combines three separate quantitative models via numerical methods to produce the statistics for the final assessment.

For each resource, a prerequisite for quantitative assessments is the development of qualitative *descriptive models* of each geologic setting in which the resource can be found. This is a description of the association between the resource and geologic units and processes.

The first of the three quantitative models is the *spatial model*, which delineates tracts that contain the geologic setting described in the *descriptive model*. In other words, the *spatial model* is a map of the areas where the geology <u>permits</u> the existence of deposits of the resource, not a of map the resource deposits themselves [2]. The second model is the *grade-tonnage model* for each geologic setting. "Grade" is the concentration (or quality) of the resource and "tonnage" is mass (or quantity) of the deposit. These models are usually expressed mathematically as multivariate probability density functions (pdfs) for the resource concentrations and ore tonnages of the deposits in the assessment area. The third model is the *deposit-density model*, a mathematical description of the expected number of deposits per unit area.

The *deposit density* and *grade-tonnage models* are statistically combined to calculate the expected size and quality distribution of deposits per unit area at various confidence levels (typically 10, 50, and 90%). Monte Carlo methods are the most commonly used statistical method because of their flexibility and mathematical simplicity. An economic model that describes the cost to set up an extraction operation and then operate it can be applied. Even a simple parametric model is usually sufficient to indicate whether the expected deposits are worth extracting. After combining with the areas identified in the *spatial model*, the final outputs are (1) the minimum number, size, and quality of economically viable deposits at various confidence levels and (2) a map of where these deposits may exist.

It is worth re-iterating that this methodology can apply to any type of resource and decades of experience has shown that this is the most useful format to provide the assessment to decision makers.

Essential Preparatory Planetary Science Studies: Each of the models described above require deep scientific understanding and statistically meaningful volumes of data. Even though USGS has the legal mandate to conduct Solar System resource assessments, it will need to rely enormously on the efforts of NASA's Planetary Science Division to succeed. Based on our feasibility study, we can point to several efforts that are essential to enable useful resource assessments for NEOs, Mars, and beyond.

In-situ observations. First, to properly assess the grade of planetary resource deposits, we require many more detailed and systematic compositional measurements. The need is for more than bulk elemental and mineralogical information. The manner in which the resource is distributed, the mechanical properties of the host material and the types of trace contaminants can greatly affect how much of the desired resource can actually be extracted. For example, potable water would be easiest to extract from the shallow subsurface of Mars if it were in sizable layers of pure water-ice covered by loose regolith. Conversely, the water would be extremely difficult to utilize if it were predominantly bound to hydrated minerals in strong rocks and contaminated with toxic compounds such as perchlorates [3]. Similarly, metals would be easiest to extract from asteroids if they were in relatively small particles disseminated within a loose regolith with few embedded sulfides or silicates. Simply passing a magnet through such material could suffice. However, if the metal is in a massive piece, cutting off workable pieces in a microgravity environment will be a challenge. Even worse would be if the metal had to be broken out of hard rock and was laden with unwanted minerals that had to be chemically or physically removed.

To ascertain these types of properties, it is necessary to conduct in-situ studies supported with detailed laboratory investigation of returned samples. Furthermore, such studies would need to be conducted on a statistically meaningful number and variety of sites. It will be essential for the landed missions involved to be able to interact with the upper meters of the surface. While the drill on the InSight lander is one possible technological path, we suggest that penetrators may allow more cost-effective investigation of a large number of sites.

Linking in-situ to remote observations. No resource assessment can realistically rely solely on collection of in-situ data. Even on Earth, such studies are expensive enough to be available only sparsely. Instead, a deep understanding of the geologic processes that formed the deposit and its host materials is required to confidently extrapolate from the immediate vicinity of the in-situ measurements. The key is to link the geologic processes of interest to measurements that can be obtained on a regional scale via remote sensing. For example, the current linkage between spectra of asteroids and spectra of meteorite samples is not robust enough to direct asteroid mining missions to the best targets. The thermal and space-weathering processes that alter the outermost layers of an asteroid may hide key spectral features indicative of the real water content of an asteroid. With the aid of further in-situ investigation of asteroids and laboratory studies of meteorites, it may be possible to discover mineral assemblages indicative of high water content that have a spectral signature more robust to surficial alteration. It is likely that confidently identifying the desired geologic setting will require combining data from multiple different types of remote sensing observations.

Remote sensing observations. The ability to map out the locations with the right geologic setting to contain high abundances of high-grade resource deposits will almost certainly require combining data sets with very different spatial, temporal, and spectral characteristics. In many cases, including NEOs, there is a shortage of bodies that have been observed with the right combination of instruments, which is at least partially due to the fact that the bodies of greatest interest are very dark and the vast majority of them are small. Similarly, the regions of greatest interest on the Moon are poorly illuminated, limiting the types of remote sensing data that are available. Even as future instruments collect robust data from these challenging targets, it will be essential to develop the tools to properly fuse disparate data sets.

Conclusion. Assessing Solar System resources will be a major element of the US space program in 2050. A robust combination of in-situ and remote sensing observations are needed to enable those assessments.

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Electrochemical Detection of Biological Catalysts as Signatures of Extant Life. J. E. Koehne, NASA Ames Research Center, Moffett Field, CA 94035 [Jessica.E.Koehne@nasa.gov]

Introduction: Liquid water is the quintessential ingredient for life. Biochemistry as we know it is not possible without it. There are two places in the Solar System, other than the Earth, where liquid water is known to exist: Europa and Enceladus. Cassini's recent discovery of Enceladus' ocean plumes has excited the scientific community about the possibility for liquid sampling and search for life. Characteristics of life are self-sustainability, its ability to evolve, and self-enclosure [1]. To enable these, chemical energy must be utilized, information must be stored, and enclosing membranes must be built. Many of these processes are accomplished with the use of biological catalysts. To search for life in the ocean worlds, detection of biological catalysts serves as a strong marker of biological activity and thus life.

Approach: Miniaturized chemical and Biochemical sensors and sensor arrays offer some of the most promising approaches to in situ planetary exploration including small-payload investigations, large class robotic missions and human space exploration. At NASA ARC, we have leveraged the basic Wet Chemical Laboratory (WCL) design from the Mars Phoenix Lander to perform additional analysis of biological targets. The overall objective is to develop new sensor-based technologies to enable bio-exploration and life detection during future missions to our solar system's icy worlds.

We have developed one such sensor technology to detect the evidence of biological catalysis. In particular, the serine protease trypsin has been chosen for a proof of concept due to its abundance in Earth-based life. Typsin catalyzes the break down of proteins through a catalytic triad consisting of histidine, aspartate and serine. Gold sensing electrodes are functionalized with probe peptide sequences labeled with a redox active reporter. Upon introduction of trysin, the redox-active tag is cleaved from the peptide and thus from the sensing electrode. The characteristic redox signature of the redox-active tag is detected using square wave voltammetry. Decreases in redox current is measured and attributed to cleavage by trypsin.

This biological catalyst sensor is one example of an expansion of the WCL platform for the search for extant life.

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CoSTrS: Cometary Survey of Trail Samples. E. A. Kramer[1] and J. M. Bauer[1,2], [1]Jet Propulsion Laboratory, California Institute of Technology (Pasadena, CA; emily.kramer@jpl.nasa.gov), [2]Infrared Processing and Analysis Center (IPAC) , California Institute of Technology (Pasadena, CA).

Introduction: The Stardust mission was a space probe launched in 1999 with the primary goal of collecting samples of the coma of comet 81P/Wild 2, and returning those samples back to earth so that they could be studied in a laboratory [1, 2] . This was accomplished by deploying a "tennis racket" with aerogel cells, which non-destructively captured refractory (non-volatile) materials from the comet's coma. These samples were returned to earth in 2006, and have provided planetary scientists with a wealth of information regarding the composition of cometary refractory materials from the coma of comet 81P/Wild 2. By studying these materials in the lab, the dust particles were studied in unprecedented detail [3, 4].

The Cometary Survey of Trail Samples (CoSTrS, pronounced "coasters") would expand upon the success of the Stardust mission by sampling the dust trails of several short-period comets. By collecting samples from several different comets, the refractory materials of these primitive bodies could be studied and compared, substantially increasing our understanding of the protoplanetary disk.

Mission concept: CoSTrS would consist of a single space probe with several aerogel "tennis rackets" that could sample the dust trails. As the spacecraft approaches the next target, a sample collection container would be deployed, then stored once the encounter was complete in order to ensure that there was no contamination between samples. Once all the samples are collected, the collection capsules would be transported back to earth, similar to as was done for the Stardust mission. By using one spacecraft to fly through several cometary trails, several different comets can be sampled with a single mission.

Why comet trails? Cometary dust trails are cosmic "breadcrumb trails" which follow the orbital path of the comets from which they originate. They are comprised of large (~mm to cm) sized particles that were emitted as a short-period comet came close to the sun. They are long-lived structures (lasting centuries or more), and thus can be used to trace the past activity of a comet. When the earth intersects with a cometary dust trail, this forms a meteor shower, the intensity of which depends on the activity level of the comet at the time at which the trail was formed.

Cometary dust trails could be a more accessible way to sample cometary nuclei than by collecting materials from the coma. Since many trails are found within the inner solar system, the mission would not need to venture far from the earth (in terms of distance and delta-v) in order to sample several primordial objects.

Enabling technologies:

- Long-duration mission: need durable spacecraft
- Need to be able to open/close aerogel containers for particle capture, and verify that they have been opened/closed
- Return the samples to Earth without damaging samples

Previous missions to be used as references: Stardust [1], Hayabusa [5], Hayabusa2 [6], OSIRIS-Rex [7]

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EXPLORING THE SOLAR SYSTEM WITH AN INTEGRATED HUMAN AND ROBOTIC DEEP SPACE PROGRAM. David A. Kring, Lunar and Planetary Institute, Universities Space Research Association, 3600 Bay Area Blvd., Houston, TX 77058 USA (kring@lpi.usra.edu).

Introduction: NASA is developing the Orion crew vehicle and Space Launch System (SLS). Those vehicles, along with an ESA service module, provide new capabilities for exploring deep space. A series of Exploration Missions (EMs) are being designed for cis-lunar space to validate spacecraft performance and evaluate crew health performance. During that validation phase and after the systems are fully operational, opportunities to explore Solar System processes will be greatly enhanced. Here I expand on activities [1] that can occur through 2030 with a forward look at how they may shape opportunities circa 2050.

Initial Mission Capabilities: In the initial EMs, Orion could be outfitted with a high-definition camera to image the Moon during 100 km altitude passes over the lunar surface (Fig. 1), an additional camera to detect impact flashes on the farside and/or in the nighttime hemisphere to complement ground-based measurements of the nearside, radiation detectors for measurements external to and within the Orion crew capsule to test crew exposure models, and a receiver to make modern measurements of radio noise on the lunar farside for comparison with an RAE-2 occultation of Earth in 1973. In addition to CubeSats already planned as secondary payloads, a communication asset could be deployed into orbit for future farside relay.

Human-assisted Robotic Sample Return: More complex missions that follow can integrate humans in orbit with robotic assets on the lunar surface in a development path consistent with the Global Exploration Roadmap (GER [2]). The feasibility and productivity of an Orion L2-farside sample return mission involving a 30 km traverse [3] and an astrophysical mission that deploys a radio antenna [4] have already been studied. Those scenarios will be enhanced if Orion has sufficient bandwidth to accommodate high data rates, including high-definition video from the lunar surface. Once an orbiting facility at the Earth-Moon L2 position is available, then longer duration farside sample return missions [5,6] can be implemented, with 100 to 300 km-long traverses and 30 to 60 kg of material returned to Earth for geologic and in situ resource studies.

Initial Destinations: Historically, two dozen successful missions have explored the lunar nearside surface. None have landed on the farside, so that vast region of unexplored territory is an obvious target of interest. A global landing site study [7] found that the Schrödinger basin, within the South Pole-Aitken basin,

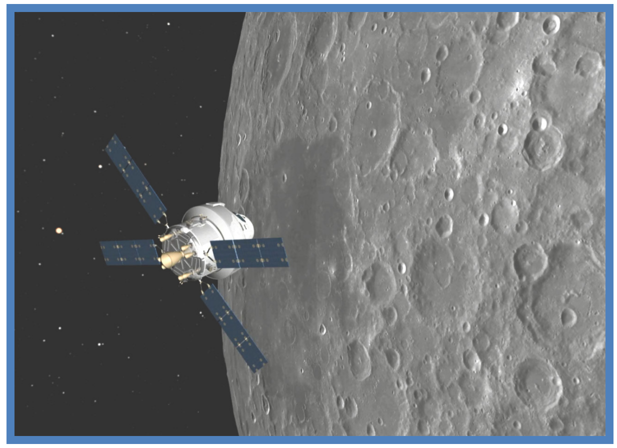

Fig. 1. Concept illustration of the NASA Orion crew vehicle and ESA service module passing over the lunar surface en route to a halo orbit about the Earth-Moon L2 position. Alternative orbits include distant retrograde orbits (DROs) or near-rectilinear orbits (NROs).

has the greatest potential for scientific return (Fig. 2). Multi-element missions can subsequently target other farside destinations within the South Pole-Aitken basin, either robotically or with humans using Lunar Electric Rovers (LERs) or Space Exploration Vehicles (SEVs) (Fig. 3). Crew on the surface would greatly accelerate scientific discovery while also testing methods for in situ resource utilization (ISRU) and sustainable exploration. Robotic assets, such as the LERs, could be used to survey additional areas (e.g., for resource volatiles), in between those crew landings. An existing concept [8] suggests crew land sequentially at Malapert massif, the South Pole, Schrödinger basin, Antoniadi crater, and the center of the South Pole-Aitken basin.

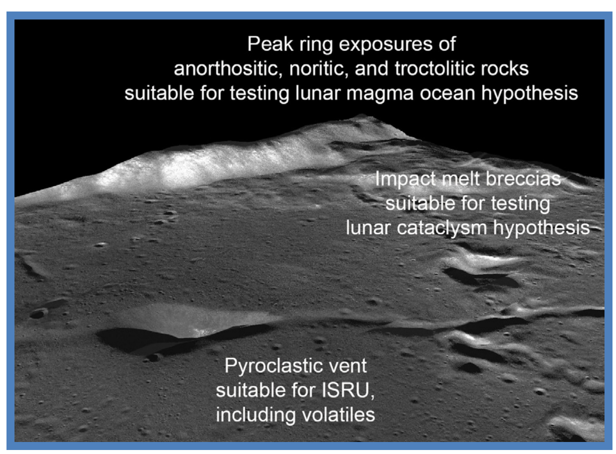

Fig. 2. Schrödinger basin is a high-priority target for both robotic and human missions.

While those initial missions target the Moon, they will address processes relevant to the entire Solar System, such as the accretion of planets, delivery of biogenic material, and the dynamical evolution of orbits. The Moon is the best and most accessible destination to address fundamental questions about the origin and evolution of the Solar System.

Demonstrating Capabilities & Retiring Risk: Human-assisted robotic missions will revalidate our ability to land on and traverse the lunar surface, ascend to and rendezvous in lunar orbit, and return samples to Earth, all of which are essential capabilities to be developed for the GER. In addition, the installation of an orbiting facility and assembly of robotic elements at L2 will validate deep space assembly operations (a Mars-forward capability), while developing the capability for crew to tele-operate surface assets (a Mars-forward technology) and demonstrating a series of crew health performance capabilities (e.g., deconditioning countermeasures, space radiation protection and monitoring, habitation systems) needed for exploration beyond the cis-lunar environment. The eventual deployment of crew on the surface will validate a capability for long-duration activities in relatively low gravity geologic settings while encumbered with pressurized suits, vehicles, and habitats (which are elements of any Mars-forward architecture).

Distribution of Assets: In general, human and robotic assets will need to be integrated to maximize productivity and safety. Asymmetrical distribution of those assets should, however, be strategically applied. To address lunar exploration objectives identified by the National Research Council [9], the best results will be obtained by a trained crew on the surface. Incremental progress can be made with a human-assisted robotic architecture until the capability to land crew exists. Those robotic assets will continue to be useful after crew are able to access the surface, either by providing additional analyses of a landing site after a crew has returned to Earth or by exploring regions not initially targeted by human missions.

Different destinations may also require an asymmetrical distribution of assets. For example, many geologically and compositionally simple asteroids are ideal targets for robotic assets, whereas complex planetary surfaces, such as the Moon, favor human assets with their observational skills, ability to reason, and ability to rapidly adapt to encountered conditions.

Technological Development Phasing: Technological capabilities to be developed include a communication relay for global access to the lunar surface; a voice, video, and data bandwidth (>1 Mbps) that exceeds current Deep Space Network capabilities; an Earth-Moon L2 orbiting platform; robotic and human lunar landers with ascent vehicles; and a crew rover. These capabilities are tractable and, in the case of the crew rover, already exists in proto-type form (Fig. 3).

Fig. 3. A proto-type LER that has been tested extensively in simulations of 3-, 14-, and 28-day-long missions with (inset) a concept SEV.

Training: While developing those technological capabilities, the program needs to develop its human assets. General geologic training of astronauts will be necessary, followed by mission-specific training. In parallel, scientists in the planetary science community will need to be trained in mission operation procedures that involve crew, building on the success of mission simulations conducted through the Desert Research and Technology Studies program.

Discussion and Conclusions: The opportunities available to planetary science will be greatly enhanced with an integrated human and robotic deep-space exploration program. It will change how the planetary science community functions. Human-assisted sample return and humans to the lunar surface are feasible in the 2020's and early 2030's. While those capabilities are being developed, the launch capabilities of the SLS will be able to routinely deploy robotic assets to both the inner and outer Solar System. The data returned from the human and robotic missions will be immense and will require a workforce able to digest that information. That transformation will be essential for a subsequent exploration phase, which may carry crew to more distant destinations, such as Phobos, Deimos, and the surface of Mars as we approach 2050.

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CONCEPTS FOR EXPLORING THE SURFACE OF VENUS. G. A. Landis[1] and S. R. Oleson[2], [1]NASA John Glenn Research Center, 21000 Brookpark Road, Cleveland OH; geoffrey.landis@nasa.gov, [2]NASA John Glenn Research Center, 21000 Brookpark Road, Cleveland OH; steven.r.oleson@nasa.gov.

Introduction: Earth's sister planet, Venus, is the closest and the most similar to Earth in size and location in the solar system, as well as one of the most hostile surface environments in the solar system. The longest lived mission to the surface of Venus lasted only two hours, and no missions have landed on Venus since the last of the Soviet missions in the 1980s. Nevertheless, Venus is a planet of great scientific interest.

Technologies for Future E ploration: A number of advances in technology allow the possibility of designing future missions which may have long lifetimes operating on the surface of Venus. The primary difficulty is the high temperature, about 450°C on the surface, with the added difficulty of high pressure (about 92 bar) as well. Technologies being developed to work in this environment include high-temperature electronics, high temperature motors and mechanical components, high-temperature power systems, and design of radioisotope-powered Stirling-cycle cooling systems. A new environment simulation chamber, the Glenn Extreme Environment Rig (GEER), has recently become operational [1] to test materials and technologies under simulated Venus surface conditions.

Conceptual Mission Designs: A number of conceptual designs for Venus missions have been done, including landed missions, rover missions [2-4], and atmospheric balloon and aircraft missions [5]. As an alternate to a robotic mission, a mission was also studied incorporating telerobotics from an orbiting spacecraft [6].

Figure 1: conceptual design for a small wind-powered Venus lander.

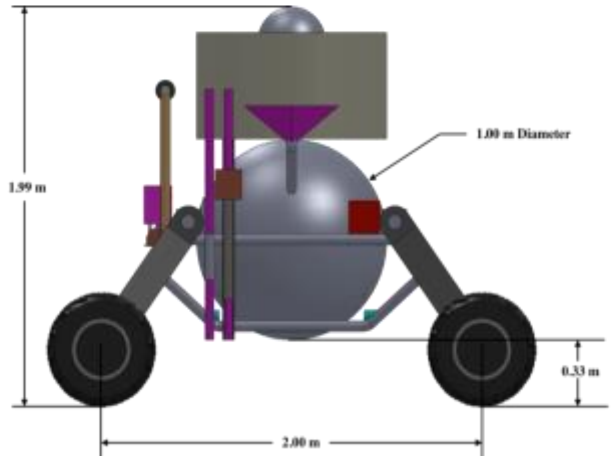

Figure 2: conceptual design for a Venus rover incorporating a radioisotope Stirling power supply and cooling system. [3]

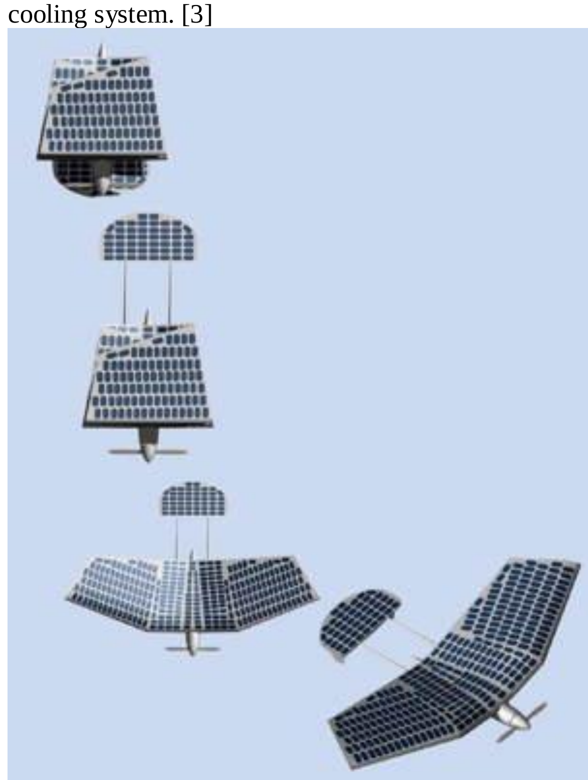

Figure 3: concept for deployment of a solar-powered aircraft for exploration of the Venus atmosphere

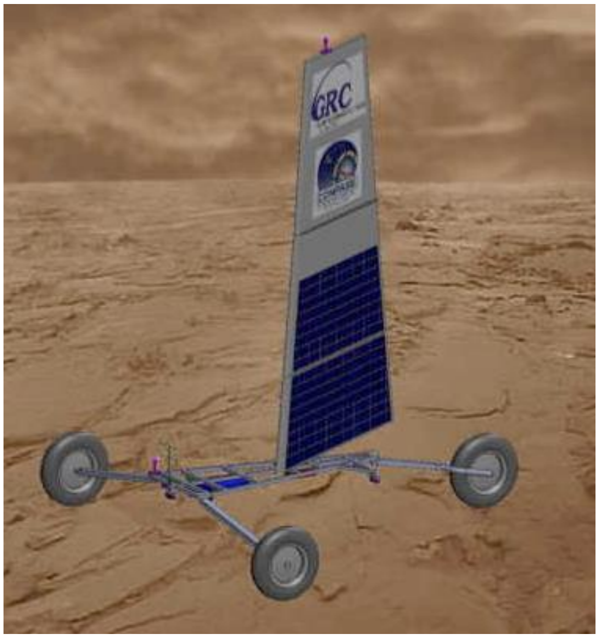

Figure 4: NASA Innovative Advanced Concepts (NIAC) Venus landsailing rover

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ENVISIONING A PLANETARY SPATIAL DATA INFRASTRUCTURE J. R. Laura, R. L. Fergason, J. Skinner, L. Gaddis, T. Hare, and J. Hagerty, U.S. Geological Survey, Flagstaff Arizona

Introduction Spatial Data Infrastructure (SDI) is a framework to support spatio-temporal data discovery, access, and utilization [1]. Implemented SDIs are a combination of people, regulatory mechanisms and policies,naccess technologies, standards, and spatial data themselves [2,3]. Given spatial data acquisition challenges and costs, it is necessary to treat spatial data as a multi-use infrastructural product [1] that provides the foundation for leveraging consistent and reliable spatial expertise from multiple institutions. Planetary spatial data without a coherent planetary spatial data infrastructure plan propagates the current inefficient state of managing this precious data resource, impedes fulfilling future goals and objectives efficiently, and squanders opportunity to fully exploit the data and expertise.

We propose the development of a Planetary SDI (PSDI) akin to the existing U.S. National Spatial Data Infrastructure (NSDI) [2] that identifies spatial data, spatial data practitioners, and spatial data interoperability as issues of national importance. This user motivated effort can serve as a framework to enable more effective longer range NASA planetary spatial data driven science planning [1,4]. PSDI is not a long range planning document or ”roadmap”. Instead, PSDI describes the facets and bounds within which spatial data planning should occur, and seeks to identify, understand, and codify spatial data usage requirements, technologies, standards, access requirements, and regulatory issues. PSDI is an initial step in developing spatio-temporal data exploitation strategies over the next 35 years.

Rajabifard [3] identifies five primary components to SDI that directly translate to the needs of planetary science: ”policy, access network, technical standards, people (including partnerships), and data”. These components are grouped into two themes: human-data interaction (data and people), and facilitating technologies (policy, access, and standards). People are the key to SDI and a realign from technology-centric to human-centric is a necessity; SDIs exist to support complex decision making and knowledge synthesis by the user community. This is a user-centric view that contrasts with the technological driven approaches being applied to long-range planning.

SDIs have developed to address three primary issues that exist across many communities that leverage spatial data. First, data collection can be prohibitively expensive. Therefore, data reusability should be a primary concern for the data provider and SDI seeks to provide a framework for high reusability rates. Second, in the case of planetary science, costs associated with data processing and generating derived data products can be high and cost-sharing or reuse of large scale derived products and tools offers an opportunity for cost reduction and collaborative relationship development. Third, cross group data sharing or tool development without a standards based regulatory environment can be exceptionally challenging and SDI seeks to deploy common framework data themes such that derived product generators are encouraged to integrate back into the SDI ecosystem. All three of these goals support high vertical and horizontal integration potential.

Motivating a Planetary Spatial Data Infrastructure Masser [5] identifies the challenges in developing an SDI to serve the needs of a broad user community that are not experts in spatial concepts and whose general usage needs are met without depth to their spatial awareness. The majority of the planetary data users are experts in some subdomain of planetary science and not spatial data experts; these users want spatial data to ‘just work’. The current focus on low level data capture and raw data storage requirements does not begin to address lowering the barrier of entry and allowing easier (standardized) data discovery, access, and utilization. The previous statement is not intended as a critique. In fact, we argue that this initial focus is critical, and the proposal of a PSDI premature without precursor work that focused primarily on data and technical concerns.

The proposed PSDI has a complimentary relationship with two other critical community services: the Planetary Data System and the NASA decadal surveys. The PDS plays a critical role not only in laying the foundation for proposal of a PSDI, but also in the success of said PSDI. In part this is achieved by recognizing that the fundamental goals of the PDS and PSDI are orthogonal. PDS seeks to be a long term archive for low-level data to allow for continued and consistent access as inevitable technological advancement occurs. In contrast, the proposed PSDI is a living framework that seeks to fill user driven needs by leveraging the data within the PDS, transforming said data to meet the standards and policies defined by the PSDI, and providing transparent data access mechanisms. The NASA Decadal Survey is a medium term planning document that encompasses science needs and goals. The proposed PSDI seeks to provide a framework (bounds) for spatial data collection, management, and community utilization that would enable the science goals outlined by the planetary community to be realized to their fullest potential.

We propose a vision for a PSDI that draws from the successful development of terrestrial SDIs, the critical infrastructural successes of the PDS in archival data management, and the needs of a diverse planetary science research community (academic, government, and most recently private). A PSDI exists to support NASA strategic goals by identifying and describing apsects of spatial data to support increased utilization. The broad components of the proposed PSDI are largely inline with [3], but the specific people, technology, and data requirements are uniquely planetary.

People: Spatial data users pervade all components of a PSDI and are the primary drivers [6]. Management of the human components includes the development and stewardship of the critical skills necessary to realize a PSDI, the outreach mechanisms to engage and educate stakeholders (data collectors, providers, and users), and the techniques to connect with non-expert and new users [7]; this is a user-centric and not techno-centric view.

Standards: Data standards support accurate geopositioning, interoperability, and usability. Spatial location is critical for both horizontal and vertical integration of spatial data sources. Accurate positioning is a function of accurate pre-launch sensor calibration, in flight calibration, and data-driven in situ calibration. Interoperability and usability of complex spatial data are also a major concern for terrestrial SDIs and significant effort has been dedicated to the development of robust specifications, e.g. the Open Geospatial Consortium (OGC) spatial standards or the Community Sensor Model (CSM).

Policies: SDI as a regulatory mechanism is successful through a combination of stakeholder engagement, organizational (whether government or otherwise) policies, and volunteer compliance. Federal Geographic Data Committee (FGDC) releases periodic policy guidelines and NASA is in an ideal position to echo these guidelines and modify as required to more fully address the needs of planetary data. These policies assist in ensuring that standards for data creation and access are standardized, as well as supporting the necessary infrastructural components of the PSDI with respect to user engagement.

Access Network: SDIs exist to share data and some organization of providers with spatial expertise must be identified. The federated nature of the separate science discipline nodes within the PDS provides a template for future PSDI access requirements and the FGDC model of organizational leads spearheading individual framework components and framework elements is ideally suited for two reasons. First, distributed ownership of the PSDI significantly increases institutional buy in. Second, distributed ownership allows for specialization within the sub-domains described here in. SDI is an inherently complex system [1]. In conjunction with policy, federated ownership supports specialization without fragmentation. From a purely technological perspective, the access network need only keep pace with the current, standards based approaches leveraged by our terrestrial colleagues as these methods are broadly applicable and well vetted by a large scientific user base.

Data: OMB [8] identifies 34 terrestrial data themes critical to national spatial data utilization. Of these, seven are considered foundational or framework data sets; the remainder are more specialized, ancillary data sets with smaller user bases. We identify three framework data themes: geodetic coordinate systems, elevation, and orthoimagery (the remaining four are Earth centered). Geodetic coordinate systems provide the basic positional framework upon which all other data themes, whether framework or not are registered. Within the planetary context the International Astronomical Union has traditionally defined geodetic control through a cadenced revision schedule [9]. Elevation data, whether point observation, vector TIN or gridded is a critical data product and key input for derived data products. The diversity in elevation data representation, collection, generation, and utilization formats has lead the FGDC to define elevation schema to support utilization of this data type. We echo that elevation data is foundational and concentrated research required to identify best practices within a planetary context. Digital orthimagery is the third framework data theme. Digital orthoimagery includes not just the availability of the highest quality available imagery, but also governs methodologies for the registration of data and accurate reporting of accuracy metrics to other framework data products.

The Role of PSDI in Planetary Science The ultimate goal of a PSDI is to provide seamless discovery, access, and exploitation of spatially enabled data for all data consumers without any predetermined requirement of spatial data expertise through the use of cutting edge technologies, standards, and transparent policy initiatives. The development of a strategic PSDI plan is foundational in realizing the ability to fully leverage NASA collected spatial data over the next 35 years. NASA plays a pivotal role in driving the development of a PSDI, identifying policy alignment with existing SDI mandates and filling policy gaps, and empowering partners to codify a user centered plan for spatial data management.

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Permanently Shaded Regions: Future Exploration Of A Unique Solar System Environment. David J. Lawrence; Johns Hopkins University Applied Physics Laboratory (11100 Johns Hopkins Drive, Laurel, MD 20723; David.J.Lawrence@jhuapl.edu).

Introduction: Permanently shaded regions (PSRs) are locations on planetary bodies that do not see the Sun for geologically long periods of time, and therefore have unique properties compared to other locations on planetary bodies. If PSRs exist on airless planetary bodies, they will have very cold temperatures (<~120 K) because they radiate directly to space with no source of heat input other than residual interior heat from the body itself and small amounts of multi-bounce thermal photons from nearby sunlit locations. The low temperatures that exist for long durations within PSRs can result in a variety of interesting effects. One of the most intriguing is that volatile materials, especially water ice, can become trapped within PSRs as a direct consequence of the cold temperatures. Thus, while the residence time of volatiles for non-PSRs is short with timescales of days to weeks, the residence time of volatiles within PSRs can be geologically long (millions to billions of years).

The type examples of PSRs within the solar system are those that exist on the Moon and Mercury. The axes of rotation for both these bodies are nearly perpendicular to their orbital plane around the Sun (1.5º for the Moon, 0.034º for Mercury, where 0º would be exactly perpendicular)[1, 2]. Because the Moon's and Mercury's rotational orientation has been stable for billions of years [1, 3], there are craters near the poles of both bodies that are sufficiently deep such that their interiors do not see the Sun, and they are therefore PSRs.

Volatiles Within PSRs: The existence of PSRs does not guarantee they will accumulate volatiles over time, but only makes such accumulation possible. There is a range of possible volatile sources that can include sources interior (endogenous) or exterior (exogenous) to the planet. Endogenous sources could be residual volatiles from ancient volcanism as well as more recent volatile releases or outgassing events [4]. There is a large variety of exogenous sources that can include comets, asteroids, interplanetary dust particles, solar wind, and even occasional giant molecular clouds that may pass through the solar system [5]. In terms of their time of delivery, all sources can in principle be continuous and/or episodic. In a broader sense, it is now being recognized that "dry", airless planetary bodies have a volatile transport system [5, 6], and when there are PSRs, such as on the Moon or Mercury, the PSRs are a key sink in such a transport system.

A fundamental result that has emerged from these studies is that in spite of similar PSR environments, the quality and quantity of volatile enhancements at the Moon and Mercury are very different. At Mercury, there is strong evidence from many types of measurements that its PSRs contain large amounts of volatiles. In contrast, while the Moon shows evidence of volatile enhancements within its PSRs, the volatile abundances are much less than at Mercury and appear non-uniform across different PSRs. Trying to understand these Mercury/Moon differences directly leads to trying to understand how the volatiles reached the PSRs and their time history within the PSRs. Much understanding has been gained, but many fundamental facts and properties of PSRs are not yet known. As a consequence, there is still significant information and data that need to be gathered about PSRs to enable further understanding. While some of these data can be obtained remotely from orbital spacecraft, measurements will ultimately need to be acquired inside PSRs from the surface of Mercury and the Moon.

It is for these reasons (and others explained below) that PSRs have become a topic of intense study and interest within planetary science. Specifically, studies of PSRs apply to all of NASA's Planetary Science Goals (**Table 1**). Because PSRs are so different than other planetary environments, they contain a wide range of fascinating effects, processes, and targets of scientific study. In addition to volatile enhancements, other interesting attributes about PSRs include unique surface charging and space plasma physics effects [7, 8, 9], potentially distinctive geotechnical properties of the persistently cold and volatile-rich regolith [10, Schultz et al., 2010], and the possible organic synthesis that may take place within PSR volatiles due to long-term cosmic ray bombardment [11]. Because of their unique nature, PSRs can be difficult to study, and even now in the early 21st century there are many fundamental aspects of PSRs that are not understood. Nevertheless, current and future studies of PSRs hold great promise. PSRs are a significant scientific resource, not only for what they can reveal about their host planetary bodies, but because they have been trapping volatiles for up to billions of years, they are a storehouse of solar system volatile materials, and are therefore a resource for future studies of solar system history. Finally, for at least the Moon, the existence of volatile enhancements, and especially water ice, can enable future human exploration to the Moon and elsewhere beyond in the solar system [12].

Planetary Science Goal	**PSR Application**
ORIGINS	Study time history of solar system volatiles [5]
WORKINGS	Study unique processes that operate within PSRs [7, 8, 9]
LIFE	Study pre-biotic but possible organic material in a cold, stable environment [11]
RESOURCES	Prospect for and possibly utilize PSR volatiles for future solar system exploration [12]

Table 1. Studies of solar system PSRs address all of NASA Planetary Science goals.

PSR Exploration in 2050: Much has been learned in the first half-century of PSR exploration. While the field started with a few speculative studies about possible volatile enhancements within PSRs [13], it has reached a well-bounded understanding of the nature of PSRs and volatile enhancements within PSRs [14]. However, while a broad understanding is now known, there are still many basic and fundamental aspects of PSRs and PSR volatiles that are still not understood. The nature of the soil and layering (mechanical, detailed composition) are still largely unknown. Models have been generated and predictions have been made about processes that operate within PSRs, but actual knowledge of such processes is limited. The major question of why the PSR volatiles are so different at the Moon and Mercury is still not resolved.

A new leap in knowledge will require landed measurements from within a PSR. Such measurements are essential but challenging. One of the biggest challenges is the need to operate a landed spacecraft in the very cold PSR environment, which is difficult for engineering (power, thermal, mechanical) and operational reasons. At Mercury, there is the additional challenge of safely landing a spacecraft in the deep gravitational well at Mercury's location near the Sun. Nevertheless, such missions would reveal fundamentally new information about PSRs (composition, stratigraphy, processes) that would likely challenge and expand our current understanding of PSRs.

There are no currently planned PSR-only-landed missions, but NASA is currently studying a lunar polar rover called Resource Prospector (RP) that would carry out investigations in sunlit regions near south pole PSRs [15]. While the RP rover will not be designed to survive in large, deep PSRs, it may still investigate small shaded regions in which enhanced volatiles might be present and PSR-like process might be operating. There are also reports that the Russian and Chinese space agencies are planning lunar polar missions, although details of PSR-specific missions are unclear. In any case, an in-situ PSR mission (or series of missions) will likely be accomplished by some or multiple space agencies and will provide significant changes in our understanding of PSR volatiles.

A sequence of such missions could be accomplished during the time leading up to 2050. After the reconnaissance work carried out by RP, a dedicated PSR-only lander could be delivered to a large lunar PSR and obtain the first in-situ data from within a large PSR. While mobility might be desired for such a mission, the information gained from even a static lander would likely transform our current understanding of PSR environments. After this initial mission, increasingly complex missions could be staged to carry out more detailed investigations of lunar PSRs. Finally, using information gained and technology developed from this round of missions at the Moon, one or more missions could be sent to other PSRs in the solar system, such as the PSRs at Mercury, and maybe even newly discovered PSRs, like what is thought to exist at the asteroid Ceres [16].

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THE OPEN GATE AY: LUNAR EXPLORATION IN . S. Lawrence[1], C. Neal[2] and the LEAG Executive Committee. [1]ARES, NASA Lyndon B. Johnson Space Center, Houston TX 77058, USA (samuel.j.lawrence@nasa.gov) [2]Dept. Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (neal.1@nd.edu)

Introduction: The Moon, with its fundamental science questions and abundant, potentially useful resources, is the most viable destination for near-term future human and robotic exploration. Given what we have learned since Apollo, the lunar frontier now presents an entirely new paradigm for planetary exploration.

The Lunar Exploration Roadmap [1], which was jointly developed by engineers, planetary scientists, commercial entities, and policymakers, is the cohesive strategic plan for using the Moon and its resources to enable the exploration of all other destinations within the Solar system by leveraging incremental, affordable investments in cislunar infrastructure. Here, we summarize the Lunar Exploration Roadmap, and describe the immense benefits that will arise from its successful implementation.

The **Lunar E ploration Roadmap** presents a sustainable strategy to make concrete advances along three themes.

______ – *Use the Moon for scientific research that addresses fundamental questions about the Moon, the Solar System, and the universe around us:* The Moon is an evolved planet in its own right – having a crust, a mantle, and core – and therefore the most accessible destination to cohesively address planetary science questions. The Moon retains a record of the formation, evolution, and impact history of Earth and the other inner solar system planets, as well as an otherwise inaccessible record of the Sun's evolution and history. There are over four decades of planetary science hypotheses that lunar geologic fieldwork will address.

The lunar surface also provides a unique and stable long-term platform for astronomy; in particular, human-tended radio observatories on the far side or optical interferometers could produce dramatic advances in astrophysics.

___________ – *Use the Moon to learn how to live and work productively off-planet, for increasing periods, enabling human settlement:* The Moon has abundant material and energy resources that can be used to decrease the costs and dramatically increase the capabilities of future Solar System exploration. Lunar resources, in particular, offer an enduring opportunity for commercial investment and bringing cislunar space fully into Earth's economic sphere while building international partnerships. Commerce is a key aspect of ensuring the sustainability of future space activity. Public-private partnerships, growing from initial government investment, will sustain infrastructure and create new spaceflight capabilities. The establishment of a lunar outpost is the most feasible method of establishing an economic anchor in cislunar space, similar as to how the International Space Station has spurred low-Earth orbit transportation.

___________ – *Use the Moon to prepare for future missions to other destinations:* The Moon is the only viable deep-space test-bed for testing technologies, systems, and operations to enable cost-effective human operations beyond low-Earth orbit. The Moon's combination of radiation, hard vacuum, and low-gravity provide a unique laboratory to study the physiological, biological, and biomedical aspects of long-duration operation on planetary surfaces. Irrespective of the well-established ways in which lunar exploration is required for the success of future voyages to Mars and beyond, the establishing a lunar outpost will help to establish the comprehensive industrial base required to successfully make voyages to Mars and beyond.

Time Phasing: Each of the three themes in the LER have been developed with time phasing in mind, and the engineering aspects have been defined by LEAG as occurring:

Early: Robotic precursors and up to the 2nd human landing (< 1 lunar day),

Middle: Initial outpost build-up to including says of 1 lunar day and part of the lunar night, including robotic support missions; and

Late: Activities associated with and following the establishment of the lunar outpost.

For scientific goals, LEAG has incorporated the NRC Scientific Context for the Exploration of the Moon report [2] findings for the prioritization of science concepts and goals that were specifically studied in that report. We have also included, through consultation with leaders in various science related communities, how science related to Earth Observation, Heliophysics, and Astrophysics could be achieved from the Moon.

Technologies: Building cislunar infrastructure does not require technologies wildly outside our experience base; rather, it is facilitated with evolved versions of currently existing technologies such as microwave power transmission, laser communications, solar power, regenerative life support, propellant storage, and telerobotics. In terms of new investments, the demonstration and flight qualification of presently well-conceptualized (but unflown) technologies for cislunar in-situ resource extraction and utilization would provide a capability required for any future sustained human space operations.

Vision for Lunar E ploration in : Successfully implementing the Lunar Exploration Roadmap will result in a variety of benefits for planetary science and exploration. While predicting events three decades hence is fraught with uncertainty, following the Roadmap will produce a dramatically altered landscape for planetary science and exploration by the year 2050. The proximity of the Moon to the Earth offers intriguing possibilities for a future where lunar surface operations are commonplace, with at least several hundred people living and working on the Moon. Examples of the kinds of activities we foresee include:

Transformational Planetary Science: Geology is a field science, and can best be done by humans, mapping and solving complex field problems to answer fundamental science questions. By the 2050s, we anticipate that in-person fieldwork would be undertaken by academic institutions (much like NASA and NSF support activities in Antarctica) yielding profound benefits for our understanding of the Solar System. A lunar outpost, for example, could enable lengthy expeditions to geology field sites across the lunar surface using both humans and human-tended robots, depending on the science question to be addressed.

Enduring Commercial Markets: Fueled by access to lunar resources, large-scale operations on the surface of the Moon and in cislunar space are commonplace, and have expanded Earth's economic reach and dramatically increased the human presence in cislunar space. From refueling assets in geosynchronous space to tourism to space-based solar-power, commercial activities in cislunar space are routine and profitable.

A New Paradigm: Cislunar infrastructure, powered by lunar resources, promises a dramatic increase in capability for NASA generally and planetary science specifically. Missions could be assembled at L2 and supplied using lunar resources, dramatically lessening current mass constraints, prior to routine departures to Mars and other destinations. As another example, returned samples requiring complete isolation from Earth's biosphere from other destinations (such as Mars, or outer planet moons) could be received and examined at completely isolated facilities on the lunar surface.

Implementation Strategy: There are near-term steps that must be undertaken to ensure that the breathtaking potential of lunar exploration is realized.

LEAG has developed a Roadmap implementation [3] strategy for the 2020s designed from the outset to advance science and have viable on-ramps for commercial activity with measurement objectives clearly traceable to the Strategic Knowledge Gaps [4].

Phase 1 – Prospect for Resources: Build upon the results of recent lunar missions to define if the resources are actually reserves. Such prospecting needs to: define the composition, form, and extent of the resources; characterize the environment in which the resources are found; define the accessibility of the resource; quantify the geotechnical properties of the regolith in which the resources reside; establish the capability to autonomously traverse several tens of kilometers to sample to determine the lateral and vertical resource distribution on meter scales; identify resource-rich areas for targeting future missions; and establish capabilities such as automated ________ sample return and curation to facilitate the assay of potential resources.

Phase 2 – Demonstrate ISRU: Based on the results of Phase 1, the next step would be to carry out an end-to-end demonstration of resource extraction and utilization, which addresses important science questions, validates key technologies, including feedstock acquisition and handling, resource storage, ISRU system longevity, and dust mitigation strategies.

Phase 3 – Lunar Resource Production: Based upon the results of Phase II, begin to utilize lunar resources to enable increasingly complex operations on the surface, including life support for human outposts and propellant for reusable landers, as part of a sustainable human-tended facility on the surface [e.g., 5]

Conclusions: The Moon is the natural "Gateway to the Solar System", representing the fundamental underpinnings for understanding Solar System processes and history. The Moon is also the critical enabling asset for any human exploration activity that the world may undertake in space, now and in the future. Lunar exploration enables an approach to Solar System exploration that involves a series of logical, incremental steps, producing mutually reinforcing capabilities that enable sustainable planetary science, exploration, and commerce. By the 2050s, creating the capabilities inherent in executing the Lunar Exploration Roadmap will enable us to go anywhere, and do things heretofore only imagined, throughout the Solar System – with clear benefits for planetary science.

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PROSPECTING AND MINING SPACE RESOURCES: PLANETARY RESOUCES' OUTLOOK AND THE PLANETARY SCIENCE IMPACT.

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Introduction: Over the next 35 years, scientific exploration of the Solar System has the potential to expand beyond being a predominantly publicly funded activity to include privately financed business ventures. Private finance can serve to accelerate research & development, fund interplanetary missions, and generate scientific data. This contribution of the private sector to space exploration can provide new data about the solar system beyond that from the normal cadence of government-funded missions.

Planetary Resources is leading the way in bringing private finance to planetary science with the aim of prospecting and mining Near-Earth Asteroids (NEAs). Beyond the business opportunity of extracting and selling space resources, the knowledge generated from our efforts will expand humanity's understanding of solar system evolution, provide further context for the diversity of meteorite parent bodies, and contribute to strategies for planetary defense.

To achieve its goals, Planetary Resources' vision for the next 35 years in asteroid resource science includes strong private-public partnerships and close collaborations with the planetary science community.

Science of Asteroid Prospecting: Prospecting NEAs is a necessary precursor to any mining expedition. The technologies, instrumentation, and data products of prospecting missions have significant overlap with traditional science-driven planetary exploration missions. The key goals of prospecting are the quantification of resources on a NEA and measurements that feed into the engineering design of a mining operation. Specifically, successful prospecting missions must produce geochemical and geophysical knowledge of the target.

The first mining goal of Planetary Resources is the extraction of water for fuel. Therefore understanding the abundance and distribution of water (in any of its forms) on an asteroid is essential and necessitates instrumentation similar to that found on a traditional planetary science mission. However, Planetary Resources will be more constrained by cost and efficiency than government-funded missions. Thus, Planetary Resources is already innovating to make smaller, more cost effective scientific instrumentation to support prospecting efforts.

The long-term mining goal of Planetary Resouces is the extraction of both industrial and rare materials. Similar to water prospecting, asteroid composition and homogeneity will be crucial metrics for determining the commercial value of any asteroidal resources. Likewise the instrumentation required for such prospecting activites is similar in function to instruments found on planetary missions.

For both the near-term and long-term goals of the company, knowledge of asteroid structure and regolith properties will be essential for informing mine operations at the asteroid. The instrumentation needed for such measurements is a combination of technologies with space heritage and technologies currently under development at Planetary Resources and elsewhere.

Although not driven exclusively by science, Planetary Resources' asteroid prospecting will create data valuable to the planetary science community. The resulting data could include compositional mapping, indications of hydration state, geophysical models, measurements of mechanical strength, and constraints on the regolith environment.

Partnerships and Collaborations: Planetary Resources will actively engage with the planetary science community in order to utilize the expertise required to develop a prospecting mission and interpret returned data products. The scope and nature of such partnerships will continue to evolve over time, but will likely continue to include joint research & development efforts, educational training in the form of student internship opportunities, and job opportunities for planetary scientists.

In the near future, Planetary Resources sees collaborations with planetary scientists expanding to include sharing data collected from asteroid prospecting missions. Given the commercial motivations of prospecting, a framework must be developed that will allow the planetary science community to benefit from prospecting data while allowing Planetary Resources to keep certain information proprietary as to remain competitive. The company is looking to work with the community to develop that framework in advance of the first prospecting mission.

Summary: Planetary Resources is working to bring commercial financing to planetary missions. The nature of prospecting missions has significant overlap with traditional exploration missions, and thus may generate valuable scientific data. Planetary Resources will continue to engage with the planetary science community to facilitate partnerhips and collaborations that will benefit both science and commercial opportunites in space.

SITE PLANNING AND DESIGN TO ENABLE PLANETARY SCIENCE AND HUMAN EXPLORATION.

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Introduction: In October of 2015, the National Aeronautics and Space Administration (NASA) hosted a workshop to "identify and discuss candidate locations where humans could land, live, and work on the martian surface". The identification of exploration zones encompassing regions of interest relevant to science exploration and investigations, along with capabilities and accommodations for sustainable human presence was a main thrust of the workshop. The integration of planetary science exploration and human exploration to enable and achieve specific and combined goals for each offers immense value. Attendees of the workshop recognized the need for this critical engagement of planetary science and human exploration systems. Furthermore, acceptance that planning the proper and efficient site layout and design of science, research, habitation, and landing facilities, paths, etc. about and within the exploration zones and special regions following planetary protection guidance/policies and associated with environment management practices to accommodate an effective and efficient infrastructure for robotic and human missions, is critical. Further evidence of the need for appropriate site design planning and implementation, with data collected over the span of several years, has been demonstrated by Earth-bound exploration regions such as McMurdo Station, Antarctica. This evidence points to the impact of past exploration on current and future exploration and has influenced and revamped infrastructure master planning and design. We may use lessons learned from this experience to assist our planetary exploration master plans.

Background: A strategy for Exploration Zone development includes consideration for stepwise buildup of surface capabilities to enable exploration in parallel with habitation and utilization. The purpose of establishing human habitation capabilities on planetary surfaces is multifold and includes the following:

- To facilitate exploration and learning
- To facilitate access to, collection, and communication of information and knowledge
- To facilitate historical and ethical preservation
- To facilitate survival in an extreme environment
- To facilitate habitation and seed long-term residence
- To seed visitation for multiple arrivals and departures

Site analysis and design helps identify and define needed elements and design and performance characteristics to support the desired functionality of the site, the interaction of built and natural elements and the magnitude of their effects on each other, and the best organization and arrangement of those elements with each other and the environment to facilitate functionality of the site, operational efficiency, sustainability, extensibility, and stewardship of the environment. A site plan expresses relationships between site elements and the environment, including orientation and potential temporal variations, and the degree of sustainability.

Moving Forward: Consideration of planning and design parameters with preliminary analytical results of planetary exploration zones (Moon and Mars) have been initiated. Parameters include physical characteristics and features such as terrain, topography, climate, seasonal patterns, albedo, and radiation. Additionally, operational characteristics including distance from landing and landing clearance, visual access, points of interest, robotic and crew activities, communication spectrum and access, safety, planetary protection, etc. are within the realm of variables that have been considered within preliminary exploration system design response options that identify functional adjacencies, buildup sequence, path and infrastructure directions, zoning, utility layout, circulation, etc.

Site planning is an iterative and integrated process, requiring input from all parties that are subsumed within and associated with the exploration and usability of the environment, and serves best when applied prior to initial exploration operations. McMurdo Station's master plan was overhauled to correct inefficient project-by-project growth and utilization and negative environmental and operational impact on exploration and sustainability. The opportunity exists to avoid this fate with timely and continued effective planning of planetary exploration zones well in advance of implementation, which will inevitably increase exploration value and return.

SAMPLE RETURN ENABLED BY A CREWED PRESENCE IN CISLUNAR OR CISMARTIAN SPACE: FARTHER REACH, BETTER SCIENCE. R. Lewis[1], P. Niles[2], M. Fries[3], F. McCubbin[4], D. Archer[5], J. Bleacher[6], J. Boyce[7], B. Cohen[8], C. Evans[9], T. Graff[10], J. Gruener[11], S. Lawrence[12], M. Lupisella[13], D. Ming[14], D. Needham[15], K. Young[16], [1,6,13]NASA Goddard Space Flight Center, Greenbelt, MD, 20771 (ruthan.lewis@nasa.gov, jacob.e.bleacher@nasa.gov, mark.l.lupisella@nasa.gov), [2,3,4,5,7,9,11,12,14]NASA, Johnson Space Center, Houston, TX 77058 (paul.b.niles@nasa.gov, marc.d.fries@nasa.gov, francis.m.mccubbin@nasa.gov, doug.archer@nasa.gov, jeremy.w.boyce@nasa.gov, cindy.evans-1@nasa.gov, john.e.gruener@nasa.gov, samuel.j.lawrence@nasa.gov, douglas.w.ming@nasa.gov,), [8,15]NASA Marshall Space Flight Center, AL 35812 (barbara.a.cohen@nasa.gov, debra.m.hurwitz@nasa.gov), [10]Jacobs Technology, Inc., Houston, TX 77058 (trevor.g.graff@nasa.gov), [16]University of Texas, El Paso / Jacobs Technology, Inc., Houston, TX 77058 (kelsey.e.young@nasa.gov).

Introduction: Sample return (SR) from Solar System bodies is a proven and powerful method for answering fundamental questions about the history and evolution of the Solar System, and has been recognized as a high priority as documented in the 2013-2022 National Aeronautics and Space Administration (NASA) planetary science decadal survey. Although there are many options for accomplishing sample return from Solar System bodies using robotic mission concepts, the human presence in cislunar and cismartian space, and on lunar and martian and/or martian moon surfaces, provides a unique opportunity to take advantage of both robust spacecraft infrastructure as well as the capabilities of humans (e.g. decreased time delays, greater situational awareness of site context, finer control over robotic and sampling assets, etc.) and human-piloted spacecraft to fundamentally improve SR well beyond current capabilities, and enable SR missions of greater range, mission duration, and potentially returned volume and mass.

Description: As mission options are under study, accompanying alternatives of potential methodologies for surface and on-orbit collection, preservation, analysis, curation, and return of samples compose a multivariate trade space for human and robotic interaction and collection/analysis services and accommodations.

Human assisted sample return in combination with robotic sample return missions provide several advantages in nearly every mission architecture:

1) *Transit of samples to Earth using a robust and reliable human capsule/spacecraft can reduce the need for investment in and mass penalties of a singular, customized SR craft.* Less mass is required to support equipment for a) protection from thermal alteration than a SR spacecraft, which is especially true for SR missions with requirements for maintaining cold/cyrogenic conditions for samples during passage through Earth's atmosphere, b) maintaining the need to carry Earth atmosphere transit hardware throughout the entire SR mission, and c) maintain the high "gear-ratio" of SR systems.
2) *The robustness of the human spacecraft allow for more complex sample handling protocols including any repackaging operations to break the sample chain to satisfy Planetary Protection requirements as well as potential intermediate analysis.* While this can also be done robotically, the adaptability of humans substantially improves the potential reliability of these operations and expands the range of possible solutions to these problems.
3) *Robotic sample return missions are excellent precursors for future human exploratio*n. They provide a means for testing human-scale equipment while simultaneously characterizing the materials likely to be encountered by the astronauts. This was seen in the Apollo missions to the Moon, which were preceeded by fifteen successful Ranger, Surveyor, and Lunar Orbiter missions that provided information critical to Apollo's successes. Experience dictates that robotic missions can be an integral part of future human exploration architecture.
4) *Sample return spacecraft could be refitted and refueled to increase the diversity of sampled bodies in the Solar System, and to better utilize NASA spacecraft investment.* Rendezvous between the robotic sample return spacecraft and a human spacecraft could allow for repair and refueling operations that enable SR spacecraft reusability. Thus a robust robotic sample return cycler could operate continuously to multiple targets in the inner solar system. This concept was partially proven with the Stardust-NEXT extended mission, wherein the Stardust SR spacecraft visited and imaged comet Tempel-1 after completing its primary mission of returning samples of comet Wild-2 to Earth. SR spacecraft are physically capable

of visiting multiple bodies but can currently perform SR from only a single body.

Implications: The development of human assisted sample return capability provides strong programattic and scientific benefits. Future human with robotic exploration on the surface of Mars and the Moon will provide a unique opportunity for ground truth discovery and collection of samples. Sample analysis capabilities on the surface are likely to be limited, therefore many of these samples will be returned to Earth for further comprehensive analysis and essential curation and preservation. To maximize science return and value, it is necessary to develop candidate scenarios that help determine the most effective methodologies, potential technology identification, surface analysis accommodations, operational handling and manipulation processes, containment devices, surface and on-orbit exchange, etc.

The “trade space” of sample return contains many different options with important differences. Taking advantage of human missions of opportunity with accommodating on-surface and on-orbit infrastructure in tandem with robotic missions will provide greatest exploration and discovery value.

A MINIATURE ELECTRON PROBE FOR IN SITU ELEMENTAL MICROANALYSIS.

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Introduction: *In situ* probes will provide an important complement to the various sample return missions envisioned for the next 35 years. The Mini-EPMA under development will enable advanced, fine-scale *in situ* mapping of the elemental composition of planetary materials. Composition provides key evidence about the processes by which rocks, soils, and ices were formed and altered (*e.g.*, accretion, differentiation, hydrothermal alteration). This instrument will be a valuable payload element for future landed missions to airless bodies, including asteroids, comets, and various planetary satellites. Operation in atmosphere would require the addition of a vacuum housing.

Sub-mm spatial resolution: The focused electron beam will permit sub-millimeter scale compositional mapping in a flight instrument, a scale relevant to petrographic structures. Modeling with SIMION [1] indicates that e-beam spot sizes under 100 µm are achievable in a flight instrument with microscale field emitters in an array, with focusing achieved by a compact electrostatic lens stack. Microfabrication techniques are used to define the growth regions for the CNT emitters as well as the grid electrode required to individually address each element in the array. The prototype cathode array will have 10 x 10 elements, leading to a 10 x 10 compositional map of the target surface. Spot pitch is tunable depending on science goals.

Flight instrument concept: In the mini-electron probe ("EPMA") flight concept (Fig. 1), electrons are drawn out of an addressable-element carbon nanotube field emitter array [2, 3] by the cathode/grid extraction voltage, then accelerated by the lens stack into the planetary/asteroidal/cometary surface at 15-20 kV, exciting X-ray line emission characteristic of the elemental composition of the surface. The X-rays are then measured by a silicon drift detector similar to those used in laboratory energy-dispersive spectroscopy (EDS) and analyzed using standard EPMA techniques to give the surface composition of the region illuminated sequentially by each electron-beam spot (100 µm). In this way, a grid of e-beam spots activated in sequence will non-destructively produce a fine-scale map of elemental composition. Microfabrication techniques are used to define the growth regions for the CNT emitters, as well as the grid electrode required to individually address each element in the array.

Mass and power: A preliminary flight instrument concept produced by the GSFC Instrument Design Laboratory calculated a total instrument mass of 3.3–3.6 kg. The model includes two electron guns and two X-ray detectors for reliability. Peak power is estimated at 12.7 W; average power at 5.7 W.

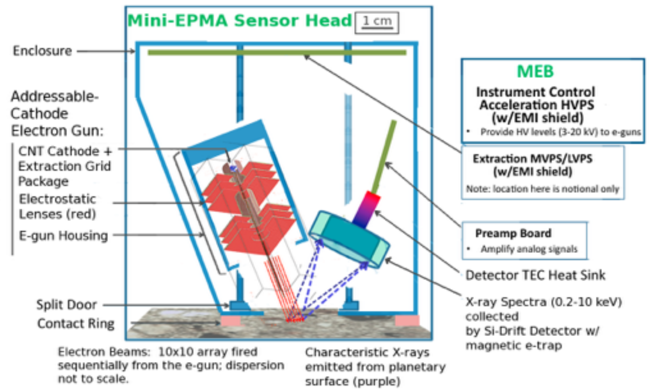

Figure 1. Preliminary concept for mini-EPMA flight instrument

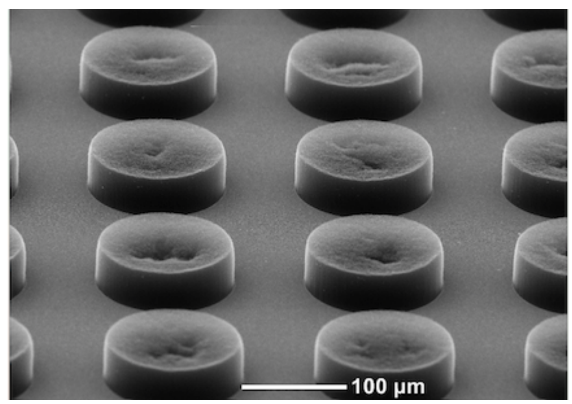

Figure 2. SEM micrograph of 10x10-element carbon nanotube forest cathode prototype grown at GSFC.

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Acknowledgments: This work is supported by NASA ROSES 13-PICASSO13-0043. J. Gaskin (NASA/MSFC) contributed as co-author on the proposal. This work also depends on the ongoing efforts of N. Costen, A. Ewin, G. Hidrobo, C. Johnson, G. Manos, D.S. Stewart, and E. Young at GSFC.

QUESTIONS ABOUT VENUS AND MEASUREMENTS NEEDED TO ADDRESS THEM FROM FUTURE MISSIONS TO VENUS. S.S. Limaye[1] and K. L. Jessup[2], [1]University of Wisconsin, 1225 W. Dayton Street, Madison, WI 53706, SanjayL@ssec.wisc.edu, [2]Southwest Research Institute, Boulder, CO, jessup@boulder.swri.edu

Introduction: Past and current missions to Venus as well as new acquisition and interpretation of data obtained during historical and recent Venus Space Exploration eras have raised some old as well as new questions about the planet and its atmosphere that will require capable missions in the coming decades to gather appropriate measurements from new atmospheric and surface based platforms. Some of these questions are contained in the "Goals, Objectives and Investigations" document prepared by the Venus scientific community [1] through the Venus Exploration Analysis Group (VEXAG), but the nuances and details need some specific emphasis in the future updates.

Old and New Questions: Many of the old and new questions about Venus that remain open relate directly to properties that are essential for our understanding Venus' circulation and weather patterns, atmospheric superrotation, and climate evolution. These questions range from basic properties of Venus - what is the precise albedo of Venus at present and, is the neutral atmosphere of Venus truly well mixed? Results obtained from the Pioneer Venus Large Probe showed a vertical gradient between 52 and 42 km [2]. Recent Analysis of MESSENGER data from the neutron spectrometer yielded a higher abundance of nitrogen at 60 km [3], extending the measured altitude range of the observed gradient in the abundance. This gradient defies the accepted belief that the neutral atmosphere should be well mixed in the primary constituents. However, the fact that both carbon dioxide and nitrogen, the two constituents of the Venus atmosphere should be in super-critical state has not been previously considered and may be the cause of this gradient. Laboratory measurements with supercritical mixtures of carbon dioxide and nitrogen also have been discovered to have such a gradient [4].

The nature and identity of the ultraviolet absorber in the clouds remains unknown, but a consideration of spectral, physical and chemical properties of terrestrial bacteria warrant questioning whether bacteria may be the absorber [5]. Recent research [6] suggests that Venus may have harbored liquid water on its surface for as long as two billion years – long enough to have evolved life, as is being increasingly considered as a possibility for Mars. Terrestrial clouds also have been discovered to harbor bacteria at altitudes as high as 41 km [6] and survive ultraviolet radiation [7] in conditions similar to those found in the Venus atmosphere. Cockell [8] has previously examined the possibility of bacteria in the clouds of Venus. Further, some exoplanet atmospheres may also be capable of harboring life [9], so examining whether or not Venus clouds may harbor life will be useful. No mission to date

The albedo of Venus was inferred from ground based observations by Irvine [10] over 30-160° phase angle range and interpreted using a model by Travis [11]. Recently Mallama [12] used spacecraft observations to extend the phase angle coverage at the low and high phase angles and inferred a much higher albedo, leading to some questions about the energy absorbed by Venus atmosphere.

The length of day on Venus also appears to vary considering that the value the inferred rotation rate from Venus Express from the rotation rate adopted from Magellan radar results [13]. The exchange of momentum between the atmosphere and the solid planet is critical.

The connection between the sun and Earth climate has been a focus of some attention for a long time, but key questions remain in establishing a causal link. Monitoring Venus climate for several solar cycles should be useful in understanding the interaction between the sun and terrestrial atmospheres, which should also be useful for understanding Earth of Venus like exoplanets.

Finally, a recent study undertaken to learn about the interior of Venus also included some measurments from atmospheric platforms including balloons [14]

These and a number of other open questions prioritized by VEXAG require new capabilities to make measurements from within the atmosphere and surface from capable platforms.

Future platforms needed: Long lived aerial platforms capable of sampling the Venus atmosphere within the cloud layer (50-72 km altitude) such as Venus Atmospheric Mobile Platform [15] and below it will enable measurements and monitoring of the atmospheric behavior in the most enigmatic altitude regions over a full Venus day. Monitoring of this altitude region over this time scale has never been successfully done without temporal or spatial ambiguity, yet this type of monitoring is critical for the interpretation and contextualization of the data gathered.. If such platforms are capable of carrying a significant payload, they will also enable monitoring the surface for any changes by repeated passes over time.

Concepts for altitude changing balloons have been suggested previously, but not yet flown on other planets. Below 50 km altitude, phase change balloons or other options may be feasible but little development has taken place for such platforms.

Some new innovative concepts using ambient wind to generate electrical power and incorporating high temperature electronics for instrument operations, data collection and transmission as are being developed in US and Europe for long lived platforms capable of making some elementary meteorological measurements near the surface will also be very useful.

Such platforms can be considered for a future Venus flagship mission. Development efforts are needed for maturation of the required platforms and instruments in the coming decade.

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THE CREATION OF A BENEFICIAL BIOSHPERE FROM CO2 IN THE CLOUDS OF VENUS. Ms. Despoina Linaraki[1] and Prof. Dr. Konstantinos-Alketas Oungrinis[2] Supervisor, [1]Brooklyn, New York, dlin.arch@gmail.com, [2] Crete, Greece, kouggrinis@isc.tuc.gr.

Introduction: The proposed paper presents a research project of a space station architectural design on the Venusian atmosphere. This research is based on human psychology and physiology, on the sociology of enclosed spaces, on the technology required to exploit the chemical elements available, and the environmental conditions in the clouds of Venus.

Study Area. The choice of study area is based on the research of Geoffrey A. Landis, Colonization of Venus, Feb. 6.2 2003 [1], in which he describes the possibility of a floating city in the Venusian atmosphere.

Research Questions. This project elevates the participation of architectural design methodology in order to address complex humanistic issues in the creation of new space communities. Specifically, the main research questions were: How the extreme environment of Venus will affect the design? How architectural design is going to be if it regards people in isolation in outer space?

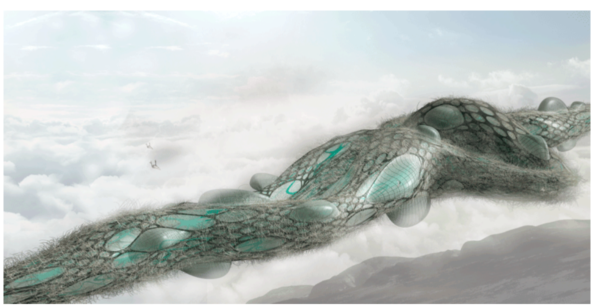

Fig. 1. Venus Space Station, image of the Venus Space Station while floating in the atmosphere of Venus.

Process Of Architectural Design: This design proposal aims to create a beneficial biosphere, it is trying to transfer an earth-like environment in the clouds of Venus, with new approaches of architectural design.

Environmental Conditions. The research takes part in multiple phases. First, it examines the types of constructions that could be created based on the use of carbon dioxide, which compose Venus atmosphere. Secondly, it analyzes the environmental conditions in the clouds of Venus, while at the same time, it examines multiple examples of aerodynamic design both artificial, like airplanes and natural, like birds. This research was an essential step in order to understand how the environmental parameters will affect architectural design in the clouds of Venus.

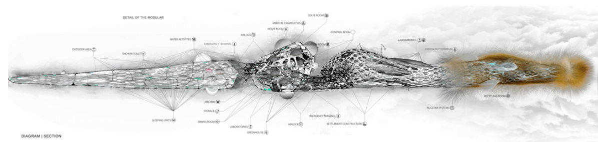

Fig. 2. Process of architectural design, Section of the construction in which appears all the basic elements such us the mechanical system, the living modular and the shelter.

Isolation in outer space. Apart from the environmental parameters this research takes into consideration the feeling of isolation and the psychological effects that it creates to the astronautes. As Scott Howe & Brent Sherwood (2009) wrote 'Living on a space station means being in a confined, limited-volume place, in close proximity to fellow crewmembers, with no chance to 'get away' [2]. This research suggest that through appropriate architectural design this feeling could me eliminated. As Susmita Mohanty, Jesper Jørgensen, and Maria Nyström (2006) argued, architectural design should be created based on psychological issues associated with long-term isolation and confinement [3].

Fig. 3, Venus Space Station, view of the Earth from Venus.

Research Outcome: The space station incorporate research evidence and investigations [4,5] that were deemed as suitable to support a friendly and homey environment for the astronauts by creating an interplay habitant. A multi-functional space is being design, which aims first to give the impression of a non-ending shape, second to avoid the feeling of isolation through different experiences, third to design an earth-like environment in the cloud of Venus and finally to protect the residents from the extreme environmental conditions. The quality of the place that has been designed is based on theories deriving from human psychology and sociology. The color, sound and light change whenever it is necessary to make them feel more intimate [6]. New experiences are formatted according to environmental parameters and human feelings.

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LOW-COST SPACE ACCESS FOR PLANETARY SCIENCE MISSIONS USING HIGH POWER SOLAR ELECTRIC PROPULSION

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Introduction:

As rideshare launches become more commonplace, secondary or small payloads continue to be challenged by the limited choice of orbits, upper stage restart capability and risk-averse nature of primary payloads to allow for flexibility in the deployment sequence. The result is that a secondary payload's final orbit is limited by its host and the propulsion capability of the individual spacecraft, particularly so for cubesat class passengers. For Planetary Science missions rideshare access to space is very difficult due to the often unique orbits and destinations. Many of these challenges can be met through the use of a propulsive rideshare adapter or Orbital Maneuvering Vehicle (OMV). An OMV that leverages High Power Solar Electric Propulsion (HP-SEP) extends the range that an OMV can be used beyond Earth orbit. The HP-SEP OMV leverages much of the development work of a chemical propulsion variant in addition to investments made by NASA into the various elements of the "SEP String" including high power deployable solar arrays, high power Hall Effect Thrusters, and their associated Power Processing Units (PPU).

The HP-SEP OMV can reduce costs for space access using rideshare and enable low cost missions beyond Earth orbit that previously could only be achieved through the expense of a large and costly dedicated rocket (see Figure 1). The HP-SEP OMV platform provides mission augmentation as well and can provide many of the services of a spacecraft bus reducing the cost and complexity of the payload.

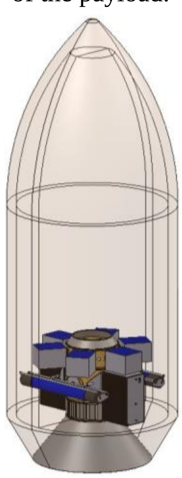

Figure 1: HP-SEP OMV Concept in F9 Fairing

Moog has analyzed, developed and supported numerous missions employing OMV functionality. In this paper a number of case studies are described to illustrate the utility, value and flexibility of the OMV as a mission enabling technology. Moog and NASA Glenn have analyzed a case using this system to spiral out from LEO to GEO and beyond to lunar orbit for a demonstration mission. This same system operationally can be used for deployment from a GTO rideshare to a variety of destinations beyond Earth orbit (BEO). A survey of potential mission applications that could be leveraged by the Planetary Science community is included (see Table 1).

Table 1: HP-SEP OMV Mission Examples

Mission Type	Mission Examples
Lunar Orbit	Lunar Cubesat Comm Relay[1], SLS EM-1 payloads[2], South Pole Aitken Basin sample return mission[2], Lunar Geophysical Network[2], Ecliptic Spinning Lunar Landers[4]
Earth Moon L2	Artemis Mission follow on, "Dark Side of the Moon" Communications coverage, Occulter that would formation fly with telescopes such as James Webb Space Telescope and WFIRST
Near Earth Asteroids	NEA Tour[5], Commercial Asteroid Mining[6], 2008 EV5 Precursor Mission (prior to ARRM)[6]
Mars Missions	Phobos and Deimos science missions[2], Mars Comm Relay[7], MARS$_{DROP}$ mission[9], Mars Discovery Class Missions[2]
Venus Missions	Venus In-Situ Explorer[2], Venus Climate Mission[2]
Distance Asteroids	Asteroid Interior Composition Mission[2], Jupiter Trojan Asteroid[2]

The performance of small satellite technology continues to improve at an exponential pace but, if small satellites and payloads continue to compromise optimal orbit for general space access or very difficult beyond Earth orbit, true potential cannot be fulfilled. In each of the scenarios identified, the particular use of an OMV gives rise to a number of shared launch opportunities that would not have previously been considered and improves the overall access to space for rideshare passengers. The OMV can provide services as a hosted payload platform further reducing the overall mission costs.

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Aerial Mobility : The Key to Exploring Titan's Rich Chemical Diversity. R. D. Lorenz[1], E. P. Turtle[1], and J. W. Barnes[2], [1]Johns Hopkins Applied Physics Laboratory, Laurel MD 20723 (Ralph.Lorenz@jhuapl.edu, Elizabeth.Turtle@jhuapl.edu,), [2]Department of Physics, Univ. of Idaho, Moscow ID 83844 (jwbarnes@uidaho.edu).

Introduction: Water is the medium for life, but organic chemistry is what makes it work. Titan offers complex carbon-rich chemistry in abundance on an ice-dominated ocean world. However, the most astrobiologically interesting sites need mobile *in situ* exploration, much as rovers are performing at Mars. Titan's thick atmosphere and low-gravity environment facilitates regional mobility to home in on the specific locations where liquid water and abundant organics have interacted.

Well-Established Titan Exploration Priorities: Long before *Cassini* arrived, it was recognized by predecessors to Decadal Surveys (for example the Campaign Strategy Working Group (CSWG) on Prebiotic Chemistry in the Outer Solar System [1,2]) that Titan's rich organic chemical environment provides a unique opportunity, and development of Titan mobile aerial exploration was identified as a desirable next step. Chemical environments of particular interest at Titan are areas such as impact melt sheets and potential cryovolcanic flows where transient liquid water may have interacted with the abundant (but oxygen-poor) photochemical products that litter the surface [3].

Early Titan studies emphasized airships and balloons, but access to surface materials combined with the required capability for sophisticated *in situ* chemical analysis presented a severe challenge to such vehicles. Thus, the 2007 Titan Explorer Flagship study [4] advocated a Montgolfière balloon for regional exploration, providing surface imaging at resolutions that are impossible from orbit due to the thick atmosphere, but assigning surface chemistry investigation and interior structure exploration via seismology (to characterize the ice thickness above Titan's internal water ocean) to a Pathfinder-like lander, notionally to land in the equatorial organic-rich dunefields.

Although Titan's hydrocarbon seas are an appealing target, and presented an exciting and cost-effective mission opportunity for the Titan Mare Explorer (TiME) capsule in the 2010 Discovery competition, the Titan northern winter season in the 2020-2030s precludes Earth view and thus direct-to-Earth communication, so affordable missions are not possible in this time frame. Furthermore, while the opportunities in physical oceanography and the intriguing but uncertain prospects of chemical evolution in a nonpolar solvent are significant, the environments that offer the most likely prospects for the most advanced chemical evolution as we understand it today are on Titan's land surface. While the dune sands themselves (as articulated in the 2007 Flagship study [4]) may represent a 'grab bag' site of materials sourced from all over Titan (much as the rocks at the Mars Pathfinder landing site were intended to collect samples from a wide area) and thus may contain aqueously altered materials, as in the exploration of Mars the approach with the lowest scientific risk would be to obtain samples directly from multiple locations, desirably informed by context information at higher resolution than that afforded by *Cassini* data. However, the limited range of surface rovers and the uncertain trafficability of Titan's surface makes either multiple landers, or a relocatable lander, the most desirable option.

Aerial Mobility: Heavier-than-air mobility at Titan is in fact highly efficient [5], moreover, improvements in autonomous aircraft in the two decades since the CSWG make such exploration a realistic prospect. Multiple *in situ* landers delivered by an aerial vehicle like an airplane [6] or a lander with aerial mobility to access multiple sites, would provide the most desirable scientific capability, highly relevant to the themes of origins, workings, and life.

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EARLY EARTH AND ITS GROWING VALUE IN THE SEARCH FOR LIFE ON EXOPLANETS. T.W. Lyons and the Alternative Earths Team of the NASA Astrobiology Institute, Department of Earth Sciences and the Alternative Earths Astrobiology Center, University of California, Riverside (timothyl@ucr.edu).

Studies of the modern Earth have long aided in our exploration for life elsewhere in the solar system. The Atacama Desert is a potential analog for the extreme environments of Mars. More recently, the cold waters beneath Antarctic ice are guiding our missions aimed at water worlds such as Europa and Enceladus. At the same time, Earth's very early chapters have provided a testing ground for refining our skills in the search for cryptic biosignatures seen sometimes in fossils—but more often in organic molecules or isotopic measurements that seldom give up their secrets easily. When viewed rigorously in the environmental and ecological context afforded by terrestrial sampling, these *in situ* data give us a complete view of environmental and biological co-evolution across time scales of millions and billions of years. Life detection on early Earth is difficult, and it should be more so on Mars. Earth, we hope, is teaching us how to get it right.

In recent years, the full dynamic range of terrestrial conditions has been embraced as a catalog of 'alternative Earths' that are unified by the persistence of habitable conditions and inhabitation for perhaps four billion years. It is remarkable that life and life-sustaining environments have prevailed in the face of a cooling Earth interior, a warming sun, shifting tectonic modes, large and small impacts, a stabilizing and varying magnetic field, changing surface redox, climatic extremes, and a multitude of other contingencies, challenges, and opportunities expected at the hands of stellar, solar system, and planetary evolution. In the end, enduring life is a testament to the power of feedbacks at the interfaces between biotic and abiotic processes on Earth. But these are universally relevant considerations. And each of these chapters, if read carefully, can inform the search for life across one of astrobiology's most exciting and promising frontiers—extrasolar planets.

The Earth analog will have enduring and likely increasing relevance for decades to come. This value is not hindered by what some see as Earth-centric myopia—that is, overworking what is known at home as our only roadmap to distant life and planets that will likely be very different. Instead, the diverse alternative Earth states of our own history are windows more generically to the processes, products, and detectable biosignatures that, when filtered through the right lens, provide universal perspective on fundamental relationships, such as that between life in the oceans and the presence and detectability of biosignature gases in the atmosphere above. Indeed, each of Earth's widely varying planetary states translates to a particular atmospheric composition that could one day be detected on an exoplanet.

From ongoing efforts to suss out these past atmospheric compositions on Earth gleaned from a myriad of biogeochemical proxy evidence tied to the ancient rock record, we learn about possible false positives such as methane (CH_4), which can be tied as easily to multiple abiotic pathways as it is to biological production. The most recent early Earth research is schooling us equally in the concept of the false negative—that is, an absence of detectable atmospheric biosignatures above an ocean brimming with life. As an example from the very early pages of our history, abundant free oxygen (O_2) was likely confined to the surface waters of the ocean where it was photosynthetically produced in disequilibrium with an essentially O_2-free atmosphere. In fact, if viewed remotely using current technology, O_2 may not have been detectable in our atmosphere for more than two billion years following its first biological production. And the famous O_2-CH_4 disequilibrium biosignature may not have been detectable at any point in Earth history. But we move forward from this point armed with a more cultivated perspective of what needs to be done.

Rather than Earth being a messenger of exclusively bad news, it instead gives us a call to arms—a motivation for telescope designs limited only by our imaginations. Findings from early Earth urge us to seek instruments with greater sensitivity, signal resolution, and a broader array of spectral data guided by our understanding of life, its cycles, its products, and their holistic relationships to the environment—both oceans and continents.

Our aim is to keep alternative Earths in the conversation for decades to come as a way of more strongly putting the 'bio' into biosignatures by viewing atmospheres for their indebtedness to the 'black box' of the complex interplay at the biotic and abiotic interfaces between the liquid and solid planet. We as a community assert, for example, that interpreting exoplanet atmospheres demands sophisticated numerical models for the possible underlying oceans and that we have lifted the lid on this black box.

At the end of the day, we are confident that spectral data from increasingly sophisticated telescopes optimized for exoplanet exploration will reveal complex mixtures of potential biosignature gases on very distant planets. But we are equally confident that the challenges of interpreting those data will be as acute as those nested in their detection. We are resolute in maintaining that those gases, their concentrations, their mixing ratios, seasonal patterns, and their very co-existence will yield accurate headlines for or against the presence of life only when filtered through an understanding of real life in real oceans impacted by continents, tectonics, and climate. Equally important will be the filter defined by a clear understanding of the abiotic possibilities that can lead to similar mixes of gases. The biogeochemical cycles in our ancient oceans, when extrapolated via models and empirical proxies, are broadly relevant to all life scenarios—even on exoplanets.

Early Earth gives us the platform to take theory or abstract speculation to a place more deeply grounded in observation and possibility—not as a literal analog for other worlds but as a natural lab for exploring how life interacts with its surroundings and leaves detectable (or not) fingerprints. It forces us to reconsider greenhouse gas scenarios in light of biological fluxes weighed against differing surface redox, ocean chemistry, biological and tectonic contributions, solar input, and related photochemistry. It raises possibilities we would not have considered otherwise. Exoplanetary science demands an increasingly mature search engine informed by the processes, pathways, couplings, controls, thresholds, and feedbacks of our resilient Earth and its oceans in their many manifestations over billions of years. Because of this diversity, Earth and its toolbox are much more than an N of 1.

Strategic Geography of the Solar System and Beyond. A. C. MacDonald[1], P. Smith[2], M. Daniels[3], P. Besha, [1] N. Joseph, [2] A. Dolgopolov, NASA Headquarters[1] (alexander.c.macdonald@nasa.gov), The Tauri Group,[2] NASA Ames Research Center[3]

Introduction: NASA is set to remain the core agent in the development of our collective relationship with the solar system—and, increasingly, other solar systems as well—as we continue to explore the cosmos through human space-flight missions and robotic probes. Our exploration activities take place within a unique physical geography but our explorations are nonetheless governed by the same types of human relationships that exist and develop between people and places everywhere. This project – a large wallmap entitled 'Strategic Geography of the Solar System and Beyond' - is an infographic representation of the geography of exploration that lies before us with narrative descriptions highlighting aspects of the human relationships and human geography that have long-run strategic implications for consideration.

The discipline of geography, the study of the relationships between people and places, offers techniques that can provide useful insight into the strategies that will allow us to manage the political, economic, cultural forces that provide the motivation and resources for our efforts. There are two broad classes of geographic analysis: physical geography and human geography. Human geography, the primary focus of this wallmap, encompasses physical, cultural, and economic considerations.

This strategic geography chart considers outer space from a human interest perspective beyond the traditional focal areas of scientific discovery and technology development. It challenges the viewer to think of the solar system and beyond as a natural environment filled with diverse worlds and geographies with which humanity is in the process of developing economic and cultural relationships and in which there are resources that can be used to advance and support the interests of the United States.

Additional Information:
The poster is very large – approximately 5 ft by 9 ft.

THE FUTURE OF PLANETARY DEFENSE. A. Mainzer[1], J. Bauer[1,3], T. Grav[2], J. Masiero[1], C. Nugent[3], V. Reddy[4], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA (amainzer@jpl.nasa.gov), [2]Planetary Science Institute, Tucson AZ, [3]Infrared Processing and Analysis Center, California Institute of Technology, Pasadena CA, [4]Lunar and Planetary Laboratory, University of Arizona, Tucson AZ.

Small bodies have interacted with Earth in the past and are certain to do so in the future. NASA and the worldwide community of astronomers, both amateur and professional, have made great strides in discovering, tracking, and characterizing potentially hazardous objects. In 2011, the community achieved the so-called "Spaceguard" goal of discovering more than 90% of near-Earth asteroids (NEAs) larger than 1 km in diameter [1][2][3][4]. Now, attention has turned to finding at least 90% of NEAs larger than 140 m, since objects of this size and above are thought to be capable of causing severe regional damage and to represent the bulk of the remaining risk of an unpredicted impact [5][6]. Significant progress has been made to date: At present, approximately 25% of NEAs larger than 140 m have been discovered [1]. The existing suite of near-Earth object (NEO) surveys primarily consists of 1- to 2-m class telescopes operating at visible wavelengths (e.g. PanSTARRS [7] and the Catalina Sky Survey[8]), with the exception of the 0.4 m space-based infrared (IR) NEOWISE survey [9][10][11][12].

However, by 2050, it is likely that efforts to identify more than 90% of NEAs larger than 140 m in diameter will have been achieved through advanced ground- and space-based surveys [5][6]. This will have clearly quantified the risk of an Earth impact from a body large enough to cause severe regional damage. In the process of carrying out such surveys such as LSST and the proposed Near-Earth Object Camera [13][14][15], a substantial fraction of smaller objects is likely to have been discovered, on the order of 50% or more of NEOs larger than ~75 m. Moreover, the statistical chance of an impact from NEOs smaller than 75 m will be well-determined, owing to the large number of objects in this size range that will have been discovered. Survey debiasing techniques can be used with this large sample to compute a statistically meaningful probability of impact from the ensemble of objects smaller than 75 m, as well as the remaining undiscovered population of larger objects.

To achieve >90% survey completeness for NEOs >140 m, the advanced surveys will necessarily have had to survey large areas with great sensitivity, covering a large fraction of the entire sky. Thus, they are likely to have discovered a large number of long-period comets (LPCs), since these have orbits with a roughly uniform distribution of inclinations and consequently declinations. Thousands of new LPCs are likely to have been discovered by 2050, supporting future missions to these objects as well as thoroughly characterizing the population as a whole and setting strong limits on the statistical chance of impact. Unlike NEAs, LPCs spend most of their orbits in the very outer solar system, and cannot be surveyed until they approach their perihelia.

By 2050, the focus of planetary defense might be expected to shift to improving knowledge of orbits for known objects on Earth-approaching trajectories, continuing to discover small NEOs that cannot be detected until they are very nearby, continuing to discover LPCs as they enter the inner solar system, and planning any mitigation campaigns that may be necessary. In particular, the Yarkovsky effect acts more strongly on smaller objects, causing their orbits to change by more than the 0.05 AU/century typical of larger NEOs. Continued monitoring of small NEOs in the 2050 timeframe and beyond will be required to characterize their orbital drift due to non-gravitational forces, and the resulting impact hazard they pose. This orbital characterization will in turn provide measurements of the mass of the asteroid, which constrains density when combined with infrared- or radar-measured diameters [16]. Thus the sample of objects with well-measured densities will grow significantly as part of the planetary defense campaigns occurring in the coming decades.

Since those objects that make close approaches to Earth are also those most likely to require the least Δv to reach, the process of surveying for potentially hazardous objects will also provide a wealth of small body targets that are energetically easier to reach, some easier than the Moon [17][18]. The targets discovered by surveys undertaken in the 2020-2030 timeframe should pave the way for low-cost missions to a slew of small bodies. In the 2050 timeframe, it is possible to envision a set of small spacecraft that explore a large number of NEOs spanning a diverse range of sizes, shapes, and taxonomic classifications to explore their detailed individual physical properties. Moreover, the large number of close-approaching NEOs that will be known will make a rich target set that can be explored for decades with large-aperture facilities such as ground-based radars and next-generation UV/optical/IR telescopes.

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The GSFC Exoplanet Modeling and Analysis Center.

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Introduction: The study of the formation, evolution and characteristics of extrasolar planets cuts across all scientific boundaries of NASA science, from Earth Science and Heliophysics to Planetary Sciences and Astrophysics: exoplanets and their host stars are coupled together through stellar radiation and space-weather interactions such as stellar winds and outflows (a combination of stellar Astrophysics coupled with Heliophysics-based models), while planetary interiors and surfaces are connected to the planet's atmosphere through surface processes, atmospheric dynamics, and even the potential impact of biological activity (studied by both Planetary and Earth Sciences). Astrophysics also provides the context – the study of the universe, galaxies, stars, their properties, and evolution – while also serving as the purveyor of the observing platforms that are used to study planetary systems around other stars; additionally, Planetary Science missions that combine in-situ and remote sensing studies of Solar System bodies can provide important context for interpreting exoplanet observations. Given this complexity and the inherent couplings across many diverse science areas, a comprehensive interdisciplinary viewpoint is needed to fully characterize the planetary environments and the potential for life to exist on worlds orbiting other stars.

As we prepare for the launch of the James Webb Space Telescope (JWST), a revolutionary tool for the study of both Solar System and extrasolar planets, and plan for future exoplanet imaging missions such as Wide-Field Infrared Space Telescope (WFIRST) and future flagship ultra-violet/optical/infrared (UVOIR) telescopes, the time is ripe for developing a community-accessible modeling and analysis framework that can help facilitate the investigation and interpretion of observations of atmospheres and surfaces of a planets both within our Solar System and beyond.

Decription: The GSFC Exoplanet Modeling and Analysis Center is meant to provide a cohesive and accessible platform for the planetary atmosphere modeling and analysis community to host their software for modeling and interpreting current and future NASA observatory data examining the atmospheres and surfaces of both Solar System planets and exoplanets. The platform would allow external researchers to install their software on a dedicated NASA computer cluster, and GSFC scientists and software experts would aid in navigating installation issues and would help to develop web interfaces for using the tools. GSFC scientists would also help to develop interfaces between modeling and analysis tools, so models from different researchers could be compared in a rigorous manner and could be linked up to provide a holistic modeling framework that could bring together physics-based models with data analysis and interpretation tools (see Figure 1). Examples of models include atmospheric chemistry models, planetary atmosphere radiative transfer, planetary parameter retrieval algorithms, and data modeling tools.

The EMAC will leverage the capabilities and resources existing within the GSFC Community Coordinated Modeling Center, an existing computing center for assisting the Heliophysics community with the development and hosting of models related to solar physics. The CCMC operates a large computing facility (1000s of processors), which is overseen by a core team of computer support staff and heliophysics scientists with modeling experience. The EMAC will operate with a very similar structure and will initially leverage CCMC capabilities, but will be designed to facilitate the hosting and integration of exoplanet and planetary atmosphere models. EMAC will begin official operations in early 2017, and will be introduced to the community through a series of virtual workshops.

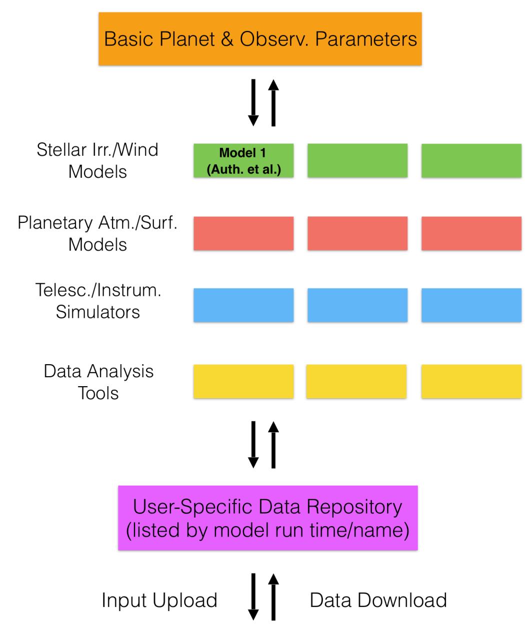

Figure 1: Example of the model integration architecture for EMAC, which will facilitate inter-model integration and comparison.

ISOTOPE GEOCHEMISTRY FOR COMPARATIVE PLANETOLOGY OF EXOPLANETS.

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Introduction: Isotope geochemistry has played a critical role in understanding processes at work in and the history of solar system bodies [see 1, and references therein]. Application of these techniques to exoplanets would be revolutionary and would allow comparative planetology with the formation and evolution of exoplanet systems. The roadmap for comparative planetology of the origins and workings of exoplanets involves isotopic geochemistry efforts in three areas: (1) technology development to expand observations of the isotopic composition of solar system bodies and expand observations to isotopic composition of exoplanet atmospheres; (2) theoretical modeling of how isotopes fractionate and the role they play in evolution of exoplanetary systems, atmospheres, surfaces and interiors; and (3) laboratory studies to constrain isotopic fractionation due to processes at work throughout the solar system.

Example of Nitrogen: Stable isotope ratio measurements combined with modeling of isotopic fractionation has played a critical role in understanding origins and workings throughout the solar system. This work has evaluated the origin of volatiles on Earth [e.g. 2], the history of Mars based on how its atmosphere evolved [e.g. 3, 4], the loss of water from Venus [e.g. 5], and the origin of nitrogen on Titan [6].

In the case of nitrogen, measurements from multiple solar system bodies have allowed us to begin to map out the origin and history of nitrogen in the solar system, as illustrated in Fig. 1 [from 7]. The nitrogen isotope ratio measured in the solar wind and the atmosphere of Jupiter are presumed to be representative of N_2 in the protosolar nebula (PSN) because the most abundant form of nitrogen was N_2. Trace amounts of HCN and NH_3 were present in the PSN, and isotope ratios for these constituents measured in comets are presumed to represent their primordial ratio. On the other hand, nitrogen isotope ratio measurements made in the atmospheres of the terrestrial planets and Titan are known to have evolved from their primordial ratio due to fractionation of the isotopes by escape and photochemistry. Modeling of how the ratio changes over time helps us to understand the origin of nitrogen in these bodies [2,3,4,6], but uncertainties remain. In particular, condensation and evaporation may play an important role in Titan's atmosphere, but little is known about the fractionation of isotopes due to these processes. Furthermore, Fig. 1 emphasizes the limited number of nitrogen isotope measurements. This makes understanding the origin of volatiles in Pluto's atmosphere and on Kuiper Belt Objects (KBOs) in general difficult. Measurements of nitrogen isotopes in Pluto's or Triton's atmosphere combined with modeling of atmospheric evolution could help discern the conditions under which KBOs formed [7].

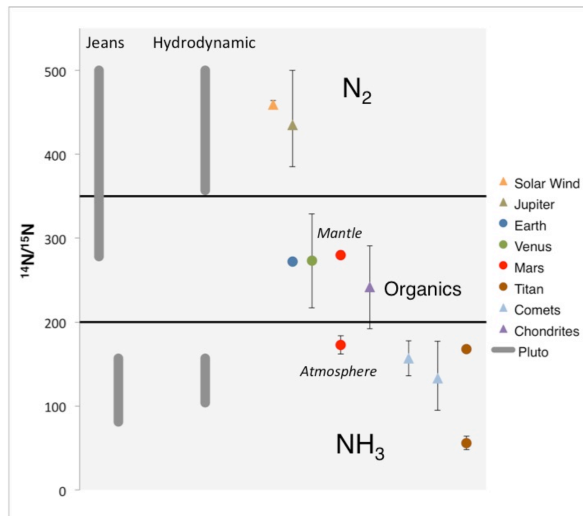

Figure 1: Nitrogen isotope ratio measurements throughout the solar system [7]. Triangles are primordial values representing $^{14}N/^{15}N$ in the protosolar nebula. Circles are isotope ratios that have evolved over the history of the solarsystem. A possible range of values was estimated for Pluto, based on the source of nitrogen and the type of escape.

The Roadmap to Exoplanet Origins and Workings: Based on this example of what we have learned from isotope studies in our solar system, we can identify three areas where further development is needed to allow us to begin evaluating origins and workings in exoplanet systems.

Observations: Observations are the most critical aspect of any exoplanet origins and workings program, but significant technological development is required.

One of the most groundbreaking projects for understanding solar system origins was the Galileo Probe Mass Spectrometer (GPMS) [8]. GPMS not only provided the nitrogen isotope ratio illustrated in Fig. 1, but also the elemental abundances and other isotope ratios in Jupiter's atmosphere. These measurements had significant implications for understanding the formation of Jupiter within the context of solar system formation. The roadmap for understanding the formation of giant planets should first include atmospheric probes sent to Saturn, Uranus and Neptune. These projects are certain to be equally groundbreaking in their impact as was GPMS. However, because sending a probe to a giant exoplanet is not realistic by 2050, it is critical to develop technology to obtain as many of these measurements as possible in the atmospheres of exoplanets through significant advances in remote sensing. These technology advancements should be tested on the giant planets in our solar system through observations that coincide with atmospheric probes that provide ground truth to remote observations. Therefore, part of the long-term roadmap to comparative planetology for the formation of giant planets in our solar system and exoplanets should include a long term program of atmospheric probes in support of a remote sensing development program.

A major limitation of isotopic geochemistry throughout the solar system is the limited number of observations available. Most of the isotope ratios illustrated in Fig. 1 are the result of a single or a statistically small number of measurements in an atmosphere or in the coma of a comet. However, both the Cassini and Rosetta missions have provided ongoing monitoring of isotopic composition of the atmosphere of Titan and of the coma of comet 67P/Churyumov-Gerasimenko (CG), respectively. For Titan, the Huygens Gas Chromatograph Mass Spectrometer (GCMS) [9] provided one-time measurements at the surface, while the Cassini Ion Neutral Mass Spectrometer (INMS) [10] and the Cassini Composite Infrared Spectrometer (CIRS) [11] measured isotopes in the upper and lower atmosphere, respectively over more than a decade. Although this combination of remote sensing and in situ efforts improved understanding of the dynamics of Titan's atmosphere [10], much more can be learned about the workings of Titan's atmosphere from futher evaluations of this extensive dataset. The same can be said for the Rosetta dataset, for which the current analysis is limited to the D/H ratio measured early in the mission [12]. The roadmap for studying terrestrial exoplanet atmospheres should first include future missions within the solar system that involve long-term monitoring using a combination of in situ and remote measurements to evaluate temporal and spatial variations of isotopic composition. This will provide important context to isotopic measurements in terrestrial exoplanet atmospheres, for which technology development must also be a priority.

Finally, future efforts should also include in situ surface isotopic composition of icy moons, comets, Pluto and other Kuiper Belt Objects to understand the differences between atmospheric and surface measurements. These measurements will not only help us to better understand the origins of these bodies, but further understanding the influence of surface processes on fractionation of isotopes will provide critical context for exoplanet isotope measurements.

Theoretical studies: Measurements of isotope ratios in atmospheres have little value for planetary origins without an understanding of how they have evolved over time. Theoretical studies to evaluate origins require models that properly contrain the influence of processes such as escape [e.g. 5, 6], photochemistry [e.g. 13], condensation [e.g. 14] and sublimation on isotope ratios as well as models that put these fractionating processes into the context of evolution over time [3,4,5,6,7,10,11,15,16]. These capabilities must continue to be developed.

Laboratory studies: Finally, laboratory studies provide ground truth for understanding processes at work throughout the solar system. In the short term the processes of condensation, evaporation and sublimation [e.g. 16] would be of high value for understanding the origin and evolution of bodies like Titan and Pluto. However, improving laboratory capabilities is essential and must go beyond the technology currently available today if we hope to apply isotope geochemistry to exoplanets.

Summary: Isotope geochemistry has played a critical role in establishing our current understanding of the origin and evolution of solar system bodies and is essential for expanding research on origins and workings to exoplanet systems. Long term efforts should focus on measurements, modeling, and laboratory studies.

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AN INTEGRATED "SANDWICH" METHOD FOR PLANETARY LANDING SITE AND EXPLORATION ZONE SELECTION.

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Introduction: Identification and selection of potential landing sites for planetary landers is often complicated by a large number of engineering and scientific considerations and constraints. Many important factors, such as scientific regions of interest, are also difficult to quantify due to their subjective nature. For most missions, lengthy discussions are required to down select the best potential landing sites from a large number of sites initially identified by experts familiar with the planetary surface. Small, rapid concept formulation teams or mission designers may be ill equipped to efficiently identify and down select promising landing sites on planetary bodies where knowledge of surface features is poor or incomplete.

We present a quantitative "sandwich" method of additively combining global maps of relevant data to highlight the most favorable regions for landing. This method can also be used to rank predefined landing sites based on any number of engineering or scientific factors. The capability and flexibility of this method make it ideally suited for rapid, first-order trade studies of potential landing sites for both human and robotic missions.

Landing Site Favorability: For candidate landing sites, an intuitive notion of favorability exists based on how well each site ranks with regard to several figures of merit (FOM). Typically these will include the elevation and slope distribution of the site as well as the density of any obstacles, such as large rocks. All else equal, a relatively flat landing site with few obstacles is favorable for most missions. Relevant data such as elevation or terrain roughness can therefore be used to quantitatively score the favorability of potential sites based on how close their figures of merit are to a set of ideal values (eg. flat with no obstacles). Hard constraints such as maximum elevation may also be enforced for each figure to represent the limitations of the landing vehicle. If each FOM M_i is scaled to a unitless range, the favorability score f for a site may be defined though simple summation,

$$f = \sum_i w_i M_i$$

where $w_1 + w_2 + \cdots + w_n = 1$ are weighting factors that reflect the importance of each FOM to determining the overall favorability. The weights must be selected by the designer based on the objectives of the mission and nature of the landing vehicle. In the case where each M_i is defined across the entire surface of a planetary body, the favorability score can be evaluated at each latitude and longitude to create a global favorability map. In effect, the individual maps of each FOM are "sandwiched" together to create the favorability map. Figure 1 illustrates this concept. This concept can be extended beyond just the landing site to include surrounding exploration zones in order to identify locations that provide a high value for exploration.

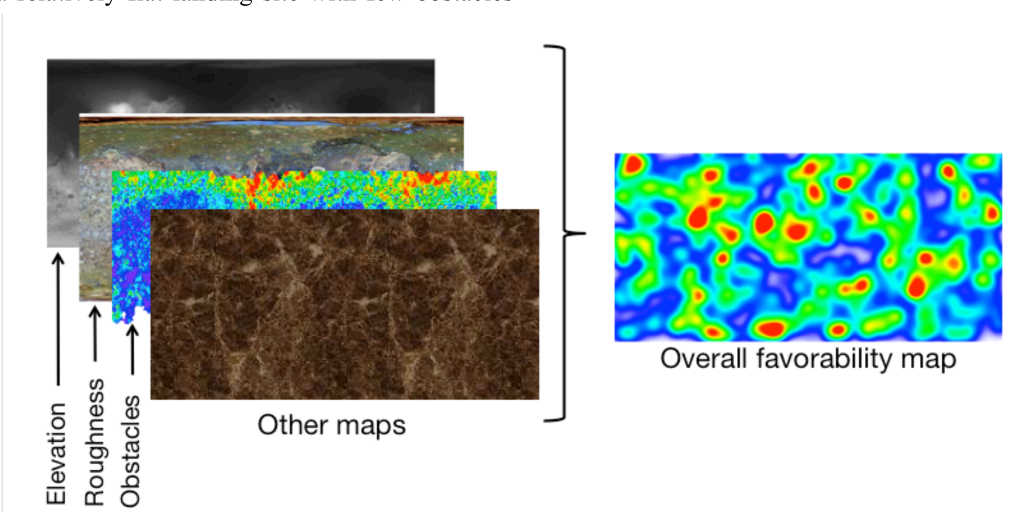

Figure 1. Method of additively combining global maps of relevant data into an overall favorability map for potential landing sites.

NASA Journey to Mars: NASA is currently in the process of down selecting landing sites proposed at the NASA Human Landing Sites Study for a future manned mission to Mars [1]. Our proposed method addresses the general problem of systematically evaluating candidate landing sites based on engineering and scientific factors. Factors identified in the NASA Human Landing Sites Study such as water sources and building materials that greatly impact location selection [2] can be incorporated in a straightforward manner using the sandwich method.

Application to Mars Landing: Many aspects of Mars' surface have been thoroughly mapped from decades of satellite observation. We demonstrate the method of "sandwiching" datasets to create a landing site favorability map for Mars that seeks: minimum elevation, minimum roughness, high thermal inertia, and moderate albedo. Elevation represents an important constraint for high-mass payloads and a constraint of <+2 km MOLA altitude is embedded in the favorability map. A 0.6 km baseline measure of terrain roughness is used [3]. Maps of thermal inertia and albedo from the Mars Global Surveyor Thermal Emission Spectrometer are incorporated [4]. The combination of high thermal inertia and moderate albedo is believed to represent regions of exposed bedrock and relatively little dust, which is desirable when landing a high-mass payload [5].

Figure 2 shows the example favorability map based on the above criteria. Regions violating the elevation constraint are omitted from the map. The weighting factors used were 0.1 (elevation), 0.4 (roughness), 0.25 (thermal inertia), and 0.25 (albedo). The weighting factors were "calibrated" by maximizing the total favor score for 14 heritage and planned landing sites, subject to user-defined bounds reflecting the uncertainly in each weighting factor. Regions of blue highlight the most favorable areas for landing.

A favorability map like Figure 2 could easily incorporate any number of further considerations, such as proximity to in-situ resources, radiation environment, or solar insolation. The method of additively combining global datasets to create an overall favorability map can also be applied to other planetary bodies of scientific interest such as Europa or Enceladus. The favorability map is useful for rapid first order trade studies to down select candidate landing sites or identify new sites.

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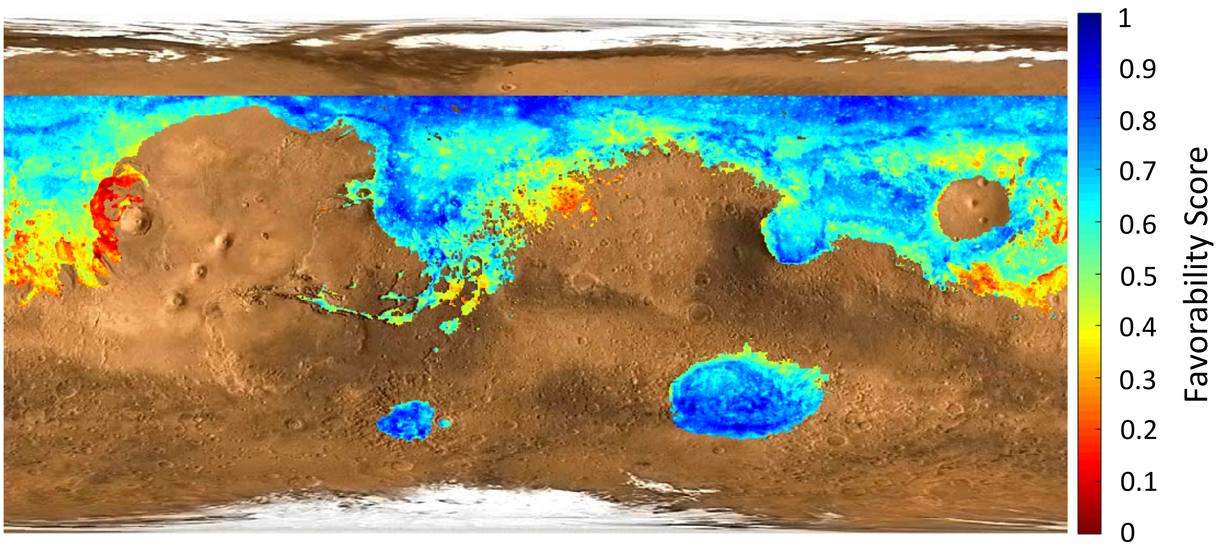

Figure 2. Example favorability map for Mars scoring elevation, roughness, and nature of the surface.

FREE-FLYERS FOR EXPLORATION AND RESOURCE MAPPING FOR ISRU AND PLANETARY SCIENCE.

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Introduction: Two of NASA's highest priority technology objectives for space exploration are to develop a sustainable human presence in space beyond low Earth orbit, and to explore the evolution of the solar system and search for life [1]. Achieving these objectives will require future space systems and vehicles to become more independent of Earth by incorporating intelligent autonomous operations and by taking advantage of local resources. For future space missions to be self-sufficient, significant technological advances must be made in finding, extracting, and processing in-situ resources in extreme environments.

Planetary surface resources are usually identified and mapped using orbiting spacecraft from an altitude of approximately 100 kilometers. Onboard gamma-ray and neutron sensors detect gamma-rays and neutrons that are emitted when incident background cosmic radiation particles interact with planetary soil. Orbiting spacecraft, such as the 1998 Lunar Prospector or the 2001 Mars Odyssey, have used such instruments to produce global maps of the elemental composition of a planetary surface. However, the signal strength that is detectable from orbit can only provide resource mapping with a spatial resolution of 150 kilometers using the best current technology.

Significant improvements in our scientific understanding of planetary formation and evolution would be enabled by higher spatial resolution mapping of the elemental composition of planetary surfaces. Rather than relying on the sporadic presence of background cosmic radiation to interact with surface materials to generate gamma-rays and neutrons, this paper envisions positioning a compact, stable, high-flux neutron source 2 to 3 meters above a planetary surface which will provide a strong source of radiation that greatly enhances the detection sensitivity. By combining a high-flux neutron source with a distributed array of gamma-ray and neutron detectors, an above-surface "free-flyer" prospecting platform, or even a rover, could be used to detect gamma-ray and neutron emission signals with a spatial resolution as high as 0.1 m. The Mars Science Laboratory's Curiosity rover has already demonstrated use of an onboard neutron source and detector system, but the MSL rover travels at a very slow speed and is not a dedicated to resource prospector. Free-flyers, on the other hand, are faster than rovers, and can potentially cover more surface area than a rover.

In addition, by utilizing a steady state neutron production rate of 10^8 neutrons per second, the neutron flux reaching the surface can be increased by a factor of ten-thousand times over the neutron flux generated by cosmic rays. This will allow greatly improved statistics so that a free-flyer moving at one meter per second over the surface will be able to collect data more quickly, and over a much larger area, than is possible using a rover, and with several orders of magnitude improvement in resolution over comparable detectors used on orbiters. This technology is applicable to the Moon, Mars, asteroids, and the moons of the large gas planets in the solar system and provide a means to fill knowledge gaps about potential valuable resources. Free-flyers will enable the detection of icy volatiles, metals, and other elements within a few meters of the surface.

This paper focusses on using a type of free-flyer called FERMI (Free-flyers for Exploration and Resource Mapping for ISRU) as a means to facilitate resource prospecting as quickly as possible and with high spatial resolution. This class of free-flyer is intermediate between the small (sub-kilogram) aerial scouts envisioned for Mars or other destinations with an atmosphere, and the large (multi-ton) lander/ascent vehicles. The FERMI class of free-flyer must be able to carry a payload of 10 kilograms or more, which in this case includes a compact neutron source and multiple gamma-ray and neutron detectors to prospect for resources This new capability will enable the reliable targeting of resources for excavation and chemical analysis, and the selection of landing sites that have the greatest value for scientific studies and for sustainablility.

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THE POSITION OF ARTIFICIAL INTELLIGENCE IN ROBOTIC SPACE MISSIONS IN THE INNER AND OUTER SOLAR SYSTEM IN 2050. A. A.Mardon[1] and C. A. Mardon[2], [1]Antarctic Institute of Canada, aamardon@yahoo.ca, [2]Antarctic Institute of Canada.

Introduction: Machine intelligence is advancing to a paradigm shift point where extra planetary space craft that are robotic will, well before 2050, have artificial intelligence. They could be stationed at various points in the inner and outer solar system in a similar manner to how we presently have automated weather stations. We could set up a data collection system from various points around the solar system. Threats such as near Earth objects impacting the planet could be monitored directly on the body and through automated telescopes in orbit. One lesson that the rovers on Mars have shown us is that longevity of a mission can reduce tangible unpredictable results. With rovers on other planets and bodies, real time observations could be monitored by the anticipated artificial intelligence that is currently in research and development. Communication using meteor burst communication techniques might allow slow but accurate data downloads from various remote locations on other planets. Science fiction has long anticipated artificial intelligence being humanity's first permanent representation off of Earth. Robitic tunneling devices might also construct subsurface human use facilities in an orderly fashion well before manned missions arrive at those celestial points.

Conclusion: With the lag time of communication with Earth, true artificial intelligence in outer space robots would increase efficiencies. If this is tied in with long duration of missions, data collection might occur for much longer periods of time than we currently see.

WHEN WORLDS COLLIDE: WITNESSING PLANETARY-SCALE IMPACTS IN THE COMING DECADES. J. R. Masiero[1], J. M. Bauer[1], T. Grav[2], and A. K. Mainzer[1]. [1]NASA Jet Propulsion Laboratory, California Institute of Technology (*joseph.masiero@jpl.nasa.gov*), [2]Planetary Science Institute.

The history of the inner Solar System is a record of cataclysmic impacts that restructured the population of bodies there in myriad ways. Collisions in the early Solar System fed the growth of the terrestrial planets, resulting in the formation of the Earth-Moon system [9]. Later pulses of impacting material formed giant craters on the Moon and implanted organics and volatile on the Earth [8]. Impacts between asteroids over the last few billion years have resulted in massive craters or compete disruption of the target body, as seen on Vesta by the *Dawn* spacecraft [13] and in the Main Belt as over 100 identified asteroid families [10]. Recently, we have witnessed apparently-asteroidal objects in the Main Belt become suddenly active as they undergo disruptive events (e.g. 2010 A2 [1]).

Disruptive impact events like this occur on a scale that cannot be simulated in any laboratory. Impact velocities are tens of kilometers per second, and released energies are far in excess of any that humankind has produced (e.g. the small Chelyabinsk 18-meter impactor released as much energy as a moderately-sized nuclear weapon [12]). Numerical simulations have allowed us to model these events, and comparisons can be drawn to the observed end-states such as family size distributions or shocks recorded in minerals [3], but there is little data probing the impact process itself. Understanding the effects of these impacts is a critical component to our models of the formation of planetary systems (both ours and those around other stars), the current interior of small asteroids, the composition of the zodiacal dust cloud, and the evolution of life of Earth.

Present-day asteroid surveys are witnessing impact-induced activity once every few years [2]. In the coming decade, new surveys such as LSST [4] and the proposed NEOCam space telescope [5] will increase our catalog of known Main Belt objects by an order of magnitude, up to ~10 million objects. This will increase the rate at which impact events are discovered, but also will provide us the tools needed to *predict* a catastrophic impact before it happens. As with potential Earth-impacting asteroids that are currently being tracked by NASA's Planetary Defense Coordination Office (e.g. *http://neo.jpl.nasa.gov*), surveys will produce probabilities for impacts between Main Belt asteroids that will require organized followup efforts to confirm. However, the low chances of impact between two asteroids will be partially offset by the large number of potential impact targets being tracked. Impact probability is also enhanced by the existence of families formed by previous impacts: these objects have similar orbital elements, and thus will have a higher likelihood of impacting each other than would be expected from a randomly distributed population of objects.

Based on estimates of the formation rate of craters larger than 1 km on Vesta [11] (that is, formed by impactors D>100 m) and observed size distribution of MBAs [6], we estimate that a collision between two objects recorded in the catalogs that will soon be available from next-gen surveys has an occurrence rate of ~0.005 per year, even before accounting for amplification due to collisions among family members on similar orbits. Thus there is a non-negligible chance that a predictable collision will occur within the 2050 timeframe. Any future surveys to fainter brightness limits will only increase this probability.

With a few years of advance notice of a collision within the Main Belt, coordinated observing campaigns could be organized to characterize the bodies before, during, and after the collision (similar to the characterization effort during the Deep Impact mission [7]). However, the ideal case would be one where an impact could be predicted with one or two decades of advance notice. Is this case, reconnaissance spacecraft could be sent to study the impact *in situ*, similar to the flyby campaign of 1P/Halley, with staggered arrival times to ensure all phases of the impact event are observed.

Certain determination of an impact between two asteroids requires a knowledge of their orbits significantly more accurate than what is available today for the majority of objects. However, near-future surveys promise a rapid growth in the data sets used to determine orbits, while near-future telescopes like JWST and TMT will be able to provide accurate astrometric measurements with precision far surpassing the current generation of telescopes. Likewise, reconnaissance spacecraft would need a standard set of instruments common to *in situ* exploration today (e.g. imager, VNIR spectrograph, dust flux counter, etc.). Thus, there are no significant technological or conceptual hurdles that would impede an investigation of this type in the 2050 time frame. Continued survey (as part of ongoing Planetary Defense activity) and regular orbital monitoring will be sufficient to enable this opportunity to study the largest impacts in the Solar System.

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TECHNOLOGIES FOR MISSIONS TO OCEAN WORLDS. L H. Matthies, M. M. Abid, P. G. Backes, L. Del Castillo, B. H.Wilcox, M. A. Jones, P. M. Beauchamp, J. A. Cutts, Jet Propulsion Laboratory, California Institute of Technology, MS 321-550, 4800 Oak Grove Drive, Pasadena, CA 91109, Larry.H.Matthies@jpl.nasa.gov,

The FY16 Budget Proposal from the Appropriations Committee directed NASA to create an Ocean World Exploration Program whose primary goal is to discover extant life on another world using a mix of Discovery, New Frontiers, and Flagship class missions consistent with the recommendations of current and future Planetary Decadal surveys [1]. The prime targets of such a program are the outer planet moons Europa, Titan, and Enceladus. As part of a broad initiative to increase technology development activities in support of planetary exploration, NASA has established technology goals for these Ocean Worlds Exploration targets.

Since missions to the outer planets invariably take decades to come to fruition, these technologies will be needed for missions well beyond 2050. This paper describes the Technology Roadmaps developed for five of these Ocean Worlds Technologies. Four of these deal with the development of key capabilities for future Ocean Worlds missions: pin-point landing on Titan, subsurface ice acquisition and handling below 0.2 m on all targets, ice sample return with cryogenic preservation, and planetary protection, also for all targets. The remaining technologies deal with survival and operation of both electronic and mechanical systems in the environments of Ocean Worlds.

The focus of roadmapping effort has been on three time frames: Near Term, Mid Term, and Far Term, which broadly considered embrace the time for Planetary Science Visions 2050. Not included in this assessment are the technologies which are being employed in the Europa Mission that is currently under development, involving a Jupiter orbiter which makes repeated flybys of the moon, or the Europa Lander mission which is currently in a study phase.

Pin-Point Landing on Titan: For entry, descent, and landing (EDL) designs like the Huygens Probe, which had a relatively steep (-65°) entry flight path angle and a long (2.5 hour) parachute descent that started at 155 km altitude [2], landing dispersions are dominated by the effects of high velocity zonal (east-west) winds at high altitudes during the parachute phase [3]. Previous studies predict 3σ landing error ellipses with major axes of 300x70 km or more, depending on season, latitude, and delivery error at the entry interface [3]. This can fit in large seas at high northern latitudes; however, several other classes of landing site require more precise lander delivery. This includes landing in the more chemically diverse lakes at high southern latitudes, near shorelines, in dry lakebeds, on the flanks of dunes, and in river valleys or deltas. Such sites would significantly broaden our understanding of Titan's organic chemistry, geologic and climate history, and potential for prebiotic processes.

We distinguish three classes of landing sites, with different technology advances required to reach them:

1. Land anywhere in ellipses considerably smaller than those possible today, e.g. in a southern hemisphere lake. This may require EDL systems with large control authority, but relatively modest final targeting accuracy.
2. Land on or near a class of feature that is widely distributed throughout an ellipse, such as near a shoreline or on the lower flank of a dune. This may require smaller control authority, but much more accurate final targeting accuracy.
3. Land accurately near a single point target, which requires large control authority and accurate final targeting.

Technical approaches to enabling such landing sites include reducing the effect of wind through faster descent to low altitude and introducing control authority, like steerable parachutes/parafoils, other types of aerodynamic control surfaces, entry guidance, and/or propulsion. Terrain relative navigation will be needed in many cases and requires advances well beyond the capabilities developed for Mars and airless bodies.

Sub-Surface (> 0.2m) Ice Acquisition and Handling: Penetration and sampling of pristine ice at depth on Ocean Worlds is high-priority because discovery of macromolecules indicating that extant life that has evolved separately from life on Earth would be one of the greatest scientific discoveries of all time. Such macromolecules can be looked-for in water that periodically erupts onto the surface and freezes, or in convecting ice that periodically interacts with the liquid water ocean, or in the liquid water itself. Intermediate depths may also be of interest on some bodies, e.g. examining organic deposits on Titan. Also, Enceladus plume vents may be explored, including possibly down to liquid water, without actual penetration of the ice.

We can divide the ice penetration, sampling and handling also into three broad classes: shallow depths of 0.2 to 2 meters, intermediate depths of 2 to several 10s of meters, and deep – from several 10s of meters all the way to the liquid water ocean interface. Shallow sampling can be accomplished by many methods, e.g. circular or chain saws, heated blades that sublimate solid ice or simply penetrate porous ice. Intermediate depths can be reached with conventional drills that use a segmented liner to keep the hole from collapsing, or, use a wireline drill that does not line the hole (used in competent material where the risk of hole collapse is low) and therefore does not have a total system mass that grows linearly with depth. Deep penetration, within the limits of mass, power, and volume of plausible near-term missions is very challenging. It may be that some novel method of melting the ice that does not involve losing heat by conduction laterally through the bulk of ice will prove feasible. Using conventional approaches, deep drilling is often thought to be an "Apollo-scale" endeavor. Whichever technique will be employed, the power sources used will have to be compatible with the environment of the specific Ocean World.

Ice Sample Return: Return of samples from Enceladus or Europa would require new technologies to keep the samples in their pristine cryogenic state and to enable transfer and preservation of the samples while meeting back planetary protection requirements. Three classes of missions were considered to identify technology development needs:

1. Europa lander sample return mission which maintains the sample between 100K - 150K during return to Earth.
2. Enceladus plume, Enceladus lander, and Europa lander sample return missions which maintain the sample between 65K - 100K during return to Earth.
3. Enceladus plume, Enceladus lander, and Europa lander sample return missions which maintain the sample below 65K during return to Earth.

To enable the three classes of missions, two technologies would need to be developed, with each technology having three phases of development to support missions with the different return sample temperature ranges. An Integrated Cryogenic Chamber (ICC) would maintain the sample at cryogenic conditions during return to Earth and until retrieved on Earth's surface. Cryogenic back planetary protection (BPP) would provide a break-the-chain process where the sample is transferred into an Earth-clean Earth Entry Vehicle while maintaining the sample in its pristine cryogenic condition.

Additionally, a Comet Nucleus Sample Return mission would be enabled by the 100K – 150K Integrated Cryogenic Chamber technology, but a CNSR mission would not require the cryogenic back planetary protection technology required for the Ocean Worlds.

Planetary Protection: There are a number of multimission planetary protection technologies that need development for application to future ocean worlds exploration. The set of planetary protection requirements a mission would need to meet for Ocean World exploration are different given the target body, the planned science investigations, and often the method of spacecraft exploration (e.g., orbiter versus lander). Meeting the requirements for these missions has become increasingly challenging given the science objectives proposed for these types of missions, such as life detection and sample return.

Methods are needed to better clean organics from hardware as well as methods to validate cleanliness of that hardware at the sensitivity needed for these types of missions. Definition of models and tools, using a systems engineering approach, for establishing a quantitative assessment of sample contamination risk by transport pathways is also required. Alternative methods for sterilization of hardware, such as gamma radiation or plasmas, need to be validated and approved to deal with heat and vapor hydrogen peroxide sensitive hardware. Lastly, technologies for sample return functions to prevent backward contamination are required for future sample return missions. Containment assurance also requires methods to break-the-chain of contact with the sampled body. Any native contamination on the returned sample container and/or Earth return vehicle must be either fully contained or removed prior to return to Earth, therefore, technologies to mitigate this contamination are needed.

Component Technologies: Located in the outer solar system where the flux of the Sun is between 1% and 4% of that falling on the Earth, Ocean Worlds are extremely cold, ranging from an estimated 35K at the poles of Enceladus to no higher than 115K at the equator on Europa. Cloaked in a dense atmosphere, temperatures on Titan are around 95k. In addition, Europa is bathed in the intense radiation environment of the planet Jupiter.

The component technology assessment is developing roadmaps for low temperature-compatible, low power, rad-hard electronics and low temperature-compatible actuators/mechanisms, including lubricants, bearings. and actuators. These are vital for instruments and end-effectors outside a warm box.

Summary: Achieving the long range goals of the Ocean Worlds Exploration Program will require a comprehensive technology development effort. A key part of this effort involves coping with the extreme environment at these fascinating targets.

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HIGH-RESOLUTION LIDAR SPECTROSCOPY FOR SOLAR SYSTEM EXPLORATION.
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Introduction: Lidar technology has provided important support for the development of modern planetary science datasets over the past two decades. Laser altimeter instruments built at NASA GSFC have provided topographic information with unique geodetic accuracy at Mars, the Moon, and Mercury. Recent developments in both laser and detector technology are now opening the door for a new class of lidar instruments, that can use any laser wavelength to illuminate planetary surfaces and characterize the reflected light with detector arrays of single-photon accuracy. Narrow wavelength bands carefully selected for each target or investigation can provide high-quality, unbiased spectroscopic information to identify, map, and monitor important species, from crustal minerals to time-variable surface volatiles. Such lidar spectrometers can play a critical role in planetary science over the next few decades, as they allow both rapid reconnaissance and detailed monitoring with efficient, versatile approaches. We propose a new class of observations with lasers for a combined geophysical, geological, and geochemical study of planets, natural satellites, and small bodies. Here, we describe major science applications that would bring enormous value to NASA's Planetary Science Vision 2050.

Capabilities: Lidar spectrometers will retain all the capabilities that made instruments such as MOLA, LOLA, and MLA successful [1-3], namely precise altimetric ranges, sub-footprint roughness, and geodetic accuracy. A drawback of current altimeters is the coarse sampling of planetary surfaces (only a very small amount of the surface being actually illuminated), due to a small number of beams and a low firing frequency. Instead of narrowing the beam divergence further, the footprint size can be reduced as much as affordable by the receiver optics (telescope size) and micro-lens elements can ensure the detector fields of view are full and contiguous. With enough detectors and a firing frequency selected based on the orbital speed, complete sensing of the surface below the groundtrack is possible with each pass (Fig. 1). This will enable complete high-resolution mapping (meter scale) and rapid-cadence monitoring (monthly scale) of planetary surfaces. Different detectors can be dedicated to different laser wavelengths to yield combined altimetric and spectroscopic measurements (Fig. 2).

Lidar instruments provide the illumination required for making their measurements. This allows operation regardless of illumination conditions, both day and night (including permanent shadow), and critically always at zero phase angle. This geometry direct-

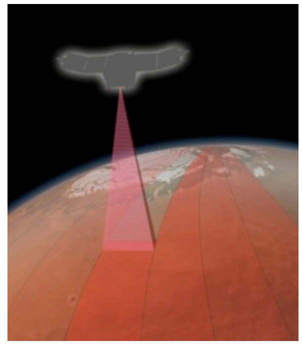

Figure 1. *Arrays of NIR photon-sensitive detectors will allow contiguous-pixel 'swaths' at high resolution. In addition to high-resolution global mapping, this transformative technology would enable rapid-cadence monitoring of small-scale processes.*

ly provides the surface normal albedo, circumventing the need for difficult photometric calibration, which could yield residual errors that may be confused with actual variations. This is of course especially valuable when using reflectance data for unambiguous spectral identification. Photon-counting HgCdTe detectors over the 0.5-5 µm range are already being matured [4], allowing near-theoretical sensitivities. Large arrays of such detectors are on the technological horizon and should be achievable well ahead of 2050. Such instruments, akin to current passive spectrometers but with active remote sensing and 3D ranging capability, will find many applications in future planetary missions.

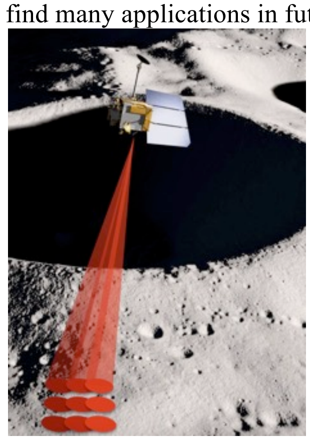

Figure 2. *Active reflectance measurements at multiple wavelengths in water absoportion bands (1.5 and 3 µm) would yield excellent sentivity to surface water. Lidar spectroscopy can uniquely contribute to lunar science, by providing high-quality spectral data under any illumination condition.*

Applications: Like lidar instruments today, lidar spectrometers will constitute desirable payload options over the full breadth of future mission concepts. We present here several scenarios that illustrate the variety of applications.

Mars: Onboard the many future Mars orbiters monitoring the Mars system, lidar spectrometers would map the polar regions at high resolution (meter scale horizontally; a few centimeters vertically) over swaths several kilometers in width. Complete coverage could be obtained over sub-seasonal time scales (around a month), allowing for subtle signals to be measured and monitored, systematically. Well-chosen spectral bands would allow CO_2 and H_2O ices to be mapped on the surface. Using vertical profiles of backscattered laser light, the 3D distribution of dust aerosols and the temporal formation and evolution of CO_2 and H_2O clouds in the atmosphere could be determined with high vertical resolution (<150 m). The availability of data over the nightside and during polar night is key to build a complete understanding of the physical and geological processes.

Moon: A lidar spectrometer could map with excellent sensitivity (<100 ppm) the distribution of H_2O/OH on the lunar surface (Fig. 1). Three bands at 1.1, 1.5 and 3 μm bands would maximize water detection and discriminate multiple phases of water [5]. High spatial resolution and dense temporal sampling would help understand the dependence of water on lunar temperature at scales relevant for future human and robotic exploration. The mobility of volatiles on the Moon, inside and outside of permanently shadowed regions, would be definitely established.

Mercury: A similar spectrometer would map the radar-bright deposits [6] that were determined to primarily consist of water ice after the MESSENGER mission [7-9]. Additional bands in the C-H stretch fundamental around 3.4 μm would enable unambiguous detection and characterization of organics, and further constrain our understanding of the formation of Mercury's volatile reservoirs. With a spacecraft carrying a sensitive gravity gradiometer, the lidar spectrometer would also provide ranging data to help the navigation at low altitudes to greatly improve the knowledge of the gravity field and thereby the knowledge of Mercury's crust and interior.

Titan: The operation at Titan of a laser altimeter similar to LOLA for instance, at 1064 nm, would not be useful because of the strong absorption of its atmosphere at that wavelength. The use of longer wavelengths in atmospheric windows is a natural capability of a lidar spectrometer, and enables global topographic mapping at high resolution (<150 m, in part limited by scattering). Such a resolution, difficult to obtain with a radar instrument, would significantly advance the fidelity and impact of studies of Titan's unique methane cycle, where lakes and rivers play an important role in our understanding of its potential habitability.

With this active remote sensing, the mapping of the whole surface is possible even with short mission durations, despite the long orbital period of Saturn. Over long missions, the complete seasonal cycle could be uniquely characterized. The relatively small data volume of lidar data compared to that required for radar or imagery to achieve similar-quality topography is another important advantage.

Small-body flyby: With limited time to acquire science data, a lidar spectrometer would be advantageous for its wide-swath topographic mapping and its active reflectance measurements. It would be immune to seasonal shadows and thus provide global mapping for reasonably fast rotators. Geodetic landmarks may also be used to improve spacecraft orbit and asteroid mass determination.

Small-body sample return: In addition to providing accurate shape information and spectral data to identify key volatiles or minerals of interest, a lidar spectrometer could act as a reliable rangefinder during close encounter and sampling. Its long-range range capability naturally makes it a prime choice for such critical task, allowing safe autonomous operations from parking orbit down to the surface.

Europa and Enceladus: The measurement of the radiation backscattered by the ice particles forming the plues observed at icy moons [10-11] would allow 3D mapping of their distribution and variability. Several wavelengths could be used to infer composition and constrain grain size.

Summary: The evolution of laser altimeter into versatile lidar spectrometer has become a recent goal of lidar specialists. Very capable instruments that can precisely and simultaneously measure shape, roughness, atmospheric backscatter, and surface reflectance at multiple wavelengths will become a reality in the near-term (Table 1) and will enable ambitious planetary science objectives. With time, they will become even more capable (e.g., thousands of detectors) and contribute to varied mission concepts over the whole Solar System.

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Table 1. Summary of the wide-ranging measurement capabilities of lidar spectrometers, with notional performance attainable with current technology.

Measurement	Capability	Comment
Topography	1-10 cm	at 100-km range
Roughness	<10 cm	at 1 m scale
Slope	<0.1°	at 10 m baseline
Reflectance	<1%	at 0° phase
Backscattered vertical profile	atmosphere and plume 3D maps	<150m vertical resolution
Wavelength	0.5 – 5 μm	selected for target
Other	navigation support, passive radiometry	

CHARACTERIZATION OF WATER IN SURFACE AND NEAR-SURFACE MATERIALS FOR STUDIES OF PLANETARY HISTORY AND RESOURCE PROSPECTING. A. C. McAdam[1], D. P. Glavin[1], J. E. Bleacher[1], Z. Arzoumanian[1,2], K. E. Young[3], K. Gendreau[1], I. L. ten Kate[5], C. A. Malespin[1,2], H. B. Franz[1,4], and P. R. Mahaffy[1]. [1]NASA Goddard Space Flight Center, Greenbelt, MD 20771, Amy.McAdam@nasa.gov, [2]GESTAR, Universities Space Research Association, Columbia, MD, [3]Jacobs, Houston, TX 77258, [4]CRESST, Univ. of Maryland, Baltimore, MD 21228, [5]Utrecht University Budapestlaan 4, 3584 CD Utrecht, The Netherlands.

Introduction: Understanding inventories of surface and near-surface volatiles, especially water as ice or structural water in minerals, will be of clear importance for human exploration endeavors and provides important information about the formation and evolution of bodies throughout the solar system.

To date, remote observations, *in situ* analyses and sample return have provided various levels of detail on the nature of water inventories in the near-surface materials on solar system bodies, including the Moon, Mars, asteroids, comets, dwarf planets, and satellites of the outer solar system. In many cases, the most thorough characterization of the nature or abundance of the water or water-bearing phases as inferred from a number of carefully selected returned samples could be performed using the vast analytical capabilities available in terrestrial laboratories which are relatively unconstrained by analysis time, power, mass, volume or other operational requirements. However, to be able to best extrapolate the knowledge gained from specific samples to larger regions of the planetary surfaces, and to select the most scientifically valuable samples in the first place, optimization of *in situ* analyses that enable a large number of operationally constrained, perhaps lower-fidelity, measurements, is needed.

In addition, for many solar system bodies sample return implementations that are expected to maintain the original state of the collected surface materials with respect to their water-bearing phases are not yet fully developed, though the development of these strategies is farther along for some solar system bodies (e.g., Mars) than others. Robust development of this capability, especially for particularly challenging materials such as samples from icy satellites of the outer solar system, would be an important goal over the next few decades. Optimization of approaches that can best characterize water-bearing phases *in situ* will mitigate risks of decreased science return due to post-collection changes in returned samples by establishing the original properties of the samples. These detailed *in situ* analyses and follow-up sample return tasks would likely be first undertaken by robotic missions, and later by crewed missions. A longer term goal, possibly achievable by the 2050s, would be to develop the procedures and technologies to characterize important volatile-bearing surface materials in crewed laboratories directly on the surface of planetary bodies to levels of detail that rival terrestrial laboratories.

Approaches and Technologies: To fully characterize the nature and distribution of water-bearing phases in planetary materials in situ, a variety of approaches and technologies are needed. First, landing areas with the potential for water-bearing phases in the near-surface need to be targeted based on orbital or remote observations. Then, these areas need to be further investigated for indications of hydrated minerals or water ice using techniques that provide reconnaissance over several meters (including to at least several meters depth), such as neutron scattering instruments [1] and thermal [2] or visible/near-IR (e.g., [3]) spectroscopy. Selected areas of interest can then be scouted on sub-meter scales with spot analyzers that can relatively quickly characterize the mineralogy or chemistry of materials in their natural state without sample processing. Examples of these types of technologies include APXS [4] or x-ray fluorescence (XRF), contact x-ray diffraction (XRD) [5], and Raman spectroscopy [6]. An advantage of these techniques is that they are often less mission resource (e.g., time, power, mass) intensive than techniques requiring sample processing. They can also study samples without disturbing the spatial relationships between sample components or disrupting any volatiles present in samples. In addition, they can be used to select the most promising samples for further analyses that are more resource intensive. Finally, samples selected based on the spot analyses can be subjected to techniques that require sample processing. These techniques may be very resource intensive but may provide the highest level of detail on the hydrated minerals or water present in specific carefully chosen samples.

Several of these technologies are being developed for, or have been used by, previous, current or near-term robotic missions, but in many cases there would be significant benefit to continuing refinement or miniaturization to best characterize water-bearing materials on future missions to Mars or other planetary bodies. In addition, because these missions will include both robotic and crewed missions, strategies need to be developed for the use of these technologies as part of robotic missions and by astronauts [e.g., 7].

Examples of enabling technologies under current development: Powder XRD has been successfully carried out on Mars with the Chemistry and Mineralogy (CheMin) instrument on the Mars Science Laboratory (MSL) rover. This approach has yielded more detail on hydrated and/or hydroxylated minerals in martian samples than previously obtained *in situ*, highlighting the strength of XRD for *in situ* studies of volatile-bearing minerals. It does, however, require processing the sample to a powder, which can be mission resource intensive and possibly disruptive to volatiles within samples. Contact XRD is a relatively new area of technology development for planetary instruments (e.g., the Chromatic Mineral Identification and Surface Texture (CMIST) instrument concept [5]). Contact XRD can be used to analyze samples in place without processing them to a powder, resulting in the ability to study phases in their original spatial context and enabling analysis of even very volatile phases such as ices. It is also less resource intensive (analysis time, power, size, etc.) than a powder XRD technique. In addition where robotic or manned mission strategies allow, this contact XRD technology can be used to triage samples for follow-on analysis by powder XRD. *In situ* evolved gas analysis mass spectrometry (EGA-MS), in which samples are heated and any evolved volatiles are detected by a mass spectrometer, has been successfully demonstrated by the Sample Analysis at Mars (SAM) instrument on MSL, which has detected a large variety of volatiles evolved from martian samples including ~1-2 wt% water resulting from adsorbed water and structural H_2O/OH in sample phases [e.g., 8, 9, 10]. *In situ* thermal analysis techniques like EGA-MS necessitate the preparation of a sample powder through scooping, crushing or drilling, as well as pyrolysis ovens coupled to a gas manifold and mass spectrometer. SAM is mission resource intensive, in terms of power, mass, volume and analysis time, but simplified and miniaturized EGA-MS approaches based on SAM are being developed for deployment on the Moon or other planetary bodies (e.g., the Volatile Analysis by Pyrolysis of Regolith (VAPoR) instrument [11, 12]). Instruments like VAPoR would reduce mission resource needs and operations complexity for future use of thermal analysis techniques on robotic missions or by astronauts on crewed missions.

Key in enhancing science return from several of these approaches would be the development of increasingly capable sample acquisition and processing techniques to enable sampling with minimal loss or changes to volatile components and which can robustly sample deeper into the subsurface (e.g., several meters) where volatile-bearing phases may be more abundant.

The further development of sampling and analysis technologies for a variety of mission concepts and planetary environments, building on past and present achievements, is a necessary step to comprehensive characterization of water-bearing materials crucial to studies of planetary formation, evolution or potential habitability.

Knowledge of the nature, abundances, and distributions of water-bearing materials on planetary surfaces and how readily the water is thermally extracted from them would also have important implications for finding and extracting water for use by astronauts.

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PRIORITY SCIENCE TARGETS FOR FUTURE SAMPLE RETURN MISSIONS WITHIN THE SOLAR SYSTEM OUT TO THE YEAR 2050. F. M. McCubbin[1], J. H. Allton[1], J. J. Barnes[1], J. W. Boyce[1], A.S. Burton[1], D. S. Draper[1], C. A. Evans[1], M. D. Fries[1], J. H. Jones[1], L. P. Keller[1], S. J. Lawrence[1], S. R. Messenger[1], D. W. Ming[1], R. V. Morris[1], K. Nakamura-Messenger[1], P. B. Niles[1], K. Righter[1], J. I. Simon[1], C. J. Snead[2] A. Steele[3], A. H. Treiman[4], K. E. Vander Kaaden[1,3], R. A. Zeigler[1], M. Zolensky[1], and E. K. Stansbery[1], [1]NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058. [2]Texas State University, Ingram School of Engineering, 601 University drive San Marcos, TX 78666. [3]Geophysical Laboratory Carnegie Institution of Washington 5251 Broad Branch Rd. NW Washington DC 20015 [4]Lunar and Planetary Institute, 3600 Bay Area Blvd, Houston, TX 77058 francis.m.mccubbin@nasa.gov.

Introduction: The Astromaterials Acquisition and Curation Office (henceforth referred to herein as NASA Curation Office) at NASA Johnson Space Center (JSC) is responsible for curating all of NASA's extraterrestrial samples. JSC presently curates 9 different astromaterials collections: (1) Apollo samples, (2) LUNA samples, (3) Antarctic meteorites, (4) Cosmic dust particles, (5) Microparticle Impact Collection [formerly called Space Exposed Hardware], (6) Genesis solar wind, (7) Stardust comet Wild-2 particles, (8) Stardust interstellar particles, and (9) Hayabusa asteroid Itokawa particles. In addition, the next missions bringing carbonaceous asteroid samples to JSC are Hayabusa 2/ asteroid Ryugu and OSIRIS-Rex/ asteroid Bennu, in 2021 and 2023, respectively. The Hayabusa 2 samples are provided as part of an international agreement with JAXA.

The NASA Curation Office plans for the requirements of future collections in an "Advanced Curation" program. Advanced Curation is tasked with developing procedures, technology, and data sets necessary for curating new types of collections as envisioned by NASA exploration goals. Here we review the science value and sample curation needs of some potential targets for sample return missions over the next 35 years.

Mercury: Results from the MESSENGER spacecraft have shown that Mercury is an endmember among the terrestrial planets in terms of structure, chemical makeup, and density, among other physical and chemical characteristics [3]. So far there are no known samples of Mercury among the meteorite collection. Sample return from Mercury would not only provide ground truth to MESSENGER results, but it would provide new insight into the chemical and physical makeup of the most reduced terrestrial planet in the solar system. Additionally, sample return from Mercury would provide further constraints on models of the formation of the terrestrial planets in terms of proximity to the Sun, size, composition, and oxygen fugacity.

Venus: Our knowledge of the surface chemistry of Venus is limited to the observations from the Venera landers [4]. As a companion planet to Earth and Mars (and the most Earth-like of the terrestrial planets) in the habitable zone of the solar system, an understanding of how Venus evolved geologically will provide insight into the evolution of the solar system.

Samples of the Venusian atmosphere would enable us to better address the nature and evolution of the atmospheric greenhouse. The lower atmosphere is a key link between surface and interior processes and characterizing the composition is necessary to constrain the chemistry occurring between the surface and atmosphere, as well as address questions on the volcanic history of the planet. Collection and storage of planetary gas samples would pose unique challenges that will require additional technological development.

Moon: NASA's current in situ sampling of the Moon is limited to the nearside samples dominated by materials from the Procellarum KREEP Terrane, a unique geochemical province not representative of the Moon in total. The top targets for lunar sample return to address larger solar system science questions are sieved regolith samples from the ancient South Pole Aitken Basin (SPA) and from the young lunar basalt flows near Aristarchus Crater (AC). These samples would (1) dramatically constrain the crater counting curve and test the possibility of the late heavy bombardment (important for all solid bodies in the solar system), (2) provide insight into the composition and extended evolution of the lunar interior (SPA lower crustal material, SPA cryptomare, AC pyroclastics, AC basalts), and (3) inform about tertiary crustal formation on the Moon and other single-plate bodies (evolved lithologies in AC ejecta).

Mars: Mars sample return (MSR) is the highest priority of the 2013-2022 planetary science decadal survey. Key objectives for MSR are to answer the questions of whether life existed in the past or exists today, were environmental conditions ever habitable, what is the history of water, what is the history of surface modifying processes (e.g., impact, volcanic, aeolian), why did the climate change, and how did the planet evolve (accretion, differentiation, magmatic, magnetic). Another important goal of MSR is to address questions about potential hazards and resources for human exploration. A key to meeting these objectives is to collect and return a strategically selected suite of samples.

The relatively short mission turnaround time compared to the icy moons ensures that Mars is a development platform for sample return missions geared towards life detection. The return and subsequent curation of Mars samples will provide new challenges related to planetary protection requirements given its designation as a Class V restricted Earth return body. However, these challenges are tractable given the 40 years of preparation NASA and the planetary science community have undertaken related to Mars sample return.

Phobos & Deimos: Laboratory investigation of material from Phobos and Deimos are necessary to address questions of their origin. Phobos and Deimos have been hypothesized to originate from debris ejected from a large impact on Mars or as captured asteroids [5]. Additionally, Phobos and Deimos sample return would serve as a precursor to martian sample return.

Ceres: The Dawn mission has shown Ceres to be a fascinating planetary body with cryogenic processes that have operated in the recent past [6]. Samples from Ceres would give unique insight into the distribution and transport of volatiles within the interiors and regolith of moderately-sized airless planetary bodies. Furthermore, the isotopic composition of the silicate and volatile components of Ceres would shed light on the chemical processes of differentiation and the isotopic composition of volatiles at the interface between the inner and outer solar system. Ceres may also play a role for in-situ resource utilization (ISRU) of water and other volatiles, given its strategic position within the solar system.

Ocean Worlds: Based on the requirement for water in Earth biology, the search for life elsewhere in the solar system has been geared towards objects that have liquid water now or in their past. Planetary bodies likely to have oceans include Europa, Ganymede, Callisto, and Enceladus. These locations offer our best chances of finding life beyond Earth. Analysis of samples from water oceans beyond Earth would also provide valuable insights on the origin of water in the solar system, as well as providing insights into aqueous biotic chemistry (in the event life is found) or abiotic aqueous chemistry (should the ocean worlds prove sterile).

Of these worlds, sample return from Enceladus is the most feasible because of its geyser-like activity [7], which would allow ejected material to be captured from orbit rather than requiring landing on the surface and subsequent re-launch. If landed sample return from an ocean world is feasible, Europa remains a prime target based on the existence of hydrothermal processes between a rocky inner shell and a subsurface ocean [8].

Returning samples from ocean worlds will require technological advances for collection and long-term storage of liquid or frozen samples that must be presumed to contain biology. Furthermore, these bodies present the same Planetary Protection challenges as Mars sample return given their designation as Class V restricted Earth return. Analytical advances will be needed as well, including development of a robust set of life detection methods to unambiguously determine whether these samples contain indigenous life.

Rings of Saturn: The rings of Saturn have been an object of fascination since Galileo first peered at the rings through his telescope in 1610. The rings are composed largely of water ice with some small fraction of lithologic components, purportedly composed of interplanetary dust [9]. The origin and age of Saturn's ring system is still unknown [9-11], but most models indicate that the rings are remnants of a Moon or giant comet that was ripped apart by tidal forces [9-11]. Sample return from each of Saturn's rings would enable comparisons of isotopic ratios within the water ice and comparisons of the minor lithic components. These data would help determine the origin and age of the rings, and they would provide valuable information about the isotopic composition of water in the outer solar system.

Comets: Comets contain the best preserved remnants of the solar system starting materials and have considerable astrobiological value. Their volatile inventory represents a link between the protosolar molecular cloud and solar nebula chemistry. Moreover, comets may have contributed a major component of the Earth's volatile inventory and organic compounds. Comets appear to have remained in a deep freeze, preserving their original components from alteration by planetary processes. Comets also contain materials from the inner solar system, so comet nucleus sample return is needed both to understand how high-temperature materials and volatiles came to coexist in these primordial bodies and to characterize the original organic materials that were delivered to Earth and other bodies in the ancient past. Returned comet nucleus samples will need to be kept organically clean and protected from high temperatures. Cryogenic sample return is a priority, long term goal.

Conclusions: Future sample return missions will present new sample handling and storage challenges and will require technological advances in the areas of cold curation, extended curation of ices and volatiles, and curation of organically- and biologically-sensitive samples [1-2]. Advanced curation will continue meet the needs of the planetary science community as NASA's exploration goals evolve.

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Introduction: Exploring the Outer Solar System (OSS) requires multi-decade advance planning. It typically takes years to decades to get a mission approved, followed by 4-6 years to launch, with cruise times from 3-13 years. Long-term concepts, planning, and funding are essential.

NASA Strategic Plan and Decadal Survey: OSS targets uniquely address NASA's top-level strategic goal to ascertain the content, origin, and evolution of the Solar System and potential for life (2011 NASA Strategic Plan). For example, how did the outer planets mold the Solar System and create habitable worlds? *The emerging priority for future exploration of the OSS is to understand ocean worlds and search for life.*

The Visions and Voyages Decadal Survey recognized many priorities for the OSS: Exploration of Europa and ice giants (Flagship missions), and New Frontiers missions to Io and Saturn's interior. Recently, ocean worlds Enceladus and Titan were added to the list for New Frontiers.

Workshop Themes

Origins: The outer planets feature prominently in molding the Solar System in a complex endgame that appears to involve: (a) migration of the outer two giant planets, Uranus and Neptune, from somewhere closer to the Sun to their present locations; and (b) giant planets scattering planetesimals into the inner Solar System, delivering water and other life-critical materials to the terrestrial planets.

Workings: The unmatched diversity of bodies in the OSS provides the opportunity for a wide variety of scientific investigations. The giant planets provide insight into Solar System formation through studies of their composition and internal structure. The satellites of the giant planets – some comparable in size to terrestrial planets – offer the opportunity to study extreme environments on worlds that have experienced very different geologic histories. The rings and magnetospheres of the giant planets illustrate currently active processes (collisions and momentum transfer) that played important roles in early stages of Solar System formation.

Life: One of the primary opportunities in the OSS is the chance to explore oceans. The OSS is replete with ocean worlds including Europa, Ganymede, Callisto, Enceladus, Titan, Triton, and possibly others. Uranus and Neptune are giant ocean worlds, akin to water worlds found in extrasolar systems. In the inner Solar System only Earth has an ocean, key to the origin(s) and evolution of life. The Roadmap to Ocean Worlds study [1] describes the initial steps to identify ocean worlds, understand the characteristics of the oceans, characterize their habitability, and search for life, and will describe future exploration priorities.

Threats and Resources: In terms of threats, comets from the OSS have a low probability of impact to Earth. As for resources, by far most of the H_2O in the Solar System resides at Jupiter or beyond. This water may not be exploited as a resource before 2050, but still motivates near-term scientific exploration.

Other (Human Exploration): Titan is the only world besides Earth with an atmosphere that can adequately protect humans from radiation while not in an unmanageable T, P range. Again, this is a very long-term interest (>2050), but motivates science.

Special Places in the OSS

Ocean Worlds: The best potential abodes of extant life are ocean worlds [1]. There is strong evidence that Enceledus and Europa – along with other Galilean satellites – contain liquid water oceans below their icy shells. Titan's surface lakes contain hydrocarbons rather than water, and the subsurface contains a water ocean. The abundance of past and present oceans in our Solar System, and proliferation of life in our own ocean, make ocean worlds compelling targets for future missions. They present serious technical challenges however, including exploration below ice shells, distance from Earth, power supplies, and for Europa, intense radiation.

Ice Giants: The ice giants Uranus and Neptune, and their rings, satellites, and magnetospheres, are dynamic systems that challenge our understanding of the origins and workings of planets. This is particularly true in regards to our understanding of known exoplanets, the majority of which are thought to be ice giants [2].

Origins: Priorities are measurements to definitively determine if planetary migration has occurred and to understand ice-giant formation well enough to reliably infer exoplanet compositions and structures with limited knowledge (mass, radius, and perhaps the abundance of trace species in their upper atmospheres).

Workings: Priorities are to understand atmospheric dynamics and the driving processes; the physics of cataclysmic, stochastic processes such as those that resulted in Uranus' tilt and the expulsion or destruction (presumably by Triton) of Neptune's native large satellites; the evolutionary diversity of the satellites, including past (and present?) oceans and cryovolcanic activity (e.g., Ariel, Triton), using the magnetic geometries offered by Uranus and Neptune to probe their interiors.

Life: Uranus and Neptune may contain unique niches for life, not only in their icy satellites, but possibly within the extensive oceans thought to exist within the planets themselves.

Gas Giants: Although Galileo, Cassini, and Juno provide much knowledge, additional study is needed.

Origins: Priorities are to search for evidence of past planetary migration by determining the abundances and isotopic ratios of heavy elements, especially the noble gases, at Saturn (as well as Uranus and Neptune) and compare them to the Galileo Probe measurements at Jupiter. Together, these measurements will establish the "ground"-truth for the bulk composition of exoplanets, and enhance understanding of the composition and structure of exoplanets inferred from their mass, radius, and perhaps the abundance of trace species in their upper atmospheres.

Workings: Our objectives are to understand dynamic phenomena in the atmospheres, interior structures, and magnetospheres of these planets. Priorities are the temporal dynamics in the atmospheres of Jupiter and Saturn, and the driving mechanisms that shape their zonal wind structure.

Life: In addition to ocean worlds, searching for evidence of planetary migration will determine the role of giant planets in the evolution of a habitable planetary system and delivering the volatile elements essential for life to Earth.

Magnetospheres: The OSS supplies a comprehensive natural laboratory for studying magnetospheric systems and provides a spectrum of comparative magnetospheres to extrapolate to those we might expect at exoplanets. Uranus and Neptune provide opportunities to study not only the nature of off-centered and highly tilted magnetic fields, but also how the extreme seasonal geometries provided by Uranus' high obliquity affect magnetospheric structure and dynamics. Jupiter and Saturn enable us to explore persistent neutral and plasma sources within the magnetosphere and their role in governing magnetospheric dynamics, auroral current systems, and radial transport. These magnetospheres also provide the variable magnetic fields necessary to probe the interiors of subsurface oceans.

Io: An Io Observer was listed as a deferred high-priority mission by the 2013 Decadal Survey, as one of 7 New Frontiers mission candidates. Tidal heating is the dominant continuing heat source in the OSS, providing a necessary component for habitable environments. Io provides the clearest expression of tidal heating, so to understand this process we need to understand how it manifests on Io. Furthermore, Io addresses the workings of processes in our inner Solar System, especially volcanism. On Earth, extremely voluminous volcanism may be the cause of several mass extinction events; Io is the only place to observe such eruptions in action.

Dwarf Planets: OPAG has joint custody of these along with SBAG. Dwarf planets share many similarities with large icy satellites, especially Triton (likely a captured KBO), and may be additional ocean worlds. New Horizons has shown Pluto and Charon to be remarkable; other KBOs remain unexplored.

Priorities for the Next Three Decades

Technology Development Priorities: Technologies are required for unambiguous (or at least less ambiguous) life discovery and ecosystem exploration. This may require a departure from classical biomarker detection, and well-integrated “smart” sensor packages capable of high-throughput sample collection and processing. Other priorities are efficient, long-term power sources and energy storage; in situ exploration technologies including sampling methods, cryogenic mechanisms, electronics and thermal control; autonomous operations; communication; propulsion and launch capability; planetary protection; and operation in extreme environments (cryogenic, high-radiation).

Notional Missions: All OSS missions in the decadal survey and New Frontiers should be completed (Europa Clipper, Ice Giant Orbiter, Io Observer, Saturn Probes, and Titan and Enceladus ocean world missions). Both ice giant systems should have orbital missions. Flyby missions to distant dwarf planets Eris, Haumea, or Makemake would be worthwhile, or a Pluto orbiter. By 2050 we imagine spacecraft going to numerous locations in the OSS, sampling plumes and oceans, deliberately searching for life. *In situ* life detection should be attempted, such as by a Europa Lander, but sample return may prove essential to identify an independent origin for life. To protect life on Earth, sample containers might be delivered to a special sample analysis facility on the Moon for screening.

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BAOBAB (Big And Outrageously Bold Asteroid Belt) Project. L. A. McFadden[1] and C. A. Thomas[2], [1]J. A. Englander, [1]O. Ruesch, [3]S. Hosseini, [1]S. J. Goossens, [1]E. M. Mazarico, [4]N. Schmerr, [1]NASA-GSFC (Code 693, Greenbelt, MD 20771 and lucy.mcfadden@nasa.gov), [2]Planetary Science Institute (Tucson, AZ cristina.a.thomas@nasa.gov),[3] Jet Propulsion Lab, CalTech (Pasadena, CA), [4]Department of Geology, University of Maryland, College Park, MD 20742.

Introduction: One of the intriguing results of NASA's Dawn mission is the composition and structure of the Main Asteroid Belt's only known dwarf planet, Ceres [1]. It has a top layer of dehydrated clays and salts [2] and an icy-rocky mantle [3,4]. It is widely known that the asteroid belt failed to accrete as a planet by resonances between the Sun and Jupiter. About 20-30 asteroids >100 km diameter are probably differentiated protoplanets [5].

1) how many more and which ones are fragments of protoplanets?

2) How many and which ones are primordial rubble piles left over from condensation of the solar nebula?

3) How would we go about gaining better and more complete characterization of the mass, interior structure and composition of the Main Belt asteroid population?

4) What is the relationship between asteroids and ocean worlds?

Bulk parameters such as the mass, density, and porosity, are important to characterize the structure of any celestial body, and for asteroids in particular, they can shed light on the conditions in the early solar system. Asteroid density estimates exist but currently they are often based on assumed properties of taxonomic classes, or through astronomical survey data where interactions with asteroids are weak at best resulting in large measurement uncertainty. We only have direct density estimates from spacecraft encounters for a few asteroids at this time.

Knowledge of the asteroids is significant not only to understand their role in solar system workings, but also to assess their potential as space resources, as impact hazards on Earth, or even as harboring life forms. And for the distant future, we want to know if the idea put forth in a contest sponsored by *Physics Today*, to surface the asteroids into highly reflecting, polished surfaces and use them as a massively segmented mirror for astrophysical exploration [6], is feasible.

Science mission plan: Missions consisting of a mother ship with a fast, direct trajectory to the Main Belt that would visit 25 or more asteroids of different taxonomic type (surface composition), with a range of estimated mass, size, spin rate and internal structuresis envisioned. A mother ship would carry both daughter and tiny-tot ships with a range of payloads described below, and following trajectories designed to both fly by and orbit a number of asteroids within a decade or two. A process to determine how many targets are deemed necessary to characterize the main belt needs to be developed and target selection incorporating scientific return is necessary. In 2014, a contest to design trajectories for multi-spaceccraft exploration of the asteroid belt was carried out, so such a plan is feasible now, though with fewer targets than desired in the future [7].

Mother and/or daughter ships would both flyby and rendezvous with each target. They would fly by at a velocity high enough to propel a penetrator package into the surface and loft material into the asteroid's wake. Another spacecraft in a following trajectory would rendezvous later to sample the ejected gas and dust, survey the surface and site of the penetrator's impact and to drop a seismometer(s) onto the asteroids and receive data from them.

Mass and Interior Structure Determination. We envision a much more comprehensive survey of the asteroid belt than exists today, and anticipate developing different approached than currently approaches. Gravity today, can be determined through the tracking of a spacecraft perturbed by the gravity field of the object of interest using radio data. A spacecraft can be sent into orbit around the objects although this would require long missions at each object. An alternative to the long orbital missions required for gravity mapping through spacecraft tracking is launching multiple daughter spacecraft to one object, in a “swarm”-like fashion, generating multiple flybys in a short period, thus negating the need to spend long periods at one object. This would result in quick and precise estimates of the asteroid’s mass and its gravitational flattening which informs us about radial density profiles. With gradiometers small enough to fit on cube-sat type spacecraft, a highly accurate gravity map of each object can be obtained. From a dynamical viewpoint, we envision the long-term monitoring of small spacecraft in the asteroid belt perturbed by various different bodies, thus being able to deliver mass estimates for a range of asteroid types.

Density estimates not only require the mass of the object to be known, but also the volume. Imaging using the high definition imager can obtain such data, as can dedicated lidars on the daughter satellites. The characterization of the spin-state of the asteroids, from imaging and gravity data, would also further constrain models of the interior structure by having measurements of the moments of inertia.

The Payload: The desired instrument payload consists of the following instruments:

1) high definition imaging camera
2) space-qualified spatial heterodyne spectrometer
3) array of seismometers
4) penetrator package

The purpose of this payload and anticipated science return is described below.

High Definition imager. Detectors and cameras are constantly under development because visible and visual images are necessary for navigation, digital terrain modelling and volume measurements. As an added bonus, we get geological context and an important sense of being at the asteroid targets.

Spatial Heterodyne spectrometer. BAOBAB's spatial heterodyne spectrometer (SHS) will be an advanced design of a miniature, all-reflective two-beam cyclical spectrometer [8, 9]. SHS can observe targeted atomic and molecular gas spectral lines at high spectral resolution (R~50,000-150,000) without the need to couple to a large aperture telescope. It comprises a grating and reflective optics tailored to a target wavelength region (VIS to UV) with a solid-state array detector. With its high optical throughput (étendue) and wide field of view (FOV), it has very high sensitivity to weak or diffuse sources. These two characteristics, enable unique high sensitivity to specific spectral features such as global temporal observations of outgasing and global values of key isotopic ratios such as D/H, $^{3}He/^{4}He$, $^{14}N/^{15}N$, $^{12}C/^{13}C$, $^{16}O/^{18}O$.

Seismic Wave Capability. As noted by Bell et al. [10] in a numerical analysis to determine the minimum number of instruments required for a seismic network on an asteroid it is feasible to detect seismic waves from an impact source ranging in size from 0.1 to 100 kg onto a 250 m radius asteroid (Fig. 1 from [10]). The range of impact velocities in their study was 2 m/s to 5 km/s and results in eqivalent magnitudes of -7 to +1. For reference a hammer blow to a metal plate would result in magnitude -6 to -2, with the above parameters. A seismic experiment package on an asteroid has not yet flown. Yet in the next 30 years, their mass, energy and transmit- and receive- mechanisms are expected to enable resolutions greater than a single source would produce allowing determination of internal structure that would distinguish between protoplanetary and condensation-formed asteroids.

Penetrator Package. A penetrator package of 2050 would consist of accelerometers, heat probes, miniature cameras and hopefully a device for elemental analysis. The design would build on previous packages proposed for scientific exploration and hazard mitigation from small near-Earth asteroids. [eg. 11, 12, 13].

Note on the project's name: The Baobab tree is found in remote places on Earth (relative to where most of us live). It is a large tree with dense canopy and its trunk can hold up to 26,000 gallons of water to survive droughts. A baobab tree grew on asteroid B612 in Antoine de St. Exupery's Le Petit Prince. The tree represents the density and complexity of the content and nature of the Main Asteroid Belt and the hope that we can see into the interior of the tree.

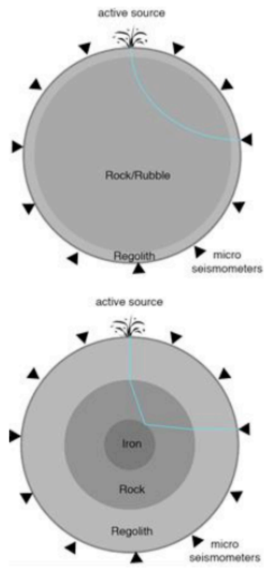

Figure 1. Simplified internal models of range of asteroid compositions used in this study. Seismic energy generated by an active source traverses interior and is recorded by seismometers on the asteroid surface. (upper panel) Homogeneous interior covered by thin layer of regolith. (lower panel) Differentiated model. from Bell et al. 2016 [10].

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GEOPHYSICAL MAPPING AND MONITORING OF ACTIVE PLANETS (GM²AP). P. J. McGovern[1] , S. J. Goossens[2,3], and F. G. Lemoine[3], [1]Lunar and Planetary Institute, USRA, 3600 Bay Area Blvd., Houston, TX 77058 (mcgovern@lpi.usra.edu), [2]CRESST, U. of Maryland Baltimore County, Baltimore, MD 21250, [3]Geodesy and Geophyics Laboratory, NASA GSFC, Greenbelt, MD 20771.

Introduction: Data collected during the initial reconnaissance of the inner solar system (through the mid-1990s) indicated ages for terrestrial planet surfaces (other than the plate tectonics-endowed Earth) of order 10^9 years, suggesting dead or at best dormant planets. However, data obtained during the last two decades, combined with careful re-analysis of previous datasets, point to substantial present-day activity at Venus and Mars. For example, Venus Express instruments have uncovered signatures of geologically recent [1] and even possibly active [2] volcanism on that planet. A re-examination of Magellan SAR images of dark-floored craters [3] suggested a mean surface age for Venus of around 150 Ma. This result was followed up by a re-calibration of the Venus impactor distribution curve giving a comparably young surface age [4]. At Mars, paleotopographic analysis indicates that a substantial portion of the Olympus Mons volcanic edifice was emplaced within the last 210 Myr [5]. Estimates of heat flux from the interior of Mars are consistent with the possibility that secular cooling is minimal or even negative (i.e., Mars is heating up) [6].

These results justify a re-examination of tectonic and volcanic activity on Venus and Mars. Findings of substantial ongoing volcano-tectonic activity on these "one-plate planets" [7] provide strong motivation to create in-depth programs of geophysical sensing and monitoring, in order to figure out how planets work beyond the singular plate tectonic setting of Earth, and also for evaluating hazards to humans exploring Mars.

Motivation:Volcano-tectonic activity levels.

Hawaii: Large basaltic volcanic edifices formed at intraplate volcanic settings ("hotspots") on Earth are the best analogs for large volcanoes on Mars and Venus. At Hawaii, extensive instrumentation provides detailed records of seismic activity. A catalog of 7022 earthquakes spanning 45 years, with moment magnitudes M_0 ranging from 3.2. to 6.6 [8], can be used to derive the Gutenberg-Richter (G-R) frequency-magnitde relation for the Island of Hawaii, expressed as $\log(N) = a - bM_0$, where N is the number of earthquakes with magnitudes greater than or equal to M_0, and a and b are constants [9]. By this analysis, (Fig. 1), one earthquake with M_0 4.9 or greater can be expected every year. Under the assumption that the mechanisms of seismicity for edifice building are similar across the planets, we use the same b for all planets [10] and scale a according to estimates of magmatic volume flux rates dV/dt at the various planets. Over the 80 Myr history of the Hawaiian-Emperor volcanic chain, dV/dt is around 1.7 x 10^{-2} km^3/yr [11].

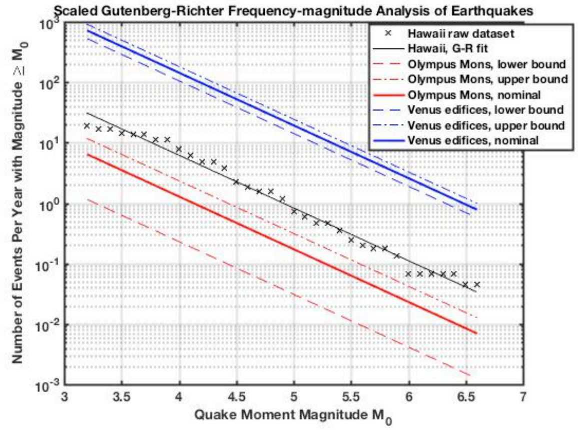

Figure 1. Frequency of seismic events with moment ≥ M_0 as a function of M_0. Black 'x's show raw data for Hawaii [8], and the black line shows the best-fit G-R relation (a = 5.93 and b = 0.872), scaled to the duration of the seismic catalog to give rates. Red lines show nominal and bounding G-R relations for quakes at Olympus Mons, Mars; blue lines show them for volcanic edifices on Venus.

Mars: Paleotopography at Olympus Mons [5] yields estimates of dV/dt for the last 210 Myr ranging from 6.33 x 10^{-4} to 6.43 x 10^{-3} km^3/s. Taking the mean of these values and scaling a by the ratio of dV/dt values for Mars and Hawaii yields a rate of at least 1 quake of M_0 = 4.1 or greater per year (Fig. 1).

Venus: Findings of a young(er) Venus surface age [3,4] greatly enhance predicted rates of volcanism. Estimates of dV/dt associated with 145 large volcanoes on Venus [12], under the assumption of a surface age of 150 Ma [3,4], yields nominal dV/dt = 3.95 x 10^{-1} km^3/yr, more than an order of magnitude greater than the Hawaiian-Emperor flux and comparable to Earth's total intraplate volcanic flux [13]. Scaling the Hawaiian G-R relation to Venus edifices (alone) yields a prediction of at least one quake with $M_0 \geq 6.5$ per year.

Monitoring: Instruments and Missions.

Seismic. Above and beyond globally oriented Mars seismic experiments like InSight [14] and successor networks, a dedicated Olympus Mons Seismic Network modeled on networks at active volcanoes on Earth [15] would allow elucidation of structures related to lithospheric flexure [16], volcanic spreading [17], and perhaps even signals (tremor) related to magma movement and emplacement [18]. 20 years of monitoring should give at least one mag. 5.6 quake and ~ 20 $M_0 \geq 4.1$ quakes to study. Such results would provide insights into the processes that controlled Martian volcanic evolution and crustal structure that are not likely to be available at any other site on the planet.

New evidence of geologically recent or even ongoing volcano-tectonic activity on Venus [1,2] provides strong motivation for seismic monitoring (see also Fig. 1), and while surface temperature conditions are extreme, progress on high-*T* electronics offers some hope of long-duration seismometers in the 2030-50 timeframe [19]. If the volcanic edifice volume flux for Venus is indeed comparable to Earth's intraplate flux, then even relatively short-duration seismic stations should find numerous large-magnitude events to study (Fig. 1). Surface monitoring could also be augmented by long-duration (buoyant) aircraft platforms.

InSAR. Interferometric Sythetic Aperture Radar (InSAR) techniques allow detailed analyses of fault and volcano deformation [20]. These analyses require repeat-pass orbital imaging of sites, which is straightforward to accomplish at rapidly rotating planets like Earth or Mars, but which presents challenges at a slowly rotating one like Venus, resulting in 243-day long cycles [e.g., 21]. A pair or even constellation of InSAR-capable spacecraft in staggered orbits [22] could mitigate the slow-rotation constraint, allowing shorter repeat-pass time baselines.

Gravity. Gravity data provide fundamental constraints on planetary interior structure [23], including time-dependent signals related to volatile cycles, such as polar cap/atmosphere exchange [24] and terrestrial water storage [25]. There are several mission mode options for next-generation gravity investigations of Mars and Venus. GRACE/GRAIL-type dual-satellite gravity missions using Ka-Band Doppler or laser-interferometer tracking [26,27] offer substantial advantages in precision and resolving power over traditional Doppler tracking, as do single-satellite gravity gradiometry missions [28]. Technological advances in gradiometry technology [29] offer orders of magnitude improvements in sensitivity over current instruments.

For Mars, while Doppler gravity tracking from MGS/ODY/MRO was sufficient to detect signals from polar cap volatile cycles [24], improvements from dual-satellite or gradiometry measurements would resolve Mars' CO_2 cycle at greatly improved resolution. Further, detection of subsurface water flow cycles on Mars (if present) would be a spectacular leap forward. Volatile cycles of this sort are not relevant to Venus. However, Venus' atmosphere perturbs gravity mapping from orbit by causing atmospheric drag at the satellite altitude and also through perturbations induced by the variability and motion of the atmosphere. These have likely contributed to irregularities and errors in the mapping of the gravity field of Venus using Magellan data, contributing to spuriously low or erratically variable gravity/topography correlations on Venus [30]. New gravity missions with high sensitivity and uniform coverage, that include methods for accounting for non-conservative force-induced accelerations on the spacecraft (for example, using precision accelerometers as on GRACE [26]), could allow the gravity field of Venus to be properly resolved, as well as producing data relevant to atmospheric studies.

Groundstation Science. A positioning satellite network at Mars would enable precision GPS-type observations [31] from fixed ground stations, and also allow autonomous rover/astronaut navigation. The GPS-like stations could be arranged in local networks to monitor deformation of volcanic edifices or signatures of surface or subsurface mass exchange. These ground stations would also deploy gravimeters, seismometers, heat-flow sensors, and strain meters.

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PLANETARY SCIENCE IN THE NEXT DECADES: THE ASTROMATERIALS PERSPECTIVE. H. Y. McSween[1] and K. D. McKeegan[2], on behalf of CAPTEM[3]. [1]Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN 37996-1410, mcsween@utk.edu, [2]Department of Earth, Planetary, and Space Sciences, UCLA, Los Angeles, CA 90095-1567, mckeegan@epss.ucla.edu, [3]www.lpi.usra.edu/captem/.

Introduction: Astromaterials include samples returned to Earth by spacecraft misisons as well as those that arrive here naturally. Research on these samples creates the knowledge base needed for science-focused Solar System exploration by answering questions that no other avenue of research can. Moreover, astromaterials are the "gift that keeps on giving" – the ability to apply new technologies that did not exist when the samples were acquired or returned greatly enhances their value.

Vision for Sample Return Missions: The decades beyond 2022 offer many opportunities to significantly advance the exploration of the Solar System through sample return missions.

OSIRIS-REx will return samples of a B-class carbonaceous asteroid, and HEO's Asteroid Redirect Mission could provide additional asteroid samples. New Frontiers target missions under consideration include sample return from a comet nucleus and from the South Pole Aitken basin on the Moon. Ample motivations for these missions were provided by the NRC's Planetary Decadal Survey [1]. CAPTEM's vision includes carrying out both of these high-priority mission concepts, whether or not they are selected for flight in the current decade. Building on these missions, CAPTEM advocates additional sample returns from the Moon to understand how the Late Heavy Bombardment, as well as continued sample returns from additional asteroids and comets – the compositional diversity of these objects will never be fully understood using remote sensing and cannot be captured by the missions currently under consideration. Sampling another asteroid population, such as the Trojans, would be especially informative.

Another goal for the next decades should be a mission to return cryogenic samples from a comet, so that we can begin to understand icy/volatile materials in the outer Solar System. CAPTEM also advocates for returning samples (collected from erupting jets by an orbiting or flyby spacecraft) from "ocean worlds" like Enceledus; such a mission offers the most technically plausible and affordable way to address the goal of seeking evidence of life in subsurface oceans. Direct sampling of the methane/ethane surface lakes on Titan would be very challenging, but return of such a sample might offer the most promising opportunity to find life or understand its organic precursors. Alternatively, a returned sample of Titan's organic-rich atmosphere is less challenging and would address the same questions.

The return of samples cached by Mars 2020 ranks among the most important goals for planetary science, as noted in the NRC's Planetary Decadal Survey [1]. CAPTEM emphasizes the need for NASA and its international partners to complete the sequence of missions that will make carefully chosen martian samples available for laboratory investigations. These analyses are viewed as a prerequisite for sending humans safely to Mars [2].

Samples returned from Venus or Mercury would constitute major scientific advances but would require correspondingly major technological leaps. However, return of Venus atmospheric samples would be valueble for understanding the origin and evolution of planetary atmospheres. Likewise, obtaining samples of surface materials or subsurface oceans from satellites of the giant planets would also have great scientific value, but their collection and return probably lies beyond 2050.

Knowledge of the elemental and isotopic composition of the Sun is fundamental. Genesis provided a two-year sample of the solar wind. A future mission of this type is justified to enlarge the chemical data base for the centerpiece of the Solar System, and to improve knowledge of processes leading to the ejection of matter from the Sun. A second Genesis-type mission could be flown as an inexpensive stand-alone, or as an add-on; solar wind collection could also be part of a lunar base.

Getting the Most out of Past Missions: The 382 kg of rocks and soils collected by the Apollo astronauts are still providing fundamentally new discoveries about the geology and history of the Moon, many decades later. Other NASA-curated collections from past missions include comet dust from Stardust, solar wind from Genesis, and asteroid regolith from Hayabusa [3]. These small samples are likely to become exhausted by 2050, despite careful curation and allocation.

The Cheapest Sample Return Missions: The Antarctic Search for Meteorites (ANSMET) program has provided >20,000 meteorites from at least 80 parent asteroids plus the Moon and Mars [3]. The continuation of meteorite collection programs will provide samples of a much greater diversity of Solar System bodies than can be visited by 2050. Cosmic dust, collected in the stratosphere by U2 aircraft, retrieved from melted Antarctic ice, and vacuumed onto soon-to-be installed atmospheric filters at the South Pole, provide samples of cometary solids (sometimes from specific comets through targeted meteor showers). Although meteorites and cosmic dust, however valuable, are samples without provenance or geologic context, they allow fundamental questions about processes and conditions in the solar nebula and on primitive and differentiated bodies to be addressed in a quantitative way.

Challenges: The Decadal Survey [1] stated that "The most important instruments for any sample return mission are the ones in the laboratories on Earth." Without adequate support through the next decades, NASA's ability to analyze extraterrestrial samples, develop new microanalytical techniques, and provide the experienced workforce needed to maximize the scientific results of future missions will wither. This community of scientists also is engaged in developing capable instruments to be flown on spacecraft. In the future, coordination of analytical capabilities and facilities with international partners will likely be desirable.

The sample return missions (beyond those already in the current prioritized New Frontiers list, for which challenges have already been noted [1]) that CAPTEM advocates and some of their technological challenges are reiterated below; these are not prioritized or chronologically sequenced, as that requires in-depth study and advice from the broader science community.

- ***Mars sample return***: The mechanics of the multiple missions that retrieve samples from the planet's surface and launch them towards Earth are already under study. The requirements for sample curation, including issues related to planetary protection, and the necessary funding are not.
- ***Sampling the Moon*** and ***additional asteroid sample returns*:** Autonomous approach and sampling when out of communications with Earth is part of the OSIRIS-REx mission, but that technology is primitive and applies only to unconsolidated regolith. It seems possible that some sample return missions from small bodies might be flown within the costs of the Discovery program, and that capability should be explored.
- ***Cryogenic comet sample return***: The ability to take a core on a comet, reaching beneath the dusty mantle to collect ices and retain stratigraphic context, is very challenging. The sample must be collected and returned to the Earth's surface in a frozen state.
- ***Sampling jets of volatile materials from an ocean world***: Cassini has already flown through and remotely analyzed jets from Enceledus, but detecting life likely requires study in a terrestrial laboratory; the challenge may lie in collecting enough material to make its return to Earth worthwhile.
- ***Sampling Titan's lakes or atmosphere***: Huygens has successfully transited (one way) Titan's atmosphere, but traveling in the other direction is harder. How to land on and sample a lake, and then launch from a liquid surface is problematic. Luckily, the lakes are smooth, but their properties are unknown. Sampling the upper atmosphere of titan is a more tractable problem, as it does not require landing.
- ***Venus sample return***: The problems encountered in sampling Venus rocks before being incapacitated by the searing heat or crushed by the dense atmosphere, and of escaping through the atmosphere and from a gravity field like that of Earth's, are legion. However, return of atmospheric samples would be more tractable.
- ***Mercury sample return***: The orbital problems in landing a spacecraft on Mercury may preclude serious consideration of sample return in the next few decades.
- ***Genesis-type solar wind return:*** Building on Genesis technology, this sample return would be straightforward, although advances in analysis technology are needed.

Summary: Samples studied in laboratories on the Earth provide otherwise unobtainable information about extraterrestrial bodies that motivates and enables future spacecraft missions. The next decades offer many opportunities to conduct missions that will return samples, significantly increasing our understanding of Mars, the farside of the Moon, asteroids, comets (including ices), jetted or surface volatiles on an ocean world, and possibly Venus and Mercury. The analyses of samples collected and returned by spacecraft is complemented by continued investigations of meteorites and cosmic dust that arrive on Earth naturally (the cheapest missions). NASA should sieze this vision.

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INTERACTIVE SCIENCE ON MARS. C. R. Mercer[1] and G. A. Landis[1], [1]NASA Glenn Research Center, 21000 Brookpark Road, Cleveland OH 44135.

Introduction: Cargo transportation systems being developed for the human exploration of Mars could substantially alter the way we conduct science at Mars . The current paradigm is to send individual highly-capable science rovers, with which a competitively-selected science team designs a traverse making intensive science investigations at a series of sequential stops. We propose shattering this investigation paradigm. Solar electric propulsion systems enable the delivery of large payloads to the Mars surface, and further provide a means to power very high capability communications systems that can transmit unprecedented data rates. This combination opens the door to the deployment of large numbers of small rovers for Mars exploration. The high communications bandwidth will allow a constellation of rovers to put together a high-fidelity, detailed model of the surface, allowing 3-D augmented reality exploration of the surface by professional and citizen scientists across the world, and opening up the excitement of walking across the Mars surface to interested amateurs and non-scientists. The result would be a new baseline: “Mars is for everybody.”A candidate conceptual mission design that we’ve analyzed would deliver 93 small rovers to three locations, with high data-rate communications limited only by the allocated spectral bandwidth and the number and size of Earth-based receiving terminals. It would be cost prohibitive to pay for 93 science teams, so citizen scientists could be employed to conduct specific science observations using an augmented reality gaming infrastructure. An augmented reality interface would simultaneously register high resolution images in an accurate areospatial map and provide an intuitive data interface to assist both professional and amateur scientsits. It could also be seamlessly integrated into gaming activities that could be developed for commercial products.

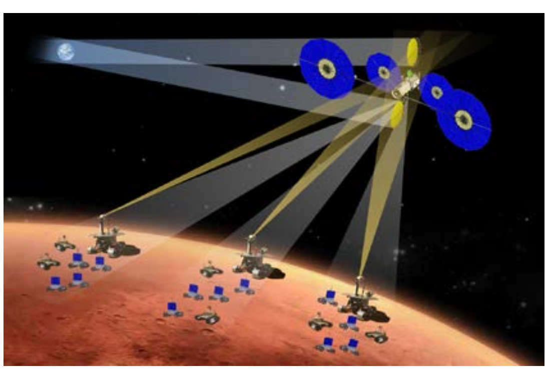

Figure 1. High Power SEP communications relay for distributed rover swarms on the surface of Mars.

Science opportunities: Previous missions have shown the high value of color stereo visual imagery in science investigations, validating the observation of Yogi Berra, “you can observe a lot just by looking.” Addition of multichannel hyperspectral bands allows adding mineralogy as well as geomorphology capabilities to visual imagery. Camera technologies have been rapidly evolving, and visual cameras are small, cheap, and highly capable; with limitations set entirely by the downlink bandwidth, rather than camera limits. For more focused science, the small rovers can serve as scouts for subsequent misisons with larger, more capable instrument suites. They could search for interesting minerals and geologic formations using small imagers and spectrometers such as an evolved version of the 2.4-kg, 5.6-W miniature thermal emission spectrometer deployed on the Mars Exploration Rovers. Searching for hydrated minerals, and detecting for instance clays, sulfates, and anhydrous ferric oxides would help to understand the water distribution across the surface of a region. Rovers equipped with small manipulators could collect and cache samples. Rovers regions could be separated by hundreds of kilometers to create a meterological network and conduct seismology studies. The regions could be placed so that two groups lie within magnetic fields and one group does not; small magnetomers could then be used to study local magnetic effects and determine, for instance, if there is correlatation of these effects with aurorae. Local methane variations could be monitored to determine baseline background levels to help assess whether levels identified in other regions might have geological or biotic origins. Depending on the level of planetary protection that could be cost-effectively achieved by these small rovers, they could be constrained to regions that are highly unlikely to harbor life or they could explicitly be sent in search of life. Although we are focused on Mars, this concept could be applied to the Moon as well. The software developed for this application could also be used for terrestrial Earth science campaigns (e.g., measuring ice sheet thickness or soil water content).

Spacecraft concept: We envision using a high-power (150-kW at Earth) solar electric propulsion (SEP) spacecraft to deliver dozens of small (<100-kg) rovers to Mars. To ensure a high level of interactivity from a nearly continuous view of a large portion of the Mars surface, we will position the spacecraft in areosynchronous orbit 17,000 km (11,000 mi) above the Mars equator. The large solar arrays used to power the SEP spacecraft during the trip to Mars will then be used to power a high-capacity communications system to transmit data back to Earth. The high-power SEP could be built by retrofitting NASA's Asteroid Redirect Mission SEP vehicle with a second set of solar arrays, thrusters, and propellant tanks to boost the power level from 50 to 150 kW. This spacecraft will deliver 30 t to Mars and will fit within the mass and volume constraints of a Space Launch System (SLS) launch vehicle. Two designs exist for solar arrays large enough (50 kW each) to serve as the retrofit power source. The number of electric thrusters (12.5-kW each) will be increased from 4 to 12 without requiring a technology change, and 8 additional tanks will bring the total amount of xenon propellant to 16 t. We will use two large (nominally 7-m) deployable mesh Ka-band antennas to relay data to and from Earth. These antennas will use novel radio-frequency power-combining techniques that draw on a small portion of the unprecedented 8 kW of power from the large solar arrays, power-combining the signals from 200-W amplifiers using opposite polarizations on two simultaneous links to return the most data possible to Earth. This allows the transmission of over 60 Mbps of data for at least 8 continuous hours every day to each region on Earth as it rotates, except for a few days each year when the Sun encroaches the line of sight to Mars. Data rates as much as 25 times higher may be possible during Mars opposition when the red planet is 5 times closer to Earth. Even with this high return-link data rate, users will still have to accommodate the 6- to 44-min round-trip time delay from forward links imposed by speed-of-light communications. Nonetheless, 10 to 80 interactions each day will be possible.

We start with three types of rovers for this mission: one optimized for surface communications between the other rovers and the areosynchronous-relay satellite, one for surveying, and a third for excavating and building. Groups of these three types of rovers can be deployed to individual sites, such as 5-km craters, to both contain the play and provide interesting visuals on the horizon. A 50-kg rover based on a low-cost lunar prospecting concept serves as the starting point for the surveyors, and for the builders we start with a 95-kg excavator based on another lunar concept. Each surveyor has two-motor skid-steer tweels (airless radial tires) capable of up to 15 cm/s speeds on less than 30° inclines, with power provided by 50-W solar arrays and 400-W-hr rechargeable batteries. Each excavator is a tracked vehicle with a center-mounted linearly actuated bucket that is capable of lifting its own weight in regolith while drawing only 100 W of power provided by 18 A-h batteries recharged by solar arrays. The communications rover has a mass of about 285 kg—similar to that of the Mars Exploration Rover—and communicates to the other rovers via space-qualified WiMax or Electra Lite Radios, and to the orbiter via an X-band antenna. Splitting the 30-t payload into three sites and using rough mass estimates of heat-shield technology and lander concepts being developed by NASA for large-scale operations to support Mars human exploration, we estimate that about 2.2 t of the three landed 10-t payloads could be allocated to rovers. This will allow 1 communications rover, 20 surveyors, and 10 builders at each site—93 rovers total in one launch—to initiate the mission. Rover operations would be public, and the science capabilities will both influence and be influenced by the rover designs.

Citizen engagement: The popular Zooniverse website has demonstrated that citizens have high interest in engaging in science activities. Applications such as Comet Hunters permit people with very little formal training to mine datasets in search of scientist-determined features of interest. A game-based science mission that provides everyone on Earth with the opportunity to operate Mars rovers could initiate and foster a new public-private partnership model for planetary science.

Synergy with Human Exploration: This interactive Mars concept will demonstrate high-power SEP, heat-shield technology for landing large payloads, high-capacity communications, and autonomous systems—all identified as being necessary for NASA's Journey to Mars. This mission could serve as an Earth-independent pathfinder mission on NASA's Journey to Mars, simultaneously reducing the risk of critical technologies and emplacing a communications infrastructure that could be used for astronaut communications on future missions. NASA's investment in the infrastructure could be followed by commercial investments in games, additional rovers, rover instruments, and a host of other options.

Summary: A direct, interactive experience with Mars will change space science—transforming it from a spectator sport into a personal activity available to anyone on Earth. The interactive Mars science mission would leverage technologies needed for human space exploration and provide a new planetary science capability.

ECONOMIC PLANETARY SCIENCE IN THE 21ST CENTURY. P.T. Metzger[1], [1] University of Central Florida, Florida Space Institute, 12354 Research Pkwy, Suite 214, Orlando FL 32826, philip.metzger@ucf.edu.

Introduction: Economic planetary science is a young discipline set to expand rapidly with potential to become a primary driver of science in this century [1,2]. Similar to economic geology on Earth, economic planetary science is concerned with utilizing resources in space for economic and industrial activity. Science is produced only as a byproduct (either incidentally or to support business decisions), but experience shows it can exceed the science produced intentionally by government investment. Commercial companies are beginning new activities in space and some national governments are setting policy to encourage them. The trends that have made this possible are: maturity of rocket technology leading to lower launch costs; autonomous robotics; and the overall growth of Earth's economy and supply chain enabling an ever widening range of activities. Supporting government-lde space exploration has long been an economic pursuit of commercial companies. The best known of the new activities is asteroid mining to produce rocket propellant for purely commercial uses such as boosting telecommunications satellites into their final orbits. Commercial companies are also pursuing the in-space manufacture of large antennas to keep up with Internet growth [2-4], beaming microwave energy to Earth to replace carbon-based energy more affordably than ground-based renewables [5], space tourism including lunar landings [6-8], and providing services and material to anyone attempting settlement (such as Elon Musk [9]). While some of these may seem fanciful, some already have reasonable business cases while the expanding space and terrestrial economies suggest the others may get there soon.

Relationship of Science with Economic Development: Terrestrial experience shows that science and economic development are mutually supportive, although some conflicts do occur. The U.S. Bureau of Labor Statistics website shows that about 65% of geoscientists are in economic geology such as mining, 18% are in research (many of whom are funded by economic interests), 12% are in government (mostly managing economic activities), and only 5% are in academia (with most of their students going into economic geology). This shows that most terrestrial geoscientists are funded by economic activity rather than pure science. Likewise, most geological data have been funded by economic mining and drilling. We may therefore expect most planetary scientists will work in economic applications or be supported by the tuition of students destined mostly for economic planetary science as our economic sphere advances into space. This will represent a great broadening of our field, both in access to data and in the number of funded scientists. This is good news for our newly graduated colleagues who would otherwise face many years of hand-to-mouth survival in soft money positions, too often leaving science in the end.

Gantman [10] showed through the publication records of scientists in 147 countries that their scientific productivity correlates strongly with two factors: how developed their country is (intensive), and the overall scale of their country's economy (extensive). More intensively developed countries have better supply chains to provide tools and opportunities for scientists. Extensively larger economies have greater freedom to command funding toward science. These mechanisms ought to work when it comes to the region we call space, as well. A greater in-space supply chain will provide better in-space tools and opportunities for working scientists, and the space economy will create economic ability to fund science. If space mining is destined to create the first trillionaires, then it is destined to create the golden age of planetary science, too.

Concerns about economic activity ruining sites of high scientific value (such as lunar polar volatiles) or running contrary to other ethical or environmental values will need to be worked through government regulation. An example is NASA's recent document providing guidelines for visiting the historic sites on the Moon. Commercial companies were contacting the author to learn the best practices to visit these during the Google Lunar X-Prize without ruining the scientific value of the sites. This led to discussions with NASA headquarters, which led to the effort to develop that document. NASA legal counsel has mentioned they may eventually amend it to become mandatory rules rather than voluntary guidelines. It is noteworthy that this process was initiated by the commercial companies seeking government involvement. More such policy will be needed in the future, and commercial mining companies desire the clarity it brings, reducing uncertainty for potential investors.

Business Case for Asteroid Mining: There is already a sufficiently clear business case for asteroid mining. When a rocket company lifts a telecommunications spacecraft, it typically goes into geostationary transfer orbit (GTO) with perigee at the altitude of low Earth orbit (LEO) and the apogee near the altitude of geostationary orbit (GEO). Some years ago, it was standard practice to include an upper stage that would circularize the spacecraft's orbit to GEO within a day. Today, it is standard practice to use an electric thruster on the spacecraft, which produces very low but extremely efficient thrust, circularizing the orbit over a period of 6 to 12 months. During this time, the spacecraft owners lose revenues in the hundreds of millions of US dollars. (This preferance indicates how expensive it is to launch an upper stage.) For asteroid mining to be commercially profitable, it needs to provide fast circularization from GTO to GEO for a price less than these lost revenues. This requires spacecraft to mine the water from asteroids, an in-space depot to store the water and convert it upon need to rocket propellant through electrolysis, and a refuelable space tug. (If the space tug runs on thermal steam propulsion instead of chemical combustion then the depot can be simplified but more water will be expended per customer.) The business expenses will include deployment of this infrastructure, ongoing space operations, and finance costs appropriate to the level of risk. Several persons known to the author (including myself) have run these numbers using reasonable assumptions and have shown there is a potential to profit. Apparenntly Luxembourg's Economic Ministry agrees since it is investing heavily in asteroid mining. NASA may help establish this activity by developing the technologies, establishing an in-space depot, and/or giving contracts to purchase water to make Mars missions or other activities more affordable. The United Launch Alliance has also set a price they are willing to pay for water in space [11].

Business Case for Additional Activities: Once asteroid propellant mining is profitable, the marginal cost of extracting metals or other materials from asteroids will be low enough to make other in-space activities economic. One example is building giant antennas that are too large to launch, enabling the Internet's continued growth beyond the looming fiber optic capacity crunch [12]. These additional activities may benefit from lunar polar deposits, which possess carbon for making plastics and other materials. Another problem we must solve in this century is the energy crunch. The population is expected to grow to 11 billion by 2100, but sociologists believe the birthrate is stabilizing because all nations are becoming developed. This assumes that all nations will in fact become developed, which necessitates more energy from sources that have high energy return on investment (EROI) [13,14]. Proposals have been offered to solve world energy problems by collecting it in space and beaming by microwave to the surface [5]. Such concepts become increasingly economic as space industry expands so that larger fractions of the necessary infrastructure can be made in space. Metaanalysis of 133 computer models suggests by 2100 the world might easily require 4 times more than today's global energy supply [15]. With the EROI dropping and energy demands rising, the future energy sector may be as large as today's entire economy. If only this fraction of our future economy were put into space, it would tremendously benefit the ecosphere. The basic idea is that human civilization has grown so large that it pushes against planet-scale physical limits, and moving industry off-planet becomes increasingly vital to our planet's health.

Space Policy to Encourage Space Development: If spacefaring nations pursue a policy of space development, it will result in greater space science in addition to solving global challenges such as clean energy and global development. A lunar outpost could be focused on developing space mining and manufacturing while the same activities make the outpost more affordable, enabling concomitant lunar science. While astronauts can be replaced by robots for most sortie science missions – probably all of them sometime during this century – one thing robots cannot do is repair and develop other robots, so astronauts are absolutely vital for this effort. Time is of the essence to address global challenges, and human astronauts on the Moon will develop space industry faster than robots alone could do. This is arguably the most highly leveraged investment humanity could ever make. This will enhance the importance of astronautics in the public's view and create even greater support for space. Thus, science can help the globe, perpetually greater science will be the result, and the citizenry will strongly support it. In summary, planetary science is about to enter its golden age precisely because it is becoming crucial to the health of our civilization and of our planet.

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PLANETARY SCIENCE WITH NEXT GENERATION LARGE ASTROPHYSICS MISSIONS. S.N. Milam[1] and H.B. Hammel[2], [1]NASA Goddard Space Flight Center, Astrochemistry Laboratory, 8800 Greenbelt Rd, Greenbelt, MD 20771, stefanie.n.milam@nasa.gov, [2]AURA, 1331 Pennsylvania Avenue NW, Suite 1475, Washington, DC 20004.

Introduction: Next generation airborne and space-based telescopes and instrumentation will work in concert with future *in situ* robotic crafts and large ground-based facilities to address key questions of chemical complexity, origin of life or biomolecules, and molecular inheritance throughout star and planet formation, to our own solar system. The Herschel Space Observatory, Hubble Space Telescope, Spitzer Space Telescope, and Kuiper Airborne Observatory have advanced research on virtually every topic in astrophysics and planetary science.

Future large telescopes offer unprecedented sensitivity and spatial resolution at wavelengths that are inaccessible from the ground due to the Earth's atmosphere, and provide global context for *in situ* missions. Their spectral regions host a number of significant molecular lines including: CO_2, H_2, NH_3, etc. For more complex species, disentangling the various molecular formation (and destruction) mechanisms, and therewith the origin of the chemical complexity observed in the interstellar medium and our Solar System, requires a multiwavelength approach to observe all molecular phases. Additionally, they provide broader perspectives in both targets and timelines for planetary missions that orbit, land, or fly-by a given target. Space observatories are not constrained to a specific target, and provide global context as well as source to source comparisons that are not always achieved from directed missions.

JWST: The James Webb Space Telescope (JWST) is an infrared-optimized observatory with a 6.5m-diameter segmented primary mirror and instrumentation that provides wavelength coverage of 0.6-28.5 microns, sensitivity 10X to 100X greater than previous or current facilities, and high angular resolution (0.07 arcsec at 2 microns) and low-moderate spectral resolution (R~100-3000) [1,2]. It offers multiple capabilities through 4 science instruments including: imaging, spectroscopy (slit, IFU, grism/prism), coronography, and aperture mask interferometry. JWST can observe all planets (Mars and beyond) in our solar system as well as Near-Earth Asteroids, Main Belt Asteroids, minor planets, comets, satellites, as well as Trans-Neptunian Objects (TNOs). JWST is currently on schedule to launch in October of 2018 and will operate 5+ years after commissioning. This mission is timely for follow-up studies from Cassini and New Horizons and also provides unique timeline observations for the Galilean system prior to Juice, a Europa mission, etc.

SOFIA: The Stratospheric Observatory for Infrared Astronomy (SOFIA) provides imaging and spectroscopic capabilities at wavelengths from 0.3-1600 microns, operating at 37,000+ ft, which is above 95% of atmospheric water vapor [3]. The observatory offers capabilities that include photometric, spectroscopic, and polarimetric observations. SOFIA provides access to the far-infrared as well as high spectral resolution that current space-based facilities do not offer. The observatory is accessible, so regular upgrades to instrumentation can be made as needed. SOFIA is a unique facility that can observe a number of targets throughout the solar system (including Venus) that cannot be observed with other space telescopes. This facility can manipulate its flight plan to optimize occultation observations of satellites, TNOs, etc allowing for a perspective not always available with other observatories or missions. It also has a long lifetime that will allow for complementary studies with future planetary missions.

WFIRST: NASA's Wide Field Infrared Survey Telescope (WFIRST) is NASA's next flagship mission after JWST. WFIRST is on track for a 2025 launch with a 6 year primary mission. This mission has two primary instruments: the Wide Field Instrument (WFI) with a 0.25 deg^2 FOV and the Coronagraph Instrument (CGI) which is designed to take images and spectra of super-Earths. Between the two instruments, WFIRST will be capable of imaging and grism spectroscopy over the wavelength range 0.7-2 micron as well as R~100 spectroscopy with an IFU [4]. WFIRST will therefore be able to facilitate an array of small body science spanning surface mineralogy of asteroids and spectroscopic studies of comets to wide area surveys encompassing the more distant bodies in the solar system, including TNO populations.

Beyond: NASA's Astrophysics division has requested four new mission concept studies to be provided for the next Astrophysics Decadal survey to follow JWST and WFIRST. These include: the Far Infrared Surveyor (now the Origins Space Telescope or OST) [5], the Large UV-Optical-IR telescope (LUVOIR) [6], the X-ray Surveyor, and an Exoplanet mission (HabEx). These studies are currently underway and will be completed by early 2018. Two of these studies are strongly considering planetary science cases in constraining the design and instrumentation – OST and LUVOIR.

On-Orbit Assembly of Large Telescopes: Looking forward to the next astrophysics generation beyond LUVOIR or OST is likely to include even larger space observatories, 25m class, that consider new innovations to assemble large mirrors and components remotely [7]. This concept builds off of heritage from JWST deployment, segments, and testing as well as servicing to Hubble and the International Space Station. Notionally, a large mirror would be segmented and modular, such that current test facilities could be used for each component. The scientific implications for 25m class space telescopes reach beyond our most imaginative expectations. With extreme sensitivity and resolution, detailed studies of habitable worlds could be readily achieved. Additionally, the capabilities within the solar system will include ground-truths of *in situ* measurements on much broader scales. For example, to date, the Rosetta spacecraft has identified a number of complex, prebiotic species through mass spectroscopy on comet 67P/Churyumov–Gerasimenko [8], that cannot be measured remotely due to low abundances and limitations in sensitivity from the ground. Large space observatories will help reveal trace species in comets, as well as other solar system bodies with unprecedented new sensitivities and capabilities. Additionally, this can be achieved for not one target, but numbers of targets to probe the true nature and composition of primitive bodies in the solar system. 25m class facilities can also offer context for Mars and Jupiter in situ measurements and even probe the composition of ocean worlds as revealed through minor atmospheric constituents, geysers, or volcanos.

Summary: NASA's Great Observatories have provided both astronomers and planetary scientists unique imaging and spectroscopic capabilities for many years. Solar System observations have typically been some of the most widely known to the community and the public. Current and new missions are now recognizing the significance in incorporating planetary science as a major role in the design, instrumentation, and operations that will reveal unprecedented science for solar system bodies. The far future astrophysics missions with on-orbit assembly for even larger space based facilities will be even more revealing and provide remote-sensing capabilities comparable to current *in situ* state-of-the-art instruments.

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The Challenge for 2050: Cohesive Analysis of More Than One Hundred Years of Planetary Data.

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Introduction

The year 2050 will mark 106 years since humans opened the door to space and to the Solar System. In 1944, *MW 18014*, a German V-2 rocket was vertically launched and became—with an apoapsis of 176-kilometers—the first human-made object to reach space. Near-space and just beyond continued to be explored over the next decade and a half. In 1957, of course, Sputnik 1 became the first artificial object to achieve Earth orbit [1]. Robotic exploration of the Solar System began when *Luna 1* was launched from Tyuratam, U.S.S.R. on January 2 1959. Its intended scientific goals included measurements of interplanetary gases, corpuscular radiation of the Sun, and magnetic fields of both Earth and the Moon. *Luna 1's* instrument suite included a magnetometer, geiger counter, scintillation counter, micrometeorite detector and other instruments. *Luna 1* discovered the solar wind and that the Moon has no magnetic field [1].

Now, 58 years after our first step into interplanetary space, human-built, robotic exploration of the Solar System has expanded to visit every planet, dwarf planets, and several small Solar System bodies. We have repeatedly sent spacecraft to the Moon and to Mars. The robotic explorers *Pioneers 10* and *11*, *Voyagers 1* and *2*, *Galileo*, and most recently *Juno* have visited Jupiter. Saturn, too, has been visited by multiple spacecraft, most recently the incomparable *Cassini* mission. We have sent flyby missions and followed up with orbital missions to Mercury, Venus, the Moon, and Mars. We have landed and operated robots on the surface of the Moon, Venus, Mars, Titan, comets, and asteroids. We have commanded robots (or will shortly command, in the case of Cassini) to enter the atmospheres of the two largest planetary bodies in our Solar System [1].

Over these 58 years of Solar System exploration, there have been more than two hundred launch attempts of crewed and robotic spacecraft intended to Explore the Solar System beyond Earth. There have been 63 fully-successful and currently-operational missions to the Moon and 22 to Mars [1] (Fig. 1).

Each of these missions has returned or is continuing to return increasingly large volumes of scientifically valuable data from increasingly complex and innovative instruments. The challenge we face today, is how to combine scientific data from earlier missions gathered with older technologies with new data from new kinds of instruments on new spacecraft. This challenge is expected to become even more formidable as more data from new instruments on new spacecraft accumulate over the next 33 years.

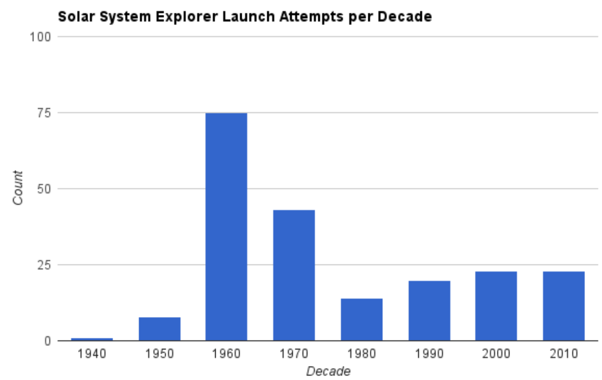

Figure 1: *Plot of the attempted and successful launches of spacecraft used to explore the Solar System. The large number of attempts in the 1960s is probably an artifact of the Space Race between the U.S.A. and U.S.S.R. Plot generated from data compiled from NASA mission websites and timelines.*

Analysis of Large, Multi-Instrument, Multi-Spacecraft, and Temporally-Disjointed Data Sets

By 2050, we will have accumulated nearly one hundred years of spacecraft observations of the Solar System. Many of the data acquisition techniques we are developing today will, by then, be standard operations. New techniques we haven't considered will be pushing the boundaries of what we only dream to be possible today.

Laser ranging provides one illustrative example. This form of remote sensing was first applied to planetary studies in 1969 with the Laser Ranging Retroreflector Experiment on Apollo [2, 3]. Since then steadily more sophisticated laser altimeters and LiDAR devices have been utilized on planetary missions. However, even nearly five decades since the first use of this technology, techniques for combining laser altimetry with stereo-imaging-derived topography are still lacking in planetary science. Such methods are only now being developed and tested for robustness and accuracy on the

Earth and there will be significant challenges to applying these methods to the sparser data available from planetary missions. This lag between the development of a new observational technology and the ability to integrate the new observations with other data sets is likely to be a continuing significant issue as we move toward smaller, more science-question-specific instrumentation. We can work today to limit this lag by planning and developing data fusion and analysis tools and techniques alongside the development of new instrumentation and before and during the planning of spacecraft missions. By 2050 we also expect planetary missions to be using new techniques to probe below the surface that we do not use (much) now. One critical difference will be the ability to look in five dimensions (x,y,z,t, and wavelength) as opposed to two or three today. Being able to work in five dimensions will require fundamentally new tools. Additionally, combining data from fundamentally different data types will be critical. One possible example is the combination of seismograms, sounding radar, Laser Induced Breakdown Spectroscopy (LIBS) spectra, drill core data, and a fifty-plus-year time-series from visible to thermal IR imaging to study the Martian surface.

One key result of recent missions is that even bodies we considered as frozen relicts of the early solar system have ongoing active processes. Past and current missions have revealed surface changes such as slope processes and dune movement on Mars, volcanic eruptions on Io, rainfall-induced (and other) changes on Titan, and new impact craters on the Moon and Mars, as well as weather on Mars, Titan, Venus, and the giant planets. Future missions with higher-spatial- and -temporal-resolution and/or a longer time baseline will improve on these records and could detect additional types of change, such as active volcanic flows on Venus, additional changes on Titan, or plume deposits on various icy worlds. As we accumulate longer records of higher-spatial-resolution data, we will be able to measure the effects of these changes and understand their causes, unlocking the diverse processes active today. We suggest that many of the key scientific breakthroughs in 2050 will focus on understanding these active processes or require a thorough understanding of the ongoing processes in order to extract information about the deeper past. These prospects point to some essential efforts needed to prepare for planetary science in 2050. First, we must develop the tools to co-analyze highly disparate data. Second, we must maintain existing data to ensure that it can effectively be combined with new observations within those tools.

We must maintain existing data in such a manner as to ensure that it can effectively be combined with future observations.

The new tools must go beyond simply overlaying diverse data in a display (though even this is a challenge given the five or more dimensions to the data collections). These tools must call the attention of the researcher to the key quantities that are significant for better understanding specific processes at a specific location. Highlighting areas that have changed with time is a simple example of this concept. Another key characteristic of the new tools is that they must promote and support collaboration between a number of specialists because no one person will be able to know the intricacies of all the disparate data sets. While current research into techniques such as data mining and remote collaborations will undoubtedly be useful, it is important to focus on the role of the human brain in recognizing and solving novel scientific problem. Some aspects of this include (1) automating rote processes that numb the brain, (2) providing statistically robust assistance in distinguishing real anomalies from noise, and (3) presentation of data in physically meaningful units with uncertainties that can be readily perceived. For example, searching for temporal changes will require better tools to automatically process and compare data. For visual imagery, this requires separating the effects of real surface changes from those due to different lighting and viewing geometry as well as camera characteristics such as resolution and signal-to-noise ratio.

As importantly as having scientific tools to combine new data types, we must also maintain the utility of old data. For example, science is still being accomplished using *Mariner 10* data from its flyby of Mercury in 1973. These data have been reanalyzed in light of new data from the MESSENGER mission [4]. *Viking* data from Mars are being combined with recent observations to understand eolian changes [5]. And our modern data sets, too, will be considered "old data" by 2050, but will still have great potential to advance science.

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EXTRAVEHICULAR ACTIVITY (EVA) AND MISSION SUPPORT CENTER (MSC) DESIGN ELEMENTS FOR FUTURE HUMAN SCIENTIFIC EXPLORATION OF OUR SOLAR SYSTEM. M. J. Miller[1], A. F. J. Abercromby[2], S. Chappell[2], K. Beaton[2], S. Kobs Nawotniak[3], A. L. Brady[4], W. B. Garry[5] and D. S. S. Lim[6,7]. [1]Department of Aerospace Engineering, 270 Ferst Dr, Georgia Institute of Technology, Atlanta, GA 30313, matthew.j.miller-1@nasa.gov; [2]NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058; [3]Department of Geosciences, Idaho State University, 921 S. 8th Ave, M-S 8072, Pocatello, ID 83209; [4]McMaster University, 1280 Main Street West, Hamilton, Ontario, Canada; [5]NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD, 20771; [6]Bay Area Environmental Research Institute, 625 2nd St Ste. 209, Petaluma, CA 94952; [7]NASA Ames Research Center, Moffett Field, CA 94035, Darlene.lim@nasa.gov

Introduction: NASA's Journey to Mars outlines a vision that includes sending humans to an asteroid by 2025 and to Mars in the 2030s. While it is expected that most of the design elements for prospective capabilities and operational concepts will focus on issues concerning astronaut safety and planetary protection, we also envision mission architectures that are strongly driven by scientific requirements that fully leverage the presence of human assets in deep space.

While the development of operational concepts and capabilities needed to send humans to Mars is underway [1]-[3], high-fidelity testing is still required to identify which concepts of operations (ConOps) and capabilities enable high-value scientific return under the operational constraints of working on Mars. One critical consideration in designing for human-robotic missions to Mars is the unavoidable communication delays that will occur between Mars and Earth. Latencies ranging from 4-22 minutes one-way light time are expected. No longer will ground personnel be able to support astronauts as they execute tasks or troubleshoot disturbances through immediate, or realtime, communications. Thus, we must examine how human spaceflight could be successful under communication latency, where crew will operate while managing asynchronous Mission Support Center (MSC) inputs.

Extra-Vehicular Activity (EVA) Design Elements: EVA is defined as "any space operation or activity performed outside the protective environment of a spacecraft therefore requiring supplemental or independent life support equipment for the astronaut [4, p. 5]." EVAs will likely be a primary mechanism for human scientific exploration within future missions. However, EVA experiences to-date have been devoted to maintenance, installation, and construction of engineered hardware – e.g. satellites and the International Space Station (ISS) [5] – and involve large contingents of ground-based support personnel [6], [7]. Few EVAs dedicated to scientific exploration have ever been performed with the exception of those that occurred during the Apollo program, where on the lunar surface communication latencies were ~1 second.

How then will we have to evolve EVAs to enable flexibility that supports scientific exploration? Exploration involves peering into the unknown and reacting to the observed. The quest for scientific discovery is an iterative and ceaseless process, as answers to research questions reveal more refined and sometimes unexpected research questions. In stark contrast, current EVA execution is highly scripted, with procedures arranged as a prioritized set of tasks, configured to maximize the likelihood of accomplishing the *a priori* set of task objectives while maintaining crew safety. Flexibility in the context of EVA execution is typically minimized because this can lead to unpredictability, which can potentially jeopardize both crew safety and the successful completion of EVA objectives. As experienced during Apollo, the operational constraints greatly shaped what was feasible to perform during EVA. Out of the 44 planned stations to be explored during Apollo, only 30 were successfully reached. Fourteen stations were forced to be dropped from the plans, mainly due to time constraints [8]. As a whole, scientific exploration and exploratory processes have served as a secondary objective on human spaceflight missions [9]. Therefore, for future missions, there is a need to better understand how we can merge EVA operations concepts with the established purpose of performing scientific exploration.

Mission Support Center (MSC) Design Elements: Deep-space operations impose a fundamental limitation on how controllable astronauts' actions are from Earth. For the past 50 years, the Mission Control Center located at Johnson Space Center has served as the central nervous system of human spaceflight, controlling and influencing all crew activities. However, for any dynamics that occur more quickly than the time it takes to complete one round-trip communication between crew and Earth, the astronauts will by default need to control their own situations, devoid of immediate input from support personnel. Sustained human presence in deep space will necessitate a profound shift in the way mission operations is conducted. We define here the concept of an MSC as a first step towards realizing this shift in operations from a control oriented focus to one that supports crew activities, leaving more authority and responsibility for the crew to make their own decisions.

The MSC concept has been recently explored in a number of analog field deployments: BASALT (Biologic Analog Science Associated with Lava Terrains) 1 & 2 and NEEMO (NASA Extreme Environment Mission Operations) 20 & 21. The MSC focus to-date has emphasized enabling the exchange of scientific expertise and preferences between Earth and crew *during* EVA operations. Crew will undoubtedly be well trained in future missions, however, they will unlikely be the experts in the multitude of scientific fields planned for future missions. In addition, these scientific disciplines will likely require a breadth of science teams, all competing for their scientific objectives to be prioritized and satisfied. The management and organization of these scientific teams will need careful thought and consideration, especially when we deal with human-scale operations. Even with the time-delay constraint, the pace of scientific EVA operations will be much greater than ever before. To-date, Martian robotic operations conduct operations on the time-scales of 24 hours to direct robotic actions. Human EVA operations will be much more dynamic, thereby necessitating a quicker turn-around capability for scientists to receive, synthesize, discuss, and formulate opinions within the MSC. If humans are to be leveraged in scientific exploration, they must be supported to achieve the highest-possible scientific return and the MSC will play a key role in providing that support.

Science-driven ConOps and Capabilities Development through analog studies: Conducting real (non-simulated) field science under simulated deep space and Mars mission conditions will directly address knowledge gaps associated with the design and development of architectures that enable scientific return, exploration and discovery under the variable communication latencies. Through these efforts we can identify the Concepts of Operations (ConOps) (defined as operational design elements that guide the organization and flow of hardware, personnel, communications, and data products through the course of a mission implementation) and supporting capabilities (functionalities that can take the form of hardware or software) that will balance operational constraints with scientific return, and manage decision-making conditions that involve astronaut crew members and MSC personnel who will be separated by both physical (space, time) and experiential factors.

BASALT, PLRP (Pavilion Lake Research Project) and NEEMO analog research programs conduct non-simulated field science under simulated planetary mission conditions. These programs are low risk, high-impact opportunities to help identify ConOps and capabilities requirements for enabling efficient and effective traverse planning and re-planning, crew scheduling, *in situ* instrument development for sample high-grading, among many other elements. However, these missions are only scratching the surface in terms of inter-disciplinary opportunities that could integrate terrestrial field science and operations/exploration research to design human missions that enable scientific return and discovery. As an example, the Ocean Exploration community has well-honed scientific operational expertise that could provide a high-fidelity analog to deep space operations. Capturing best practices associated with these and other communities will enable NASA to efficiently build a library of ops concepts and capabilities that can then be used to evolve current mission design elements related to human scientific exploration of our Solar System.

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FORMATION OF RECYCLE FLUID WATER ON ANY SPACE SURFACE AS SUPPOTS OF LIFE.

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Introduction: Water and air on Earth-type planets of the Solar System has been discussed by *molecular existences* of global water and air based on facts of water- and air-planet of Earth, because "huge database of active planet Earth" accumulated precisely by human activity is considered to be applied easily to other Earth-type planets [1-3]. The main purpose of the paper is to elucidate new model of water volatiles of extraterrestrial planets and satellites compared with separated water and air molecules on Earth [3-6].

Characteristics of three shock-wave events: Shock-wave processes of meteoritic impact, earthquake and volcano are produced at high velocity over sound speed at high pressure and temperature (Fig. 1). The related activity of earthquake and volcano produced on the crustal rocky ground is used to be short duration (Table 1). On the other hand, activity of meteoritic impacts on the crustal rocks in the sky can be observed as first detection in air to be changed the orbits with human's defense strategy (Table 1) [1, 6].

	Mercury	Venus	Earth	The Moon	Mars	Asteroids
Size	Medium	Large	Large	Medium small	Medium	Small
Density	High	Higher	Highest	Lower	Medium	Lower
Materials	Rock	Air, Rock	Air, Water, Rock	Rock	Air, Rock	Rock
Water Molecules	Local?	Local? Air (minor)	Global, Local	Local?	Local? Air(minor)	Local?

Fig. 1. The size, density, materials and water volatiles of four Earth-type planets, the Moon and Asteroids. Earth shows global systems of three materials with global and local waters. Venus and Mars show two water-materials of H and O ions without global water system, but possible water ions on the rocks [3, 6].

Water-related ions and volatiles of planets: Materials are classified as rock (solids), air (gas) and water (liquid), where water-planet of Earth has all three materials globally in cyclic system [1]. Venus planet has global air and rocks as in Mars (Fig.1). Although global water molecules (or water ions) have been obtained only water planet of Earth, however local water molecular *ions* with smaller amount might be stored in all solid rocks of other planets (Mercury), the Moon and Asteroids, as shown in Fig.1 [3-6].

Global systems of the Earth-type planets: Earth-type planets have all solid rocks in global cyclic systems, where "*global and cyclic* materials" are used for cyclic system of rock (solids), air (gas) and *water* (liquid) on the surface to shallow interior. However, other global systems of air and water volatiles with light elements are completely different with the water-planet of Earth changed continuously and dynamically. The airless and waterless planets at the primordial period of the Solar System which are main images of the present planets (except water-Earth), show all solidified rocks which might have contained volatile elements and ions (including *fluid water* molecules) during the collision processes of the celestial bodies, where the main process mixed volatiles and heavy elements in the rocks should be explained by "local fluid water molecular ions related with irregular impact-related distribution". Figure 2 shows global distribution of three materials (air, water and rock) on Earth, whereas other planets of Venus and Mars have only two global materials (air and rock) without *global water* molecules [3-6].

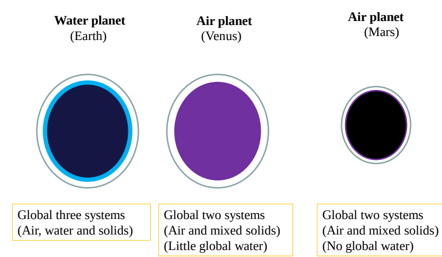

Fig.2. Schematic diagrams of global three systems of air-water-rocks (Earth) and two systems of air-rocks (Venus and Mars) [3, 6].

Local and global waters of planets: Local fluid water ions have been mixed with solid rocks from the primordial to present situations of each planet without global ocean system. However global water system on planet Earth is difficult to explain simply the huge amounts of *water* (H_2O) and stable location between air and rock systems based on only one planet, which might be required by huge planetary collision process to produce fluid water by dynamic exchanges of three global materials (Fig.3). Therefore, it is proposed herewith for formation of global water system to be mixed with interior water and carbon dioxides ions of two planetary supplies by rapid process which are called by "giant-like impact process" on the primordial Earth planet to be remained fluid water molecules between the air volatiles and the solid rocks with moderate temperature and gravity (Fig.3) [3-6].

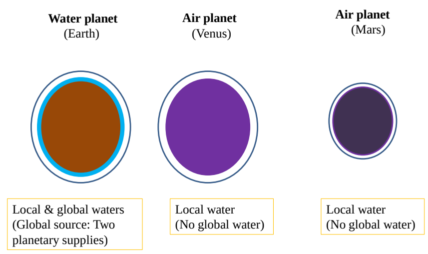

Fig.3. Schematic diagrams of global and local fluid water on three planets [3, 6].

Characteristics of atmosphere formation: Global atmospheric gas of planets should be continued to be erupted from the interior of the planets mainly with temperature and the gravity effects. Venus and Mars with volcanoes (non-Earth-type) along the equators followed with the planetary rotations have been released partly volatile molecules of carbon dioxides and water ions previously [3-6].

Characteristics of global ocean-water system: The presence of ocean-water of Earth planet has been applied for the evidence of past-global ocean water because of volatile ions in the interior deposits. However, the phase diagrams of the fluid (water and carbon dioxide) indicate that liquid phase can be stable only by sandwiched with solid and air phases [3-6]. Therefore, global ocean water system might be formed for global air system of any planets (Venus and Mars) from local interior resources of the fluids, though it is difficult supply continuously from local fluid ions enough for global ocean-water system.

Possible processes for changes in air composition: Primordial planet's atmosphere shows bulk composition with much carbon dioxide gas (than water ions or so) due to more stable at high temperature and pressure conditions generally. In short, it's significant challenge of changed atmospheric composition for future habitable planet on Venus or Mars. In fact, colder carbon dioxides on Martian air are generally possible relatively by probable process of the melting and solidification. On the other hand, hot carbon dioxides (on Venus) are generally difficult to be changed locally and globally. It might be possible to apply any natural collisions and our artificial method to change *hot carbon dioxides gas* solidified [3, 6] on the surface (to shallow interior) for global system in any planets (with compact machine) [1-6].

The possible formation of water system: Volatile systems of air and water separated from global volatiles-bearing solid rocks produce planets of clear rocks with higher density as in Earth and Venus. In short, there are two dynamic methods to form globally water system on Venus and Mars of "step-by-step method", and "rapid evaporation to cooling method". The present study suggests that it should be not impossible to form *global water* system by any impact-collisions and recent manmade methods [7].

Formation of fluid from primordial rocks: Pure water molecules can be produced from cooled vapor gas, but mixed fluid water (with mixed ions from primordial rocks) might be formed by our method by heating primordial rocks with volatiles ions [7]. The result might be applied for compact water-CO_2 gas production way from primordial rocks at 2050 space exploration to support astronauts and human activity on any extraterrestrial surfaces.

Summary: The present study can be summarized as follows:
1) Three materials of global rock, air and water can be found in the inner Solar System, though ocean-water system can be obtained mainly water- and air-planet of our Earth produced by planetary collisions of planets. 2) Formation of global air and/or global ocean water systems for waterless planets of Venus and Mars might be possible by planetary collisions, interior volatiles uplift process (by the planetary tidal rotation) and effective rock-fluid water exchange methods. 3) Larger air-planets of Venus and Mars have global air with higher pressure of water planets by natural impact processes and manmade method of heated volatile-bearing rocks widely. 4) Global changes of colder air (Mars) and hotter air (Venus) are possibly changed to global ocean-water systems by global processes of planetary collisions in future, together with manmde heated rock-fluid method widely. 5) The present result can be applied for compact water-CO_2 gas exchange method from any primordial rocks at next 2050 space exploration to support astronauts and human life activity on any extraterrestrial surfaces.

Acknowledgements: Authors thank to all scientists for discussing present study.

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THREAT OF HUMAN EARTH AND NATURAL RESOURCE SUPPLY BY ASTEROID IMPACTS.

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Introduction: Our planet Earth is very active water planet formed about 4.6 billion years ago, by revealing continuous activities with the biggest changes in the our solar system. Our intelligent human beings can observe major shock-wave phenomena of meteoritic impacts, earthquakes and volcanic eruptions by surface ground changes mainly after the shock- wave processes. However, we cannot stop any natural shock- wave events of earthquake, volcano and meteoritic impact by artificial methods on the terrestrial surface, because they are natural continuous processes of their changes beyond human recognition generally. These huge disaster reduction and mitigation depend largely on the intellectual supports for the leaders of each country on our Earth. In this study, it proposes basically new possible features of less hazards against the asteroid impacts on our Earth with tsunami for our risk strategy in human society and Earth's damages, and its contribution of Earth's natural resources by concentration to our human society [1-6].

Characteristics of three shock-wave phenomena: Shock-wave processes of meteoritic impact, earthquake and volcano are produced at high velocity over sound speed at high pressure and temperature (Fig. 1). The related activity of earth- quake and volcano produced on the crustal rocky ground is used to be short duration (Table 1). On the other hand, activity of meteoritic impacts on the crustal rocks in the sky can be observed as first detection in the sky to be changed the orbits with intelligent strategy (Table 1) [1, 6].

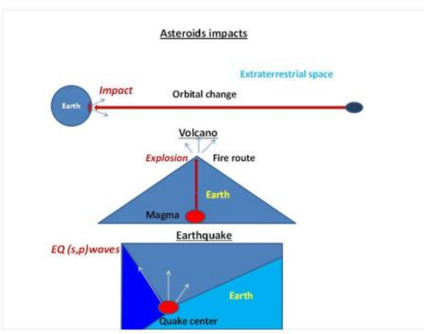

Fig. 1. Shock-wave processes of meteoritic impact (with tsunami), earthquake and volcano [1, 6].

Characteristics of asteroid collision: Asteroid collision with tsunami events to continuous changes of our Earth planet are general collision evolutions in the global solar system. In short, we should observe asteroid and meteorites from terrestrial stations and extra-terrestrial sites to be changes the orbits artificially as shown in Fig.2 and Table 2 [1, 4, 6].

Table 1. Characteristics of shock-wave processes.

Shock wave	Location and any detection
Earthquake, volcano	Detection on crustal ground, from.. the interior source without stops.
Asteroid collisions	Activity from sky to Earth after the entry. Plan of stop before the entry.

Table 2. Two detections of asteroids to Earth planet.

Observed site	Detection site and roles
Terrestrial site	Main observation from Earth, together with the Space Station.
Extra-terrestrial	Observation and change the orbits of the Asteroid before Earth entry.

Earth with human disasters by the collisions: Macroscopic cycles of Earth planet from formation and broken process include microscopic cycles of life (including human being) from birth and death process. Therefore death process of life organism should be replaced to the next generation or new species as continued movements, which are the same process of younger Earth planet without primordial rocks. In this sense, we should make less damages by the best protection methods against any shock-wave processes of asteroids collision with tsunami, earthquake and volcano (Table 3) [5, 6].

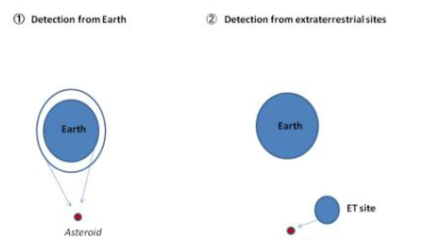

Fig. 2. Detection and changes the orbits of asteroids to our Earth planet [1, 6].

Effective strategy against asteroid collision: Earth planet has very strong power to be kept and continued planetary activity against any shock-wave damages as seen the geological history [2-4], which we can check it by younger aged rocks and remnants on the surface. However, human life should think and invent more effective circumstances for the next generation and replaced new species (Table 4) [5, 6].

Table 3. Two types of Earth and life cycles

Type	Recycle process
Earth	Change from old (primordial) to younger (broken) rocks.
Life	Changer from birth (high molecules) to death (static inorganic molecules)

Effective strategy against asteroid collision: Earth planet has very strong power to be kept and continued planetary activity against any shock-wave damages as seen previous geological history [2-4], which we can check it by younger aged rocks and remnants on the surface. On the other hand, human life should think and invent more effective circumstances for the next generation and replaced new species finally (Table 4) [5, 6].

Table 4. Effective strategy of Earth and life

Objects	Strategy to be survived
Earth planet	Less damage to Earth rocks by two filters of air and ocean water.
Life (human)	Life species to be lived more longer to next generation step.

Highest ocean impact energy among three types: Active planet of Earth body has multiple global energy characteristics of Earth-type shock waves [1]; that is, surface volcano and interior earthquake and extraterrestrial shock waves of collisions by asteroid, meteorite or comet (Fig. 3). Ocean impact energy shows the highest energy on Earth-type shocked energy [7]. On the other hands, surface eruption of volcano can be observed on all celestial bodies, because volatiles in the deeper interior are pulled to surface by gravitational forces among main celestial activities [1,7]. In fact, typical surface energy of "volcano" is observed globally by interior driving forces of the "water-Earth-type" planet, and locally by any tidal forces of "Venus-type" of Mars, Io and Venus etc. relatively [7].

Summary: The present study can summarized as follows [5, 6].

1) Shock-wave processes on Earth planet are meteoritic impact, earthquake and volcano, where activity of meteoritic impacts above the crustal rocks can be observed as first detection in the sky to be changed the orbits.

2) Asteroid collisions with tsunami events to continuous changes of our Earth planet are general collision evolution in the global solar system, which .can be observed asteroid and meteorites from terrestrial stations and extraterrestrial sites to be changed the orbits artificially.

3) Macroscopic cycles of Earth planet from formation and broken process with tsunami events include microscopic recycles of human life from birth and death process, where death process of life organism should be replaced to the next generation or new species as continued movements as in the water-planet Earth.

4) Earth planet with global ocean shows continued planetary activity against any shock-wave damages and planetary way, where human life should make more effective circumstances for the next generation and replaced new species finally.

5) Earth planet has the highest surface energy of asteroid impacts through global ocean with followed volcanic event, which are triggered to be elemental concentration to be formed various metallic and nonmetallic ore resources for human society's application. This is considered to be space resources on planetary bodies.

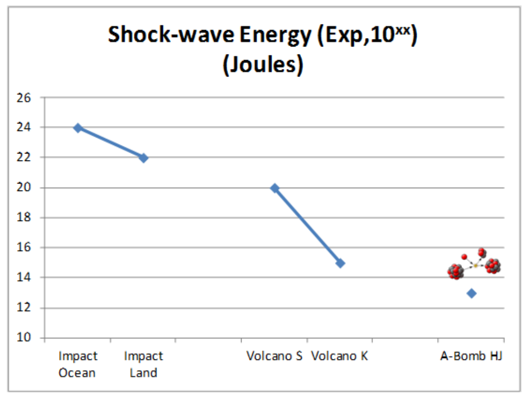

Fig. 3. Earth-type shock energy compared with impact (ocean and land), volcano (sea-coast S and land K) and atomic bomb (Hiroshima, Japan as standard one).Ocean impact energy shows the highest energy on Earth, which are triggered to be main causes of elemental change and concentrations to be formed as natural resource of active planet Earth, together with "space resources". [5].

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Cryogenic Propulsion Systems for Planetary Science Missions. S. Mustafi[1], L. Purves[2], W. Willis[3], C. A. Nixon[4]
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Abstract: Liquid hydrogen (LH2) and liquid oxygen (LO2) cryogenic propellants can dramatically enhance NASA's ability to explore the solar system due to their superior specific impulse capability. Although these cryogenic propellants can be challenging to manage and store, they allow significant mass advantages over traditional hypergolic propulsion systems and are therefore enabling for many planetary science missions. New cryogenic storage techniques such as subcooling and the use of advanced insulation and low thermal conductivity support structures will allow for passive long term storage and use of cryogenic propellants for solar system exploration and hence allow NASA to deliver more payload mass to targets of interest more quickly, launch on smaller and less expensive launch vehicles, or both. These new LH2 and LO2 cryogenic storage technologies and a notional design for a new small 890N LH2 and LO2 engine were implemented in a design study for the Titan Orbiter Polar Surveyor (TOPS) mission and the resulting spacecraft design was able to achieve a 43% launch mass reduction over a TOPS mission, that utilized a traditional hypergolic propulsion system with monomethyl hydrazine (MMH) and nitrogen tetroxide (NTO) propellants. This discussion describes the cryogenic propellant storage design for the TOPS mission and demonstrates how these cryogenic propellants are stored passively for a decade-long Titan mission that requires the cryogenics propellants to be stored for 8.5 years. This cryogenic propulsion system has the potential to significantly benefit any planetary science missions that require high ΔV maneuvers, specially to destinations where solar electric propulsion is challenging to use, such as the ice giants, Uranus and Neptune, that have been identified as targets in the decadal survey.

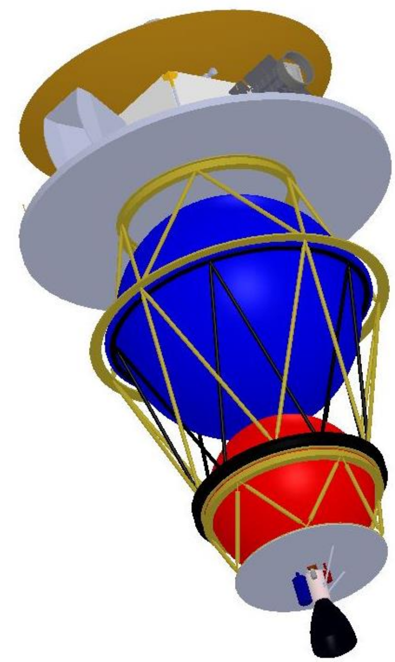

Figure 1: Titan Orbiter Polar Surveyor (TOPS)

HEAT FLOW MEASUREMENTS ON MOONS AND PLANETS FOR THE NEXT THREE DECADES. S. Nagihara[1] and K. Zacny[2], [1]Department of Geosciences, Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), [2]Honeybee Robotics, Pasadena, CA 91103(zacny@honeybeerobotics.com).

Introduction: Researchers have long recognized the importance of measuring the endogenic (internal) heat flow of the planetary bodies for understanding their origin and thermal evolution. It was more than 40 years ago, when the Apollo astronauts made heat flow measurements at two locations on the Moon [1]. Since then, no more heat flow measurement has been made on the Moon or any other extra-terrestrial body to this day. ESA's *Rosetta* mission had a heat flow probe on its lander, but it did not deploy successfully.

We see two reasons for the lack of progress in accumulating planetary heat flow data since the Apollo program. First, technologies necessary for enabling heat flow measurements on robotic missions had not been fully developed. Second, there have been relatively few landing missions, and heat flow and geophysical measurements were not their primary objective.

We believe that the recent technological advances [2] make it possible to collect high-quality heat flow data on small lander missions. NASA's *InSight* mission is expected to deploy a heat flow probe on Mars in 2018 [3]. In addition, the latest Decadal Survey [4] has recommended the Lunar Geophysical Network (LGN) mission, which will include a heat flow probe as payload, as one of the candidates for the New Frontiers program. Here we discuss the recent advances in planetary heat flow instrumentation and what we may be able to achieve in the next three decades.

Measurement Methodology and Instrumentation: A heat flow probe typically measures conductive heat flow. It can be deployed from a lander or a rover. The probe penetrates into the subsurface and makes two separate measurements: the thermal gradient and the thermal conductivity of the depth interval penetrated. Heat flow is then obtained as the product of these two measurements.

The thermal environment of the surface of most extra-terrestrial bodies is heavily influenced by the insolation. In order to sense the flow of the endogenic heat, the probe should penetrate below the so-called thermal skin depth, where temperature is unaffected by the insolation. The skin depth is a function of the period of the insolation cycles (e.g., diurnal, annual, etc.) and the thermal properties of the surface material (regolith, rock, ice, etc.). The surface materials' texture and composition influence the thermal properties. Therefore, skin depth varies among planetary bodies. For the Moon, a panel of scientists assembled by NASA has recommended 3 m as the target depth of penetration for heat flow measurements [5].

On Earth, rotary or percussive drilling is used to excavate a hole for heat flow probe deployment. The auger or drill pipe is extended until it reaches the desired depth. That is how the Apollo astronauts deployed their heat flow probe [1]. However, such an approach may not work on lander/rover missions mainly due to the limited space available and the complexity of extending the drill pipe, one section at a time.

For future robotic missions to the Moon, we recently developed a compact (shoebox-size), modular heat flow instrumentation that uses a pneumatic excavation system in deploying its probe [6]. In this system, thermal sensors are embedded on a flexible, glass fiber composite stem that spools out like a steel tape measure, as it penetrates deeper into the subsurface (Figs. 1-3). As the stem spools out, it forms a hollow cylinder of ~1.5-cm diameter to gain mechanical strength. When it touches down, it pushes a penetrating cone into the regolith. Simultaneously, Helium gas jets, emitted from the cone tip, blow away loosen material with 1:6000 excavation efficiency in the lunar vacuum (e.g., 1 g of gas capable of lofting 6000 g of regolith particles).

When the cone reaches a depth targeted for thermal measurements, it stops excavating. A short probe attached to the cone tip (Fig. 4) is pushed into undisturbed regolith at the bottom of the hole, and measures the temperature and the thermal conductivity. After that, the probe resumes excavation to the next target depth. By repeating this stop-and-go sequence, we obtain the thermal gradient and the thermal conductivity of the depth interval penetrated. When the probe reaches 3-m depth, the temperature sensors embedded on the fully extended stem monitor long-term stability of the thermal gradient.

The latest prototype of this heat flow probe (Fig. 3) was tested in compacted lunar regolith simulant, NU-LHT-2M, in vacuum and reached 2-m depth in 2 minutes. Its thermal conductivity probe (Fig. 4) has also been tested separately with the JSC-1A simulant in vacuum, and yielded sensitivity down to 0.001 W/mK [7].

Future Applications: This heat flow probe has been developed primarily for the use by the LGN mission [4]. By collecting data at multiple locations on the Moon, we will characterize the geographic variation of heat flow. That will allow us to better contrast the possible difference in subsurface Thorium abundance between the KREEP terrain and the surrounding areas [8], and more tightly constrain the bulk composition of the Moon [9].

The heat flow probe can also dual as a heat source for subliming volatiles in the subsurface. It can be a useful tool for resource prospecting on the Moon.

Another potential destination within the next few decades is Europa. NASA is already planning a lander mission there. Our heat flow instrumentation is a modular system and can be adapted for deployment on the icy satellites. By using a stronger material for the stem and a more robust excavation mechanism (e.g., heaters subliming the ice), it may be able to penetrate into the ice shell. Measurement of the endogenic heat flow on Europa will allow us to further understand the dynamics of the ice shell and the heat budget of the subsurface ocean.

Conclusions: With the recent technological advances, planetary science communities are well positioned for expanding the coverage of heat flow measurements on extra-terrestrial bodies, especially the Moon, in the next three decades.

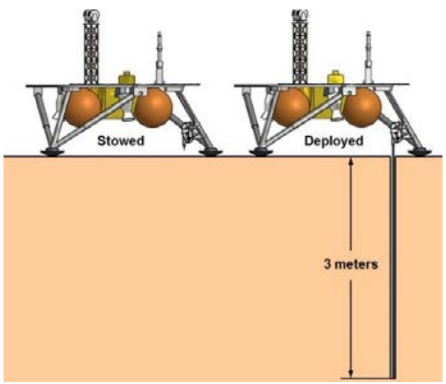

Figure 1: The heat flow probe attached to a leg of a lander in stowed (left) and deployed (right) configurations [6].

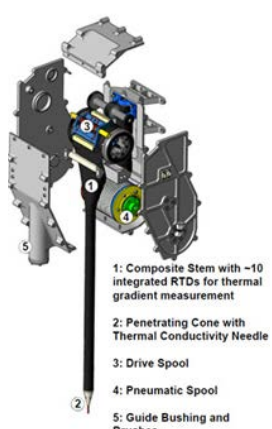

Figure 2: Schematic diagram showing the major components of the planetary heat flow probe [6].

Figure 3: A photograph of the latest prototype of the heat flow system in a stowed configuration.

Figure 4: A photograph of the prototype of the cone tip and thermal conductivity.

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SCIENCE AND EXPLORATION SYNERGIES - 2050. C. R. Neal[1], [1]Dept. Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (neal.1@nd.edu).

Introduction: The structure of NASA separates planetary science from exploration, with planetary science being located in the Planetary Science Division (PSD) of the Science Mission Directorate (SMD), and planetary exploration in the Human Exploration and Operations Mission Directorate (HEOMD). However, some current and missions in formulation are starting to blurr this separation. This presentation examines the possibilities for better integration of science and exploration between now and 2050 to maximize the return from planetary missions. As the Lunar Reconnaissance Orbiter Camera (LROC) motto states, which was the mantra of the late Mike Wargo, "*Scientia facultas Explorationis, Exploratio facultas Scientae*" or in poorly translated English vernacular "*Science facilitates Exploration, Exploration facilitates Science*".

Current Synergies: Science and exploration synergies are being pursued by the LRO and Mars 2020 missions. The LRO mission was born out of the Vision for Space Exploration during the Bush administration [1]. It was part of the then Exploration Systems Mission Directorate and was formulated to yield information to reduce risk for future human landings on the Moon [2]. The objectives/requirements definition team meeting for this mission represented the creation of the Lunar Exploration Analysis Group (LEAG) in 2004 at the LPI [3]. After launch on 18 June 2009 and 2 years of operation, this directed exploration mission transitioned to SMD-PSD and became a science mission. LRO has been and continues to be a highly successful mission and it is now in its third extended science mission that is producing excellent science (and exploration) data that informs us not only about the Moon, but processes relevant to other planetary bodies in the Solar System. The LRO mission is considered to be the archetypal example of exploration and science cooperation that NASA has flown to date.

Another example of science and exploration synergy is the Mars 2020 PSD sscience mission [4]. Here, two instruments are funded through HEOMD – the Mars OXygen ISRU Experiment (MOXIE) and the Mars Environmental Dynamics Analyzer (MEDA). Gathering information to facilitate human exploration of the current horizon destination, Mars, is a step along the path towards one day sending humans to the red planet. As with LRO, this mission will yield data that will inform both science and exploration.

Missed Opportunities? The two examples above are a great start to forging better synergies between science and exploration. However, there are a number of recent missed opportunities that highlight the need for better communication and integration between the two mission directorates. The first is the Korea Pathfinder Lunar Orbiter (KPLO), which is scheduled to launch in December 2018 [5]. The Advanced Exploration Systems (AES) division of HEOMD has facilitated NASA involvement in this mission [6], and proposals have been submitted from US investigators to place instruments on this orbiter. However, there is currently no official NASA science involvement in KPLO, although a participating scientist program has been promised.

With current US Space Policy focused on an asteroid as a near-term human exploration target, it is good to see SMD-PSD involvement in the Japanese Hyabusa-2 mission [7]. The recently launched New Frontiers-3 selection, OSIRIS-REx sample return science mission to the asteroid Bennu is repleat with significant scientific objectives and will return ≥60g of sample [8]. However, it is unclear if the exploration potential of either the Hyabusa-2 or OSIRIS-REx asteroid sample return missions have been explored by HEOMD from either an ISRU and/or risk-reduction perspective.

Developing Future Synergies: There are definite overlaps between planetary science and human space exploration for certain Solar System destinations, namely asteroids, the Moon, and Mars. There is now an oppoprtunity for long range planning so that science and exploration goals can be combined to produce more capable and effective missions (either competed or directed) than would be achieved by SMD-PSD or HEOMD alone. By blurring the lines between different mission directorates, any "turf war" could be defused, cooperation enhanced, and the NASA budget would be more effectively used. One option could be for a portion of the budget to be dedicated for science and exploration purposes. Such a budget could be used to facilitate competed missions the that would advance human exploration and planetary science. This budget would be administered by PSD and HEOMD personnel that are intimately involved in understanding the specific destination targets. Another avenue to facilitate inter-mission-directorate cooperation is to elevate all human destination targets to program status, similar to the current Mars Exploration Program that currently resides in PSD. The asteroid, lunar, and martian science and explortation programs would be jointly administered by SMD-PSD and HEOMD. Obviously these administrative changes would require a Planetary Science and Exploration budget, but the result would be increased science return as well as increased impetus toward human space exploration beyond LEO.

Example of Science and Exploration Synergy: Lunar surface volatiles represent a highly important science and exploration target. This example presented is one that I am familiar with, given my background, but there are other examples for asteroids and Mars. The presence of volatile deposits at the lunar poles has been unequivocally demonstrated by the LCROSS mission [9]. Volatiles are also present *within* the Moon, as shown by sample analyses of pyroclastic deposits (e.g., [10]) and also from orbital data (e.g., [11]). These deposits have implications for the delivery of volatiles to the terrestrial planets, lunar formation, and those at the poles may contain the building blocks of life. These aspects address several major questions in the NASA's current science plan [12]. The current decadal survey for SMD-PSD [13] indicates that lunar volatiles are an important science target to be addressed by future missions. The surface volatiles also represent potential resources that would enable human exploration through production of life support consumables as well as rocket fuel for either return journeys back to Earth or to enable deep space exploration. HEOMD actually has a mission in formulation to explore a polar region for volatiles with a rover [14]. The Resource Prospector Mission (RPM) will address several lunar Strategic Knowledge Gaps [15] in terms of polar volatiles. The problem is that RPM has minimal, although critical, cabability and the mission duration is only several days. If there was a campaign to explore lunar volatiles through a Lunar Science and Exploration Program, it is probable that more capable rovers would be available. Given the international missions to the Moon this century (China = 3, including one lander; India = 1; European Space Agency = 1; Japan = 1), international cooperation/collaboration with such a campaign is certainly an option. Russia has already unveiled a lunar polar campaign [16] through a series of missions that will be conducted in collaboration with the European Space Agency. SMD-PSD has initiated discussions on how US scientists can be involved with such missions. Given the resource-oriented nature of these polar missions, it would be advantageous for HEOMD to also be at the table for such discussions.

Vision 2050: Science and exploration synergies have the potential to advance us into the Solar System, through expansion of knowledge and literally by sending humans well beyond LEO. By having science and exploration work together, advances will be made much faster than at present. We are seeing the beginnings of such cooperation but it could be much more effective. This requires a modest rethinking of how missions to certain destinations are funded and operated. The synergies between science and exploration could be developed and enhanced by creating joint programs specific to targets of mutual interest – asteroids, the Moon, and Mars, as I noted above. However, by 2050 these initial programs could be brought together under a Science and Exploration Division or even a Mission Directorate. This entity would focus on long-term planning for integrating science with expanding the human race beyond the LEO and potentially beyond Mars. And let's not forget about the currently burgeoning space commerce sector. Involving this sector in the initial robotic precursor Science and Exploration missions could result in more significant public-private partnerships being developed in the future. This would be facilitated by the new division/mission directorate focused on science and exploration synergies. Once humans visit an asteroid or land on the Moon and Mars, they will be conducting scientific investigations as they explore these new worlds – just as the Apollo astronauts did all those decades ago. The necessary robotic precursor missions can do the same - *Scientia facultas Explorationis, Exploratio facultas Scientae*.

Summary: Better communication and collaboration between science and exploration will be mutually beneficial for planetary science and human exploration. Forging this relationship has begun, but this appears to be on a mission-by-mission basis. Long-range planning that involves SMD-PSD and HEOMD strategic partnerships have the potential to achieve so much more than they could alone. Illustrations of such partnerhips are presented here, but how they are implemented is up for discussion.

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A MULTI-DECADAL SAMPLE RETURN CAMPAIGN WILL ADVANCE LUNAR AND SOLAR SYSTEM SCIENCE AND EXPLORATION BY 2050. C. R. Neal[1], S. J. Lawrence[2], and the LEAG Executive Committee [1]Dept. Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (neal.1@nd.edu), [2]ARES, NASA-Johnson Space Center, Houston TX 77058, USA (samuel.j.lawrence@nasa.gov).

Introduction: There have been 11 missions to the Moon this century, 10 of which have been orbital, from 5 different space agencies. China became the third country to successfully soft-land on the Moon in 2013, and the second to successfully remotely operate a rover on the lunar surface [1]. We now have significant global datasets that, coupled with the 1990s Clementine and Lunar Prospector missions, show that the sample collection is not representative of the lithologies present on the Moon [2]. The M^3 data from the Indian Chandrayaan-1 mission have identified lithologies that are not present/under-represented in the sample collection [3,4]. LRO datasets show that volcanism could be as young as 100 Ma [5] and that significant felsic complexes exist within the lunar crust [6]. A multi-decadal sample return campaign is the next logical step in advancing our understanding of lunar origin and evolution and Solar System processes.

Current Decadal Survey (DS) [7]: South Pole-Aitken (SPA) Basin Sample Return has been a named New Frontiers class mission in the last two DSs [7,8]. [7] also states (p. 133) "*Other important science to be addressed by future missions include the nature of polar volatiles, the significance of recent lunar activity at potential surface vent sites, and the reconstruction of both the thermal-tectonic-magmatic evolution of the Moon and the impact history of the inner Solar System through the exploration of better characterized and newly revealed lunar terrains. Such missions may include orbiters, landers,* ***and sample return***." It is difficult to conduct a lunar sample return mission under the current Discovery cost cap; international cooperation and/or commercial partnersips are ways to propose a Discovery nearside lunar sample return.

Sample Return Targets: Given the wealth of orbital information now available for the Moon, we can propose targeted sample return missions beyond what is outlined in [7]. Multiple nearside and farside targets are proposed (**Fig. 1a,b**). Note that these locations are examples of locations for the the types of samples that would greatly advance our understanding of the Moon *and* the inner Solar System. **Figure 1** is not meant to be an all-inclusive compilation of potential sample return sites. These sites will need to be adjusted on the basis of landing safety, accessibility, etc. Here, science is the only driver for these locations.

Spinel- and Olivine/Orthopyroxene-rich lithologies were discovered using M^3 data [3,4]. These are not well represented in the current sample collection (Apollo and Luna, as well as lunar meteorites), although a small clast in ALHA81005 is spinel-rich [9]. Such lithologies are vital for understanding the composition of the lunar crust and possibly the upper mantle, and to test the lunar magma ocean (LMO) hypothesis.

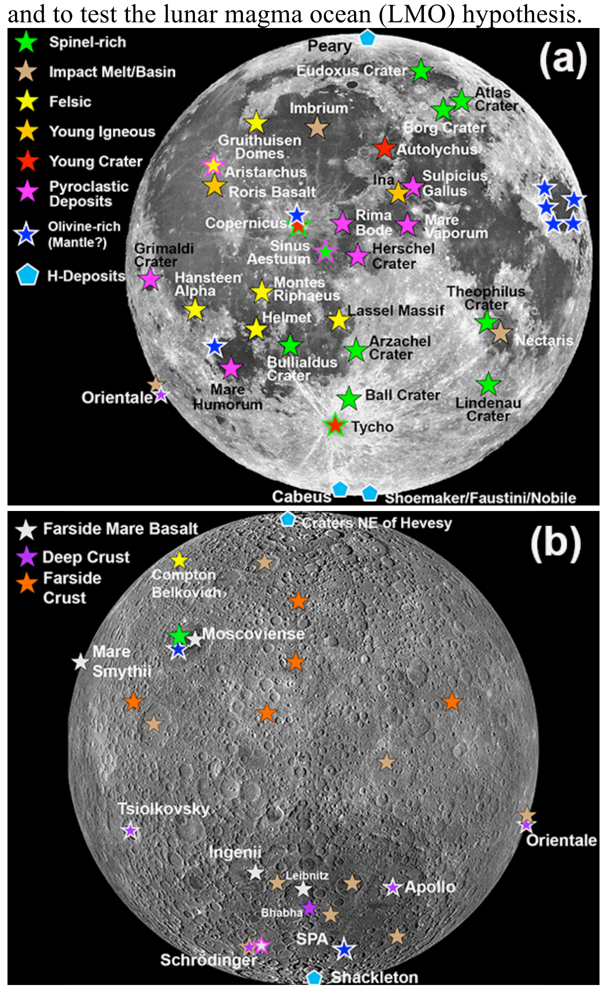

Figure 1: Examples of sample return locations: (a) nearside, (b) farside. Where >1 sample type can be obtained from a single site, symbols = multiple colors.

The locations for "**Impact Melt/Basin**" are intended to represent returning impact melts from such basins to constrain the impact history of the inner Solar System. This activity also includes "**Young Craters**" are also included in an attempt to constrain the impact flux at times older and younger than the 3.8-3.9 Ga ages of impacts that dominate the samples returned by Apollo. "**Felsic**" locations are those that have been ideintifed from orbital datasets to be silica-rich (and contain high Th abundances and a distinct peak in the Moon's thermal emission near 8µm, the Christiansen feature, associated with Si-O stretching vibration [10,11]). Felsic lithologies are present in the sample collection, but are relatively small (a few grams at the most). Orbital data demonstrate the presence of massifs at the Gruithuisien Domes, Hansteen Alpha, Aristarchus, Lassell, Compton Belkovich [6,12]. Sampling these massifs will enable tests of granite/rhyolite petrogenesis through silicate liquid immiscibility [13] and/or LMO processes.

Young Igneous samples include the young basalts defined by crater counts [14], as well as irregular mare patches [4]. The composition of these young basalts has important implications for understanding the composition of the mantle as well as the thermal evolution of the Moon. Sampling of **Farside Mare Basalts** will also address these science issues.

Pyroclastic Deposits are critical for understanding the volatile budget of the deep lunar interior. Experimental petrology on the glasses returned by Apollo suggest they are derived from greater depths than the crystalline mare basalts [15]. The presence of volatiles in the Apollo 17 orange and Apollo 15 green glasses [16,17] make pyroclastic deposits important for science and exploration (i.e., *in situ* resource utilization - ISRU).

Hydrogen (volatile) Deposits are identified from orbit to be present in and around some permanently shaded regions (PSRs) (e.g., [18]). We know very little about these deposits and landed missions such as Resource Prospector and far more capable follow-on missions are required. Sample return of such materials could contain ancient materials that address Solar System science questions (building blocks of life, source signature of inner solar system volatiles, etc.). Understanding the nature, distribution, and accessibility will be important for ISRU and human exploration.

Deep Crust and possibly lunar mantle can potentially be sampled around central peaks and deep areas within SPA. Having a sample of the deep crust or even the upper mantle will help constrain the Apollo geophysical data as well as the more capable and globally distributed Lunar Geophysical Network, a named New Frontiers mission for the NF-5 call later this decade.

Farside Crust (highlands): example locations are given (Fig. 1b). Comparing these samples with Apollo, Luna and lunar meteorite highlands lithologies is important for understanding crustal heterogeneity. It will also test if ferroan anorthosites are the dominat crustal lithology, as predicted from the LMO hypothesis.

Outcrop Sampling: None of the samples in the collection were collected from unequivocal in situ outcrops. Properly oriented samples are required from various terrains and of different ages to truly test the whether the Moon ever established a core dynamo [19].

Technology Development. Sample return has become a next step for studying many planetary bodies (Moon, Mars, asteroids). For the return of rock and regolith samples, very little technology development is needed. However, cryogenic sampling, return, and curation will require investment. If this is started now by 2050 such sample return will be possible.

Human vs. Robotic Sample Return: The United States has not yet robotically returned a sample from a planetary surface, but has returned samples successfully 6 times from the Moon with humans. The Soviet Union is the only country to have achieved robotic sample return from a planetary surface and did this successfully 3 times. These 3 missions brought back a total of 0.3 kg of regolith. The 6 Apollo missions returned a total of 382 kg of rocks, regolith, and core tubes. The trained human eye on the surface allows significant dscoveries to be made (e.g., Genesis Rock (15415) and Seatbelt Rock (15016) from Apollo 15; the Orange Glass (74220) from Apollo 17). Having humans involved in sample collection is critical for maximizing the return mass and sample types (Fig. 2). By 2050, we assume a permanent human presence on the Moon that will facilitate extensive sample return possibilities. We have potential to advance both lunar and Solar System science and exploration in this way.

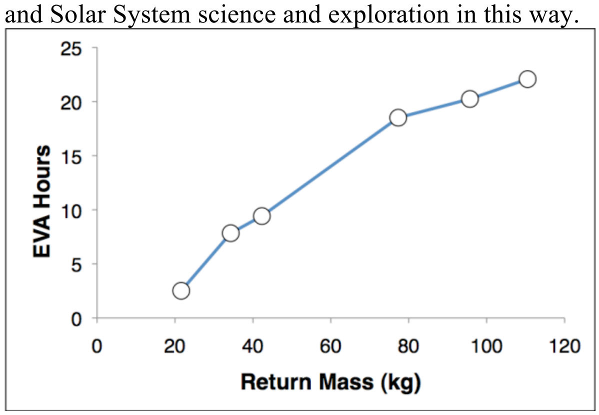

Figure 2: Human returned sample mass is positively correlated with EVA hours [20].

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ENABLING TECHNOLOGIES FOR A FUTURE LUNAR & PLANETARY GEOPHYSICS NETWORK.

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Introduction: While recent re-analysis of geophysical data from the Apollo missions have advanced our understanding of the Moon's internal structure [1], seismic activity [2], heat flow budget [3,4], and electrical conductivity [5], significant unresolved questions remain. General models of the processes that contributed to the formation of the present-day lunar interior are currently being challenged (e.g., [6,7]) and many questions remain as to lunar origin and evolution. While reinterpretation of the Apollo seismic data has led to identification of a lunar core [1], it has also produced a *thinning* of the nearside lunar crust from 60-65 km in 1974 [8], to 45 km in 2002 [9], 30 km in 2003 [10], and 31-38 km in 2006 [11]. With regard to the deep interior, Apollo seismic data have been used to infer the presence of garnet below ~500 km [12,13], but the same data have also been used to identify Mg-rich olivine instead [14]. Clearly, a global lunar geophysical network is required to define the nature of the lunar interior. Such a network would also add tremendous value to the GRAIL and SELENE gravity data.

The small size of the Moon means that it has preserved its primary differentiation. It represents an end member in terrestrial planet differentiation so identifying the global interior structure and composition of the Moon is critical for Solar System science. Identification of lateral and vertical heterogeneities, if present, will yield important information about, for example, the presence of a global lunar magma ocean (LMO) as well as investigating the stratification in the mantle from LMO cumulate overturn [15]. Advancing our understanding of the Moon's interior is critical for addressing these and many other important lunar and Solar System science and exploration questions.

In 2007, the National Academies [16] designated understanding the structure and composition of the lunar interior (to provide fundamental information on the evolution of a differentiated planetary body) as the second highest priority lunar science concept that needed to be addressed. Fueled by this endorsement, two major efforts at establishing a new Lunar Geophysical Network (LGN) followed. ***2008***: NASA-SMD Planetary Science Division formulated the International Lunar Network (ILN) mission concept [17], which attempted to enlist international partners to enable the establishment of a global geophysical network on the lunar surface, but the effort never materialized with a change in Space Policy in 2010. ***2010***: the LUNETTE dual-node geophysics lunar mission was proposed to NASA as a Discovery-class mission [18], but lost out to the single-node InSight Mars geophysical observatory [19]. It was found that a true network consisting of a minimum of four long-lived geophysical stations would not fit within the cost cap of a Discovery-class mission, and in 2013 the Planetary Decadal Survey recommended that NASA include the Lunar Geophysical Network (LGN) for a New Frontiers (NF)-class mission in the decade 2013-2022, as part of the NF-5 call. This is described in detail on pages 130-132 of [20] and summarized on page 15: "*This mission consists of several identical landers distributed across the lunar surface, each carrying instrumentation for geophysical studies. The primary science objectives are to characterize the Moon's internal structure, seismic activity, global heat flow budget, bulk composition, and magnetic field*." With the NF-4 call poised for release at the time of writing this abstract, the time is now to take stock of the current status of enabling technologies for a new LGN.

Better than Apollo: The Moon represents the only planetary body, other than Earth, for which we have geophysical data (so far). A future LGN should be better than and learn from the Apollo experience. Each station should contain a seismometer, heat flow probe, electromagnetic sounding instrumentation, and a laser retroreflector for nearside stations.

Seismometer: the Apollo passive seismometer [21] consisted of three long period sensors (X, Y, Z, all with detection limits of 0.3nm at 0.004-2 Hz) and one short period sensor (Z with a detection limit of 0.3nm at 1 Hz). The seismometer for the LGN needs to have ≥4 sensors that have at least an order of magnitude better sensitivity than that used during Apollo and over a much broader frequency range (0.1 to >10 Hz).

Heat Flow: Apollo heat flow was measured at the Apollo 15 and 17 sites and consisted of two probes ~11 m apart, with each probe consisting of two sections reaching 1.5-m and 2.4-m depths, respectively [22]. Measurements of absolute temperature were to ±0.05K. Thermal conductivity (0.009-0.014 W/mK) was determined for two depth intervals with ~15% accuracy from modeling the downward propagation of annual thermal waves [22]. The instrument used by LGN should be able to measure temperature every 20 cm to a depth of 3 meters and a relative accuracy of 0.01K. Measurements should be taken every hour. Thermal conductivity should be determined at several intervals (at least every 50 cm).

Electromagnetic Sounding (EMS): Wideband magnetic fields were measured at the surface by Apollo 12, 15, and 16, and from orbit on Apollo 15 and 16. Electrical conductivity of the mantle was determined from the transfer function between Explorer 35 and Apollo 12, but suitable spatial and temporal overlaps for the transfer functions for the other stations, as well as data degradation, have limited the robustness of EMS [23]. A dense magnetometer network would enable EMS by gradiometry (geomagnetic depth sounding). Better yet, measurement of electric and magnetic fields (magnetotellurics) provides an independent conductivity profile at each site. Natural-field variations can be supplemented by artificial fields (transmitters) for better resolution of the upper mantle/lower crust.

Lunar Laser Ranging: LLR is the only Apollo experiment that is ongoing. Laser retroreflectors were placed by the Apollo 11, 14 and 15 missions and the two Soviet Lunokhod rovers (Luna 17 and 21 missions) also carried retroreflectors. The restricted range of the LLR network means tidal librations are poorly constrained. The variations of pole direction, physical librations, and solid-body tidal distortions provide information about the Moon. Expansion of the network with the next generation of retroreflectors will constrain tidal librations. The new retroreflectors must give at least a factor of two better return signal.

Science: Integrating datasets obtained by the geophysical network allows a compregensive examination of the structure and composition of the lunar interior. For example, the heat flow probes yield crustal estimates. Combined with EMS, the temperature profile of the deep interior can be modeled along with mineralogy. The seismic and LLR data also yield structure and compositional information of the lunar interior and the high fidelity data would enhance the usefulness of the GRAIL and Selene gravity data. The network must be globally distributed and last at least 10 years.

Technology Development: There are ongoing efforts within the United States to improve planetary seismometers, heat flow probes [24,25], and corner cube laser retroreflectors [26]. In terms of magnetometers and electrodes, the instruments are developed, but the deployment mechanism will need some refinement.

During the ILN effort some lander development was pursued at MSFC, but geophysical lander technology and instrument deployment still requires fine tuning. However, given that there are several commercial transportation companies that may be available to deliver packages to the lunar surface, this capability is currently being developed by the commercial sector.

Maybe the biggest issue is power supply. Ideally these LGN stations should have a minimum life of 10 years. The longer the time these stations are active, the greater the likelihood that more stations could be added by subsequent launches, either by international cooperation (i.e., as in ILN), the United States, and/or commercial entities. Power becomes critical in enabling network longevity, thus also enabling the addition of stations to the network over time. Development of highly efficient nuclear power sources (e.g. ^{238}Pu Radioistope Thermal Generators) with multi-decadal capabilities are enabling for creation of multi-station geophysical and other long-lived monitoring networks (e.g., space weathering, exosphere variations, etc.).

Vision. The need for the LGN has been recognized by the last decadal survey [20]. Commercial landers could carry additional stations to enhance the network and/or create local networks in areas of specific ineterst. However, by 2050 human presence should be in the lunar vicinity if not on the lunar surface. It is critical that the LGN be established prior to renewed human lunar activity because we currently do not know the exact locations or causes of the shallow moonquakes – the largest magnitude seismic events recorded by Apollo (at least 1 event/year of magnitude ≥5; [27,28]). Establishing infrastructure near shallow moonquake epicenters needs to be avoided.

Establishment of the LGN porior to renewed human activity can allow the effect exploration has on the lunar environment to be studied. Enhancing LGN stations with advanced dust detectors and mass spectrometers (e.g.) will show how the environment responds to multiple landings in a month, mining activities, and sustained activity in one or several regions. This would address Objective Sci-A-1 of the LEAG LER [29].

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THE DEFLECTOR SELECTOR: A MACHINE LEARNING FRAMEWORK FOR PRIORITIZING DEFLECTION TECHNOLOGY DEVELOPMENT.
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Introduction: Impacts on the Earth by natural Solar System objects (i.e., asteroids and comets) can pose a significant threat to human lives and infrastructure. Several ground- and space-based observing campaigns have been dedicated to detecting and tracking Near Earth Asteroids, but research concerning the best methods for deflecting a hazardous asteroid impactor once it has been detected is still in the theoretical stages.

Several technologies have been proposed for impactor deflection, including nuclear explosives, kinetic impactors, and gravity tractors. However, none of these technologies has been developed and fully tested in space. Developing and testing every proposed deflection technology is currently prohibitively expensive. However, if humanity waits until a clear impact threat is detected to select which technologies to use, there may not be time to develop and deploy the chosen deflection technique before the impact. Determining now which technologies are most likely to be useful would allow policy and funding decision-makers to effectively prioritize a subset of the proposed deflection technologies.

Theoretical studies of the various proposed deflection technologies have focused either on modeling the capabilities of a single technology, or comparing the abilities of the different technologies to address specific impact scenarios. No comprehensive study comparing the effectiveness of the various proposed technologies on deflecting the likely hazardous object population has been published.

We have developed a model to map the distribution of parameters of a hypothetical impactor population to the set of technologies that can deflect these objects. Our model, the Deflector Selector, is designed to address the following question:

1. Which deflection method has the highest likelihood of deflecting the broadest range of possible impactors?
2. Which impactor characteristics is the choice of deflection method most sensitive to?
3. Which areas of the impactor parameter space are not covered by current deflection technologies?

Framework: The Deflector Selector model consists of a machine learning algorithm that takes as its input the characteristics of a hazardous object (e.g., orbital parameters, size, etc.) and outputs the deflection technologies capable of deflecting the object. To train the algorithm, we produced a set of training data using orbital integrations to simulate the application of a change in velocity, ΔV, to deflect a hazardous object, and a literature search of deflection technologies to calculate which technologies could apply that ΔV, given the object's size.

Orbital Simulations. We performed simulations of asteroid deflections using an *N*-body integrator that included the gravitational effects of Jupiter, Venus, and Mars, as well as the Sun and th Earth. We first generated a population of Earth-impacting orbits by rotating the orbits of all known Apollo and Aten objects in space such that the objects' orbits intersected the Earth's, then integrating the orbits of the objects and the planets backwards in time from the moment of collision to time $t = -15$ yr. When run forward in time, the objects are guaranteed to collide with the Earth at $t = 0$ yr.

We then simulated the instantaneous application of a deflection technology (such as a nuclear explosive or a kinetic impactor) to an impacting object by adding a random ΔV to the object's velocity in the direction of its motion at a random lead time before Earth impact. For each of 8,000 impactor orbits, we ran 200 instantaneous deflection simulations. We also simulated the application of slow-push rather than instantaneous technologies, such as gravity tractors, but applying a ΔV/year at every timestep of the integration. We ran 100 slow-push deflection simulations for each impactor orbit.

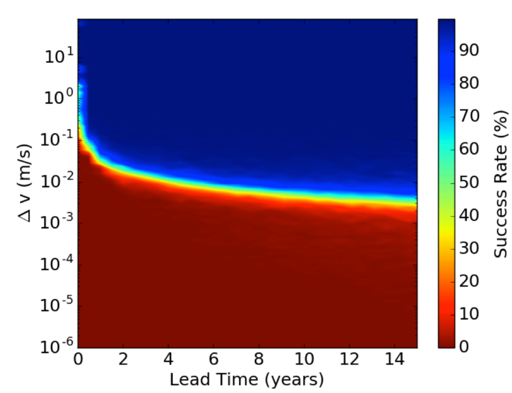

Figure 1: Summary of the instantaneous deflection orbital simulations.

Figure 1 summarizes the results, showing the percentage of simulations that resulted in a successful deflection for every combination of lead time and ΔV applied. As expected, larger ΔV values increase the proportion of successful deflections, and the magnitude of the ΔV required to increase this success rate increases sharply for decreasing lead times.

Technology Specifications. Our orbital simulations can only reveal which values of ΔV are required to deflect an incoming hazardous object, given its orbit and a lead time. To map these ΔVs to the proposed deflection technologies, we conducted a literature search in order to calculate the ΔV values that each technology can apply, given the object's mass. We considered the three most plausible technologies: nuclear explosives, kinetic impactors, and gravity tractors. For each technology, we calculated the required ΔV to achieve a success rate of 100% for a given lead time, using the results from our orbital simulations. We then used deflection technology studies to estimate whether each technology could apply such a ΔV, given an impactor diameter and assuming a constant density of 3 g/cm^3.

Our results are summarized in Figure 2, which shows the predicted success rate of each of the three technologies on our simulated impactor orbits, given the object's size and the lead time between technology application and Earth impact.

Machine Learning. The purpose of the orbital simulations and technology capability estimates described above was to develop a set of training data to feed to a machine learning algorithm. Once the machine learning algorithm is trained to predict the success probability of each technology given a hazardous impactor's size and orbit, we can then run the algorithm on a realistic simulated population of impactors to predict which technology is most likely to be effective in the event that an object is detected on a collision course with the Earth.

We used a machine learning algorithm known as a decision tree, which has the benefit of calculating the relative importance of the various parameters (object size, orbital elements, etc.) in deciding whether a technology would be successful or not.

Results: To test the training data pipeline and our decision tree algorithm, we used the extremely simplified population of simulated impactors created from Aten and Apollo orbits. Our orbital simulations and technology calculations produced a data set in which each point consisted of the object's size, semi-major axis, eccentricity, and inclination, the lead time, and a β parameter representing the object's internal strength, and four corresponding labels representing whether the detection was successful, and whether each of the three technologies was capable of applying the deflection. We trained the algorithm on 80% of the data and then used the remaining 20% as validation to test the algorithm's accuracy. We performed this cross-validation technique ten times, each time randomly selecting 80% of the data set for training and 20% for validation. The measured accuracy of the trained algorithm was ~98%, indicating that this data set is well-suited for classification using the decision tree method.

Future Work: Based on our very simple simulated impactor population, the Deflector Selector decision tree predicted that nuclear explosives are the most likely to be effective in deflecting a hazardous impactor. Now that the model is complete, our next steps will be to refine the model to reduce the number of assumptions involved, consider additional technologies and object parameters, and use a more realistic simulated population of potential impactors. Our first priority will be to estimate more realistic lead times as a function of the hazardous object's orbit. We anticipate that our model will be a valuable tool for researchers in planetary science and technology development, and ultimately for policy and research funding decision-makers.

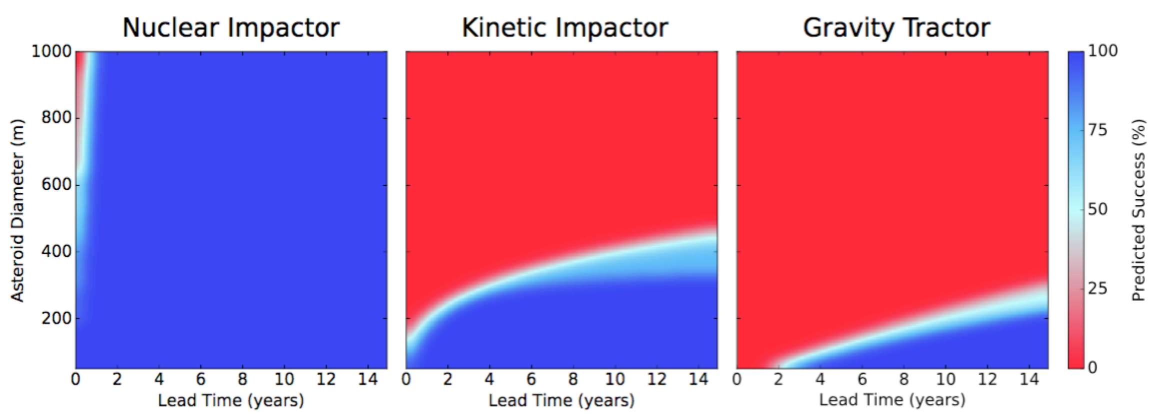

Figure 2: Predicted success rate of each technology, given the impacting object's diameter and the lead time.

THE NEXT REVOLUTION IN PLANETARY TOPOGRAPHY AND GRAVITY. G. A. Neumann[1], E. Mazarico[1], X. Sun[1], J. B. Garvin[1], F. G. Lemoine[1], D. E. Smith[2], A. Genova[2], J. W. Head[3], S. Goossens[4], P. J. McGovern[5], [1]NASA Goddard Space Flight Center, Greenbelt MD USA (gregory.a.neumann@nasa.gov), [2]Massachusetts Institute of Technology, Cambridge, MA 02139 USA, [3]Brown University, Providence, RI 02886 USA, [4]CRESST, U. of Maryland Baltimore County, Baltimore, MD 21250 USA, [5]Lunar and Planetary Institute, Houston, TX 77058, USA.

Introduction: After the dawn of the space age, humankind had succeeded not only in characterizing the global shape of its own planet but that of its Moon, Venus, and Mars, up to spherical harmonic degrees and orders between 12 and 18 [1]. These determinations from partially sampled data were accompanied by similarly resolved models of the gravitational potential, with which first order geophysical questions could be posed. With the advent of diode-pumped lasers and advances in radar, our knowledge of shape has today advanced by one to two orders of magnitude in precision, exceeding that of Earth in places (Fig. 1). Our Moon has been mapped (Table 1) with multi-beam lidar [2] and a dedicated gravity experiment [3]. The availability of both datasets with high resolution and accuracy were transformative to elucidate its interior evolution, structure of the crust, and the early history of the solar system. An important prospect for NASA's Planetary Science Vision 2050 is to obtain similar datasets over all terrestrial bodies, so as to be able to compare and contrast the processes that control their evolution. The next great challenge will be to measure the transfers of mass and momentum between the solid surfaces of Mars and Venus and their atmospheres. The internal structure underlying the surface topographic expressions of volcanism that are prevalent on each of these bodies must be elucidated as well, for we have evidence that the terrestrial bodies are still undergoing tectonic and internal deformation.

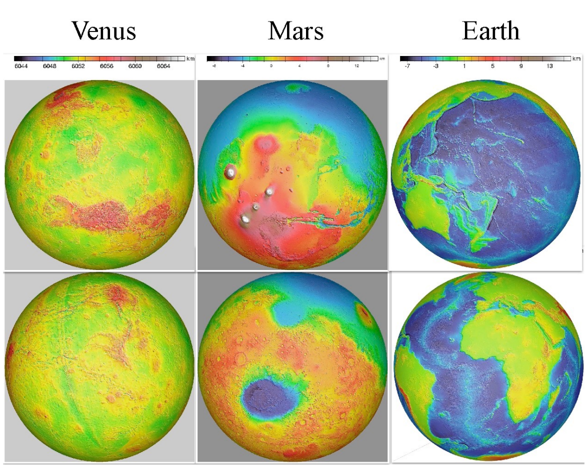

Figure 1. Shape of terrestrial planets in opposing hemispheres relative to respective datum, with identical color stretch over 20 km vertical range.

Moon: The LOLA altimetry illustrates the utility of a comprehensive dataset, capable of measuring slopes with 0.05° precision on 25-m baselines, and surface roughness, curvature and Hurst exponents at comparable precision. Moreover the correlation between fine-scale topography and gravity is found to be greater than 0.98, suggesting that great improvement will be made for other planetary shape measurements (Fig. 2).

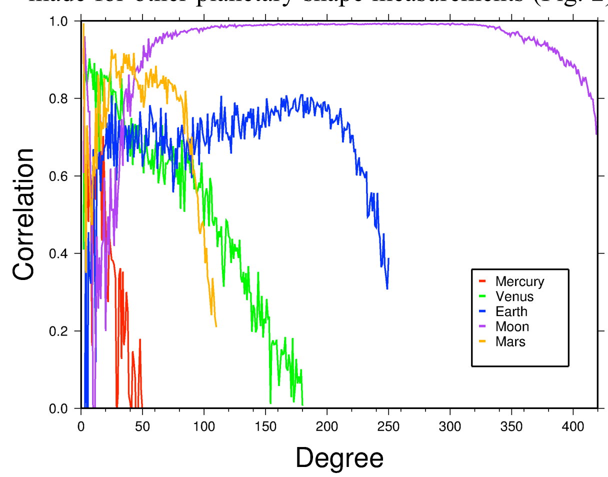

Fig. 2. Correlation of gravity with planetary topography vs. spherical harmonic degree [Zuber 2013].

For the Moon (purple curve), the high correlation makes possible global and regional assessment of the the bulk density stratification and porosity of the regolith and upper crust. Geophysical interpretation of the gravity signal after removing this correlation yields subsurface density contrasts giving rise to gravity gradients (Fig. 3) that reveal a previously unseen era of rifting following differentiation and thermal expansion.

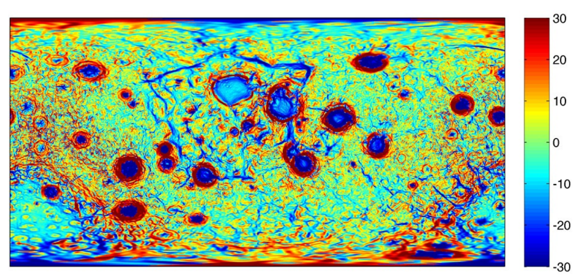

Fig. 3. Bandpassed lunar vertical gravity gradient map in Eötvös (10^{-9} m^{-2}) centered on the near side. [4].

Mercury: Northern hemisphere altimetry at better than 0.5 km resolution was obtained by the Mercury Laser Altimeter (MLA) [5], but global coverage constrained by stereo imaging and occultations has large uncertainties. A global spherical harmonic degree 128 model has been archived [6], showing a small offset of the center of figure from the center of mass (COM) (unlike at the Moon and Mars), but the major aspects of shape related to the flattening and elongation of the body (degree 2) remain uncertain and will benefit from the anticipated results of the BepiColombo Laser Altimeter reaching the planet in the next decade. New approaches from orbit including multi-wavelength lasers will be needed to resolve distribution of volatile species in permanently shadowed regions and their composition. Although BepiColombo will obtain a more uniform quality in gravity field recovery [7] than MESSENGER due to its eccentric orbit, a follow-up mission with a dedicated payload such satellite-satellite tracking or a gradiometer is required to bring our knowledge of Mercury's crust and internal structure to the level we now have at the Moon.

Venus: Magellan provided ~3 million altimetric profile data points [8] that have been interpolated to ~15 km x 15 km (with 80 m vertical precision relative to center-of-mass in most cases). A spherical harmonic degree 719 model that merges Magellan, Pioneer Venus, and Venera 15/16 data is available [9]. While atmospheric transmission windows at micron wavelengths exist, cloud scattering losses may forever make the surface inaccessible to precise mapping by orbital lidar. Digital delay-Doppler processing of direct Ku- or Ka-band radar altimetry promises to provide much smaller altimetric footprints (~150 m) than previous systems and provide Mars-like topography. Limited suborbital approaches or interferometric/stereo mapping at radar wavelengths could also be implemented with today's technology, with further efforts devoted to mitigating ambiguities, layover and atmospheric effects.

The outstanding questions that need to be addressed by refined topography and gravity relate to the internal crustal and thermal evolution of the planet, the evident tectonic deformation of the surface regolith, underlying characteristics of lithosphere, the history of water, the resurfacing of major portions by volcanism, paleoflow directions, and surface coupling with climate. Incremental advances should result if selection of proposed geophysical missions proceed, but a comprehensive topographic map at scales finer than 100 m will be needed. The first decade should focus on cartographic control for all datasets and better knowledge of rotation rate variations, best provided by a dedicated altimetric survey. Refinements to gravitational moments, tidal responses, and precession rates over longer baselines than previous work must continue.

Mars: Near-global altimetry at ~0.5 km resolution (with larger equatorial gaps) and 1-2 m vertical precision was obtained by the Mars Orbiter Laser Altimeter (MOLA) [10] in 1998-2001. MOLA provided global shape profiles with 300-m along-track resolution and resolved seasonal changes in surface height due to CO_2 frost deposition with 0.1 m precision. Polar coverage at latitudes higher than 87 degrees was very limited. The spacing of ground tracks is marginal for addressing questions of fluvial deposition, glaciation, paleoshorelines, lacustrian formation, and subsequent exhumation by hydrothermal and aeolian processes.

A hydrological-cycle-oriented mission to Mars would (1) quantify the annual variability of the Martian polar caps and directly measure the volume and extent of time-variable deposition of volatiles and dust; (2) map thicknesses and volumes of all polar layered deposits in order to understand the history of deposition of these layered materials on time scales from 10,000 to tens of millions of years, putting limits on the modern hydrologic cycle from the uppermost layers; (3) determine exhumed paleoflow discharge rates and duration. With multi-beam digital lidar capabilities achieving 1 cm vertical precision at 30 m or finer footprint scales, and the ability to measure corresponding changes in gravity at zonal degrees up to at least 5, these hydrological fluxes may be characterized geologically and in the present era.

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Table 1. Spherical harmonic degree of knowledge, and possibilities for the future using techniques such as cold-atom gradiometry in "drag-free" systems for Venus and Mars. In PDS unless otherwise noted, ranges supplied where confidence varies with location.

	Topography	**Gravity**	**Gravity by 2050?**
Moon	2600	1200-1620	1800
Mercury	8-128	30-100	1800
Venus	360-719 [9]	180	250-300
Earth	10,800	2159	
Mars	2600 [9]	120 [11]	225-250

SCIENTIFIC INVESTIGATIONS ASSOCIATED WITH THE HUMAN EXPLORATION OF MARS IN THE NEXT 35 YEARS

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Introduction

A human mission to Mars would present an unprecedented opportunity to investigate the earliest history of the solar system. This history that has largely been overwritten on Earth by active geological processing throughout its history, but on Mars, large swaths of the ancient crust remain exposed at the surface, allowing us to investigate martian processes at the earliest time periods when life first appeared on the Earth. Mars' surface has been largely frozen in place for 4 billion years, and after losing its atmosphere and magnetic field what remains is an ancient landscape of fomer hydrothermal systems, river beds, volcanic eruptions, and impact craters. This allows us to investigate scientific questions ranging from the nature of the impact history of the solar system to the origins of life.

We present here a summary of the findings of the Human Science Objectives Science Analysis Group, or HSO-SAG chartered by MEPAG in 2015 to address science objectives and landing site criteria for future human missions to Mars (Niles, Beaty et al. 2015). Currently, NASA's plan to land astronauts on Mars in the mid 2030's would allow for robust human exploration of the surface in the next 35 years. We expect that crews would be able to traverse to sites up to 100 km away from the original landing site using robust rovers. A habitat outfitted with state of the art laboratory facilities that could enable the astronauts to perform cutting edge science on the surface of Mars. Robotic/human partnership during exploration would further enhance the science return of the mission.

The Benefits of Human-Robot Exploration

The essential feature, from the point of view of science planning, of a potential human mission to Mars would be the presence of humans on the surface. However, we do not envision the scientific content of a human mission to Mars as only the science that would be done by astronauts' hands. Science efficiency during a crewed mission could be substantially enhanced by complementary operation between humans and robots on the surface of Mars. This would include work directly done by astronaut-explorers, human supervision and control of robotic assets around the habitat, and human supervision and control of robotic assets well outside the exploration zone (>100 km away).

The key question then is what are the kinds of scientific activities that would either be enabled or significantly enhanced by humans on the surface of Mars? Our analysis concluded that while humans can do many tasks that could also be performed by robots controlled from Earth, humans provide exceptional abilities in performing the following:

Establishing geologic context:

Humans in the field can rapidly collect and process visual data to determine stratigraphic relationships, superposition relationships, rock types, structures, and landforms.

Sampling

Human situational awareness improves the likelihood of identifying important samples of opportunity using judgment and experience to combine multiple streams of data to build a conceptual model of the site to test multiple working hypotheses.

Sample preparation and analysis in a habitat-based laboratory

Humans can manipulate and prepare samples in an unlimited variety of ways, ensuring that the right kinds of measurements are made on the most important part(s) of the sample to address the investigation.

Performing field investigations and analyses

Many field instruments and sensor systems benefit from troubleshooting and optimization in order to improve the targeting or data collection parameters of the sensor. Humans both speed up the rate of measurement as well as improve its quality.

Robotic assets working along side astronauts would also provide several important advantages to a human mission. For example, sterilized robots may be able to explore special regions (areas where liquid water may be present) in order to minimize contamination and collect essential samples in the search for life. Robots could also provide long term autonomous monitoring at a fixed station allowing for the crew to perform other tasks. Finally robots could provide effective reconnaissance that could be utilized to maximize the time of the crew on the surface and identify important sites for more intensive study. Robots operating beyond line of sight of crew could extend the human presence beyond the edge of the Exploration Zone (telepresence) including exploring other regions on Mars.

Much of this will be important during human exploration of other solar system bodies as well, and human exploration has the potential to provide substantial science return at a wide variety of destinations.

High Priority Science Objectives

Many different scientific objectives could be pursued that would be appropriate for the capabilities of a crewed mission. However, a potential human mission would be constrained in mass, power, volume, cost, mission risk, astronaut risk, and other factors. The high priority science objective set will need to be continually adjusted within these constraints and limited resources. In addition, while priorities can be more easily defined within a particular scientific discipline, consensus priorities that cut across different disciplines will require much more work within the scientific community. Given those caveats, high priority scientific objectives have been mapped out in three general areas: Astrobiology, Climate/Atmospheric Sciences, and Geological Sciences.

Past habitable environments with high preservation potential for ancient biosignatures are the primary target for our understanding of the history of habitability of the Planet. Robotic missions have identified some past habitable environments, and based on results collected thus far, we expect past habitable environments to be preserved in many locations across the surface of Mars. These include sediments derived from lakes, rivers, and peri-glacial environments, as well as igneous rocks that preserve evidence for ancient hydrothermal environments. Biosignatures indicating the existence of past life can be identified through morphological, chemical, and mineralogical analyses of the geological materials. These analyses can be performed at the rock outcrop, in a laboratory on the Mars surface, or by laboratories on Earth examining returned samples.

Discovering evidence for existing life on Mars would be an extraordinary discovery and would allow us to study the biology that is likely to be completely alien from our own. Locations on Mars that allow for the presence of liquid water would be the primary target for this search which would have to be conducted carefully under strict planetary protection protocols.

While we have been able to study the martian atmosphere from orbit and at the surface in a few locations, much uncertainty remains about the atmospheric state and forcings near the surface. Robust measurements by meteorological stations distributed across the human exploration zone would provide new insights into how the martian atmosphere behaves. Additional measurements of surface materials and atmospheric properties would allow us to better understand sources and sinks for dust, water, and CO_2 and the cycling of these materials. Furthermore, geological investigations will yield insight into past climate states and the evolution of the martian atmosphere over time and under different orbital configurations.

The origin and geological evolution of the planet would be pursued through the characterization of surface units to evaluate the diverse geologic processes and paleo-environments that have affected the martian crust. Geologic mapping and sample analysis would allow us to determine the sequence and duration of geological events, and establish their context within the geologic history of Mars to answer larger questions about planetary evolution.

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RIDDLES OF THE SPHINX: TITAN SCIENCE QUESTIONS AT THE END OF CASSINI-HUYGENS.

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Introduction: Since July 2004, the *Cassini* spacecraft has been orbiting Saturn, making repeated close encounters with Titan, its largest moon and the only moon in the solar system to possess a dense atmosphere. By the end of the mission in September 2017, *Cassini* will have amassed a vast wealth of scientific data about Titan collected by 12 instruments during 127 close flybys. These include: images and spectra from four remote sensing devices; particles and fields measurements from six further instruments; and radar and radio measurements of the atmosphere and surface at multiple wavelengths.

In January 2005 the Huygens probe descended by parachute to the surface, making the first in-situ measurements of the neutral atmosphere and surface with six on-board instruments, including winds, atmospheric composition, temperature-pressure structure, hazes, and surface characteristics.

The international *Cassini-Huygens* mission has made huge advances in our understanding of this enigmatic world, the greatest stride forward since the *Voyager 1* encounter of 1980. However it is clear in the closing stages of the mission that many mysteries remain. During a meeting of the *Cassini-Huygens* science team in October 2016, Titan scientists were invited to consider how many of the high-level questions from the start of the mission have now been answered. The team concluded that while some of the pre-*Cassini* mysteries are now largely "solved", some of the most perplexing questions remain only partially understood, while new riddles have also emerged from the data.

Key Questions: the questions are divided into four broad thematic areas, while recognizing that in practice these subject areas are all tied together: (1) history; (2) interior and surface; (3) lower and middle atmosphere; (4) upper atmosphere and exosphere.

History:

(1A) How did Titan form, and was this early or late in the solar system?

(1B) Why does Titan have an atmosphere, and how has it changed over time?

(1C) What is the age of the features we see on Titan's surface?

Interior and surface:

(2A) How thick is the icy shell and how deep is the ocean?

(2B) Is Titan geologically active today?

(2C) What materials are exposed on the surface?

(2D) What factors influence the distribution of the lakes and seas?

(2E) What is the composition of the lakes and seas?

(2F) What degree of prebiotic chemical complexity has been reached in surface environments?

Lower and middle atmosphere:

(3A) How can we explain the observed variations in Titan's hydrogen profile?

(3B) How can atmospheric models be reconciled with observations of clouds in the lower atmosphere?

(3C) Why is the stratospheric axis tilted with respect to Titan's solid body?

(3D) What is the reason for the detached haze layer?

Upper atmosphere and exosphere:

(4A) What chemical processes lead to the formation of complex molecules, including aromatics?

(4B) How rapidly is Titan's methane escaping into space?

(4C) What gives rise to the observed electron density profile?

(4D) Do we see the expected nitrogen torus?

Conclusions: In this paper we present a viewpoint on the most important questions remaining for Titan science at the end of the *Cassini-Huygens* mission. New data will be accumulated by powerful ground and space-based observatories in the years after *Cassini*; however, some of the most important questions will await new, focused spacecraft missions to Titan in the decades from 2020 to 2050 to be more fully answered.

THE TRANSNEPTUNIAN SOLAR SYSTEM IN 2050. K. S. Noll[1], J. A. Englander[2]; [1]Goddard Space Flight Center, Greenbelt MD 20771, keith.s.noll@nasa.gov, [2]Goddard Space Flight Center

Introduction: In the past 25 years we have learned that transneptunian space is filled with a rich array of bodies including some of the most dynamically primitive objects in the solar system. Currently more than 1500 bodies have well characterized orbits, but these objects are merely the tip of a vast and mostly unexplored population that may hold the keys to understanding the origin of planets, their subsequent dynamical evolution, and the chemical inventory available to support habitable environments. Transneptunian space holds enormous potential for new discovery over the next three decades but also presents significant challenges to future investigations. Several achievable steps are possible within the scope of current technology.

Spacecraft Missions: The New Horizons spacecraft has completed a spectacular flyby of the Pluto system[1] and will perform a flyby of a small Kuiper Belt Object (KBO) in early 2018. Given the decades-long timescale required for mission development and execution of this type of mission, it is quite possible that by 2050 that New Horizons will remain the only direct exploration of the Kuiper Belt. However, there are some options for missions that could be accomplished:

Kuiper Belt targets. Several targets in the Kuiper Belt would be high-value targets for future New Horizons-like missions. These include the Haumea system, an elongated fast-rotator with two small satellites, a collisional family[2], and an unusually pristine ice surface, and Makemake, a Pluto-like dwarf planet with a methane-ice rich surface and a large secondary, among others. Mission feasibility is a strong function of Jupiter gravity assist alignment and the ecliptic latitude of the targets. Suitable power and propulsion are key enabling technologies for such missions.

Kuiper Belt analog targets. Based on current planetary migration models, the objects in the present day Kuiper Belt originated in the protoplanetary disk exterior to the original positions of the giant planets[3]. Instability-driven planet migration scattered these objects to the current Kuiper Belt and to the Trojans and Hildas. Centaurs are objects leaking from the Kuiper Belt and are currently on unstable giant-planet-crossing orbits that bring them to smaller heliocentric distances. Each of these populations share an outer protoplanetary disk origin but have subsequently experienced different thermal and collisional environments. Many different missions to these targets are feasible with current or near future capabilities.

Observatory-Based Science: Two ground-based surveys from modest aperture telescopes, the Deep Ecliptic Survey (DES) and the Outer Solar System Origins Survey (OSSOS) are responsible for the discovery and orbits of the largest number of well-characterized KBOs[4,5]. The Hubble Space Telescope has been pivotal in characterizing KBOs, in particular through the discovery of numerous binaries in this population. In the coming decades we can expect more discoveries from deep all-sky surveys like LSST. Space-based, wide area surveys and/or dedicated facilities capable of high angular resolution and broad-band photometry could play a major role in deepening the current inventory of objects. Binaries are abundant in the transneptunian population and provide the opportunity to derive mass-based physical properties[6]. Imagers that fully sample the PSF of space-based observatories like the ACS/HRC are the best technological approach to observing these faint systems with small angular separations.

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PLANETARY DEFENSE: AN INTEGRATED SYSTEM OF DETECTION, EVALUATION AND MITIGTION. Joseph A. Nuth III[1], [1]NASA's Goddard Space Flight Center, Code 690, Greenbelt MD 20771 USA (joseph.a.nuth@nasa.gov).

Introduction: The concept of Planetary Defense is less than 40 years old, yet we have made enormous strides, working with small quantities of resources over this time period. We now detect and track more than three orders of magnitude more asteroids than we even knew existed 40 years ago and there are methods that have been proposed for deflecting potentially hazardous objects given sufficient lead time. Plans are even being made to test impact-induced deflection as well as the Gravity Tractor technique with upcoming, but not yet approved, NASA missions DART and ARRM.

Our current detection and mitigation schemes however focus almost exclusively on asteroids, by far the most likely impactor over the long-term, though not necessarily the most deadly integrated threat. Comets, though probably 100 times less likely to impact earth, are also larger than typical earth-impacting asteroids and will impact, on average, at considerably higher velocity. Comets will also impact on much shorter timescales following their initial detection than will a typical asteroid, thus greatly reducing the probability that we can divert or destroy such threats.

Different Threats: Detecting asteroids and mitigating their potential for impact is relatively "easy" compared to mitigating a cometary impact. Most asteroids travel in well behaved orbits relatively close to the earth, thus detection is possible. Because of the Planetary Defense work done to date, no large asteroid is likely to impact the earth without several decades of warning. Since relatively minor changes to an asteroid orbit can propagate over time to change the time it will cross the Earth's orbit, it is fairly easy to eliminate the threat when an impulse can be imparted to it many decades prior to the predicted impact .

A new comet, or a very long period comet, arrives with little warning. Comet C/2013 A1 (Siding Spring), an Oort cloud comet discovered on 3 January 2013 by Robert H. McNaught at the Siding Spring Observatory, is a great example. Comet Siding Spring passed within 135,000 km of Mars on 19 October 2014. The total time from it's discovery to closest approach to Mars was less than 22 months. This short warning timescale is much less than would be expected for a typical asteroid impactor.

Comet Siding Spring entered the inner solar system perpendicular to the ecliptic plane. While most asteroid impacts have a relative velocity of ~20 km/s, Comet Siding Spring had a relative velocity of ~56 km/s at Mars. Since collision energy is proportional to v^2 this comet would have ~9 times the energy of a typical impact by an asteroid of similar size. Such high relative velocities for comet-planet collisions are not unusual.

Meteor Showers demonstrate potential relative collision velocities of comets with Earth. Comets shed debris as they orbit the Sun. The Earth passes through these debris trails as it orbits the Sun and these debris trails are the sources of meteor showers. Each meteor shower represents a possible collision between the parent comet and the Earth that did not occur. There are more than 65 known meteor showers with relative velocities ranging between 3 and 71 km/s for all "cometary" sources: these include short and long period comets, new comets as well as dead comets.

The impact threat from asteroids is much higher than that from comets (>100::1). However, comet impacts are likely to be more energetic. Comet orbits are generally farther from the ecliptic and more eccentric than asteroid orbits: so their impact velocities are much higher when they cross the orbit of the Earth. Comets are larger than most asteroids but are also less dense (more water, less rock). The smallest known comets are seversal hundred meters in their longest dimension while the largest are many kilometers or even hundreds of kilometers in size.

Comets provide much less warning from discovery to impact than typical asteroids and it is therefore much harder to mitigate such potential impactors. The time required to launch a high reliability planetary mission is approximately 62 months from the date that the mission is approved. The schedule can be compressed by cutting out various reviews and eliminating tests, but these short cuts greatly diminish the reliability of such a mission. Cutting this time down to on the order of 12 months to deal with a threat such as Comet Siding Spring would result in a very low reliability mission. It is imperative to reduce reaction time to less than a year from high certainty of impact to launch without compromising the reliability of the mission.

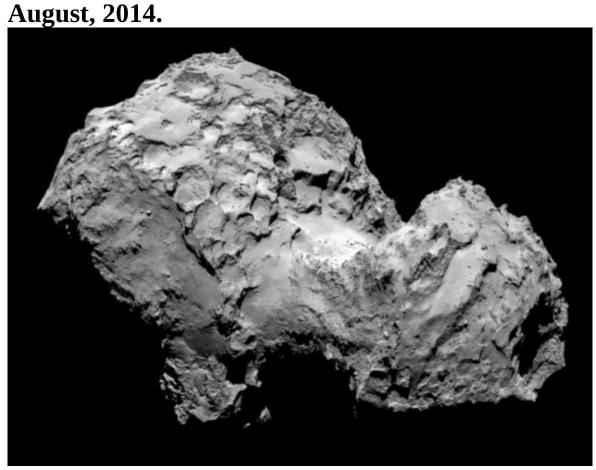
Recommendations: To reduce reaction time without compromising mission reliability we can build an intercept spacecraft that could carry a NED and put it into storage (with periodic testing). In addition we should also build a simple observer spacecraft and put it into storage as well. We would launch this observer spacecraft on "warning" to gain data to refine the comet's orbit and to maximize the effectiveness of the interceptor.

Building a high reliability spacecraft can be done easily prior to need, on a “normal” schedule if there is no reason to rush. All normal design reviews and all spacecraft component and integrated tests can be performed to ensure all works as expected Stored spacecraft can be launched within a year as was demonstrated by the DISCOVR launch of the previously stored TRIANA earth-observing satellite. This plan reduces the time to launch an interception mission by about four years. This interceptor could also be used to mitigate against a “sneaky” asteroid that might be detected coming from an orbit we currently find diffiult to monitor (such as in the direction of the Sun). We would then launch the interceptor when the impact threat reaches a pre-defined level of certainty.

An observer spacecraft is highly desirable. An observer spacecraft can document the comet’s shape, spin axis and rotation rate to enable the most effective mitigation mission possible (*e.g.,* where and when should the intercept occur for maximum effect). The need for such an observer is amply demonstrated by the Rosetta Mission. The best ground- (and space-) based observations of Comet 67/P Churyumov-Gerasimenko suggested that it should be a solid bi-pyrimydal shaped body. The reality was quite different. Comet 67/P Churyumov-Gerasimenko is not a symmetric target and it is easy to understand why the impact of a nuclear device will have significantly different effects if applied at some random spot over the surface of the comet.

An observer spacecraft could also provide a very accurate position for the incoming comet to refine its orbit. While this position would only be at one very precisely timed and measured point on the orbit, it would be a better position that can be obtained from the ground until just before impact.

Above: Artist's impression of the nucleus of Comet 67/P Churyumov-Gerasimenko, portrayed far from the Sun with little to no activity (Image via ESA–C. Carreau) based on remote sensing observations, including those taken by the Rosetta spacecraft as it approached the target two years before rendezvous. Below: Image of Comet 67/P Churyumov-Gerasimenko obtained by Rosetta after arrival in August, 2014.



Triton Hopper: Exploring Neptune's Captured Kuiper Belt Object

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Abstract. Neptune's moon Triton is a fascinating object, a dynamic moon with an atmosphere, and geysers. Triton is unique in the outer solar system in that it is most likely a captured Kuiper belt object (KBO)—a leftover building block of the solar system. When Voyager flew by it was the coldest body yet found in our solar system (33 K) and had volcanic activity, geysers, and a thin atmosphere. It is covered in ices made from nitrogen, water, and carbon-dioxide, and shows surface deposits of tholins, organic compounds that may be precursor chemicals to the origin of life.

Exploring Triton will be a challenge well beyond anything done in previous missions; but the unique environment of Triton also allows some new possibilities for mobility. We developed a conceptual design of a Triton Hopping probe that both analyzes the surface and collects it for use to propel its hops. The Hopper would land near the South Pole in 2040 where geysers have been detected. Depending the details of propulsion chosen the Hopper should be able to jump over 300 km in 60 hops or less, exploring the surface and thin atmosphere on its way. This craft will autonomously carry out detailed scientific investigations on the surface, below the surface (drilling) and in the upper atmosphere to provide unprecedented knowledge of a KBO turned moon and expanding NASA's existing capabilities in deep space planetary exploration to include Hoppers using different ices for propellant.

Triton is roughly 2700 km in diameter with a surface of mostly frozen nitrogen, mostly water ice crust and core of metal and rock. Its gravity is half that of Earth's Moon and its atmosphere is 1/70,000th of Earths or 0.3% of Mars.

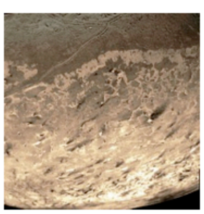


Figure 1.1—Voyager Image of South Pole of Triton Showing Geysers

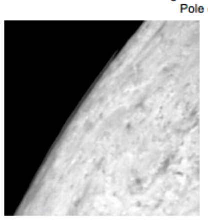


Figure 1.2—Voyager Image Showing Thin Atmosphere

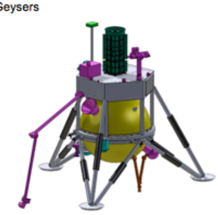


Figure 1.3—Triton Hopper Concept

The mission concept studied investigated the full surface and atmospheric phenomenon: chemical composition of surface and near subsurface materials, the thin atmosphere, volcanic and geyser activity. Measurements of all these aspects of Triton's unique environment can only be made through focused *in situ* exploration with a well-instrumented craft. And this craft will be provided revolutionary mobility, nearly global, using in-situ ices as propellants.

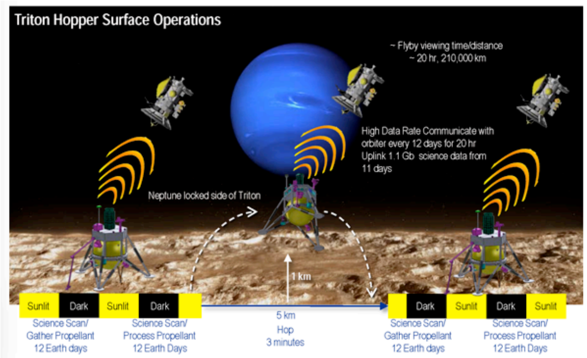
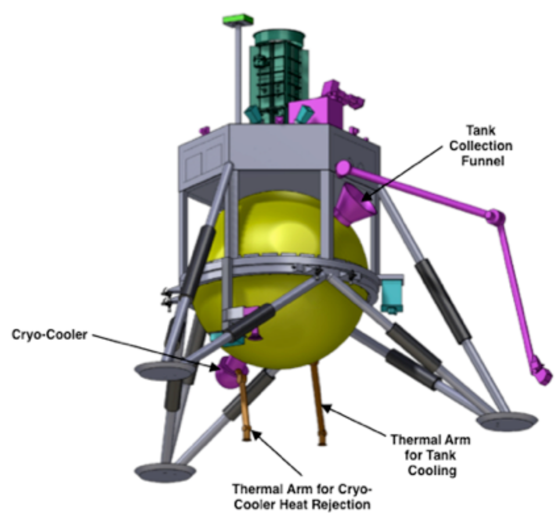


Figure 1.4—Triton Hopper Surface CONOPS

While other concepts have looked at gathering gases at Mars to propel a hopper, long periods of time are needed to gather the thin CO_2 atmosphere. Several gases, mainly nitrogen are on the surface in a readily dense ice form and just need to be picked up, vaporized and used for propellant.

This paper will describe the mission options to get to Triton, a notional descent system and the design of a hopper to explore large parts of Triton. Trades on propellant gathering and propulsion will be explained.



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Phase 1 Design: The conceptual design of a submarine for Saturn's moon Titan was a funded NASA's Innovative Advanced Concepts (NIAC) Phase 1 for 2014. The proposal stated the desire to investigate what science a submarine for Titan's liquid hydrocarbon (–180 °C) seas might accomplish and what that submarine might look like. Focusing on a flagship class science system (~100 kg) it was found that a submersible platform can accomplish extensive science both above and below the surface of the Kraken Mare (Figure 1). Submerged science includes mapping using side looking sonar, imaging and spectroscopy of the lakes liquid at all depths, as well as sampling of the lake's bottom and shallow shoreline. While surfaced the submarine will not only sense weather conditions (including the interaction between the liquid and atmosphere) but also image the shoreline, as much as 2 km inland.

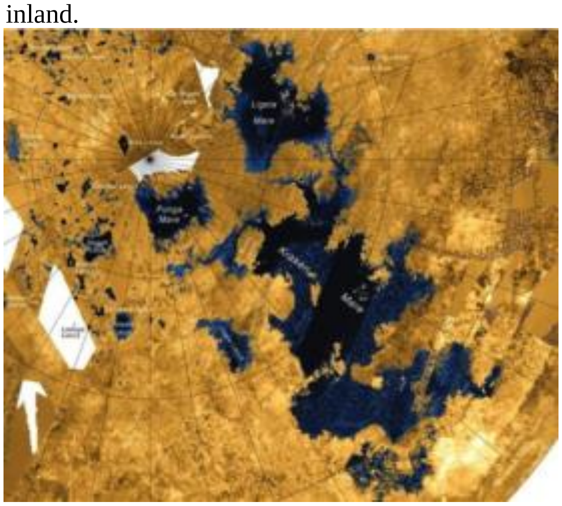

Figure 1—Titan's Seas or Mare in the Northern Hemisphere

This imaging requirement pushed the landing date to Titan's next summer period (~2047) to allow for lighted conditions. Submerged and surfaced investigation are key to understanding both the hydrological cycle of Titan as well as gather hints to how life may have begun on Earth using liquid/sediment/chemical interactions. An estimated 25 Mb of data per day would be generated by the various science packages. Most of the science packages (electronics at least) can be safely kept inside the submarine pressure vessel and warmed by the isotope power system.

The baseline 90 day mission would be to sail submerged and surfaced around and through Kraken Mare investigating the shoreline and inlets to evaluate the sedimentary interaction both on the surface and then below. Depths of Kraken have yet to be sensed (Ligeia to the north is thought to be 200 m (656 ft) deep), but a maximum depth of 1,000 m (3.281 ft) for Kraken Mare was assumed for the design). The sub would spend 20 d at the interface between Kraken Mare and Ligeia Mare for clues to the drainage of liquid methane into the currently predicted predominantly ethane Kraken Mare. During an extended ninety day mission it would transit the throat of Kraken and perform similar explorations in other areas of Kraken Mare. All in all, the submarine could explore over 3,000 km (1,864 mi) in its primary mission at an average speed of 0.3 m/s. The phase I submarine design and some of its attributes are shown in figures 2 and 3.

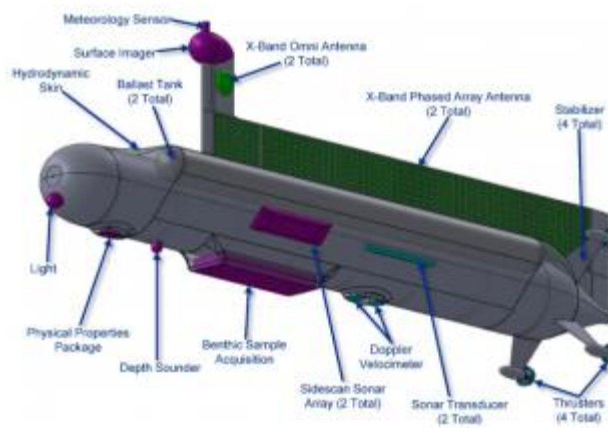

Figure 2—Phase I Titan Submarine – Standalone – External

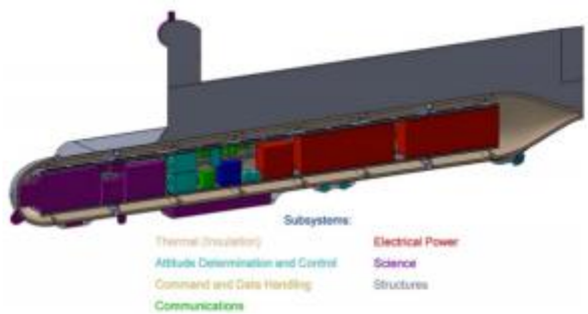

Figure 3—Phase I Titan Submarine – Internal

Phase Designs: A Two year phase II was awarded the team in 2015. Phase II is currently at a half-way point with good results on modeling and testing of Titan Sea mixtures, saturations, and efferevescence which will have great impact on Sub design. The first of two Phase II designs was completed, this time focusing on Ligea Mare and assuming deployment and communications/navigation support from an orbiter. The use of an orbiter allows for earlier arrival, slower transit speeds and most strikingly communications from the bottom of the sea – removing the need for surfacing to communicate. The conceptual design is shown in figures 4-7. It includes the same suite of instruments for sea and sea bed chemical analyses, surface and subsurface imaging, and surface weather sensing.

Current results, plans for phase II completion and steps beyond phase II will be discussed.

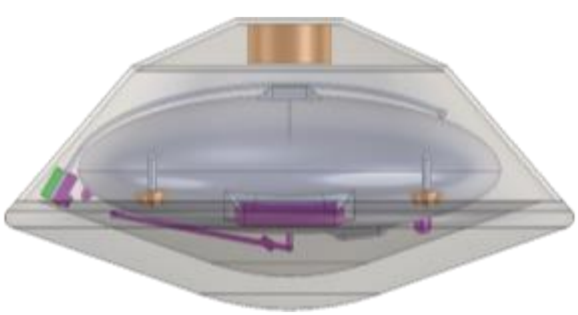

Figure 4. Phase II Orbiter Supported 'Titan Turtle' Submarine in Huygens sized Aeroshell

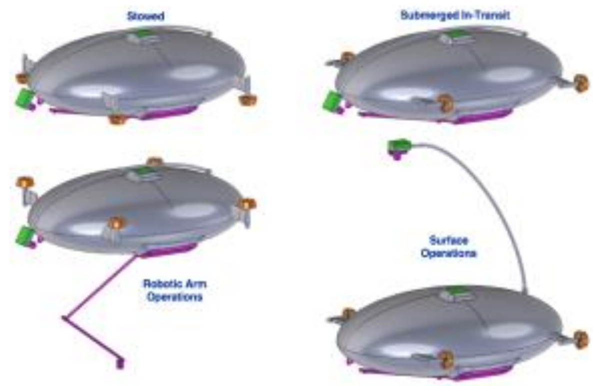

Figure 5. Phase II Orbiter Supported 'Titan Turtle' Submarine in various operational phases

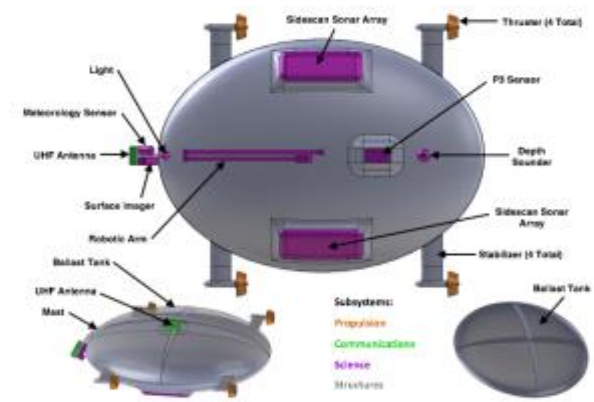

Figure 6. 'Titan Turtle' Submarine External Components

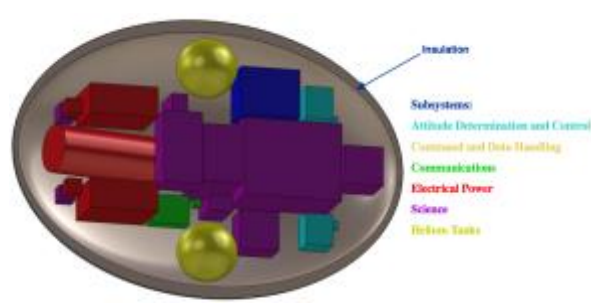

Figure 7. 'Titan Turtle' Submarine Internal Components

References: Oleson, SR, Lorenz, RD, Paul, MV, NASA/TM-2015-218831 Phase I Final Report: Titan Submarined

A Plan for Searching for Life at Mars and Europa. T Owen[1] and S. J. Bolton[2], [1]University of Hawaii, [2]Southwest Research Institute,.

This vision consists of a comprehensive search for evidence of extra-terrestrial life, focusing on domains where there is evidence of liquid water.

Mars sample return:
Mars remains the most likely habitat for extra-terrestrial life in our solar system. Unlike all previous searches, we will investigate places on Mars where there **is** water (ice that melts) instead of places where there **was** water. The samples will be returned to Earth for exquisite analysis in ultra-clean laboratories. We will focus on two environments: the rims of impact craters whose inner walls show evidence of recent mud slides (originating at the crater rims where sub-surface ice can be exposed) and the edges of the water ice components of retreating polar ice caps.

Strategy
Collaborate with imaging scientists to review all images of Mars to locate best places on Mars and the best times to explore them.

- Develop and test new "micro-rovers" that can navigate these difficult terrains, select and preserve samples at low temperatures.
- Test system end-to-end on analogue terrains on Earth: "find-collect-preserve-damp samples – transfer" (to Earth-return spacecraft)
- Examination of samples in ultra-clean laboratories. This step has been extensively and brilliantly executed by the APOLLO program.
- In this chain of events, the sticking point is the development of the rovers. Yet there is ample experience now of vehicle motion on Mars which will provide a huge head-start for this project.
- Sample return puts all the high-tech analytical equipment on Earth, where it can be coseted and kept up to date. Collaboration with existing laboratories using nano-technology will save heaps of money. Collaboration with foreign investigators would be encouraged, again following APOLLO.
- This approach to finding life on Mars has two fundamental improvements over previous attempts:

  a. Samples have recently been in contact with Mars water.

  b. Samples are analyzed by the most sensitive protocols on Earth.

Europa Sub-surface Ocean:
Is there an ocean of liquid water beneath Europa's icy crust? If there is, is it possible that life has begun and survived in this environment?

Given the uncertainties here it seems inappropriate to promote a highly expensive mission to look for possible microbes in this possible ocean. Instead, we propose a "slash-and burn" approach.

Strategy
Send a bomb to break a hole in the ice with a "chase plane-s/c" that follows it and takes movies of what happens. The chase plane could be equipped with a mass spec (Waite et al. at Enceladus) to analyze the plume produced by the explosion. At that point, people can assess the situation and decide on the next step. This is the bottom rung of the ladder used to detect life on other worlds.

Centennial Missions: Conducting Planetary Science on Century Timescales. A. H. Parker[1], [1]Southwest Research Institute (aparker@boulder.swri.edu).

Introduction: How do we explore the evolution of surfaces, atmospheres, interiors, magnetospheres, and orbits of the worlds in our solar system over timescales stretching beyond a single human lifetime? Datasets collected in a consistent manner over very long timescales are crucial for identifying and characterizing processes operating over climatological, geological, and astronomical timescales. Reliable sunspot counts date back continuously to 1849 and consistently back to 1610, revealing long-term variations in solar activity. Meteorological stations have recorded land temperatures on Earth continuously for nearly 140 years at some sites, providing crucial input to models of weather, climate, and land-use effects. NASA's Landsat program has monitored the Earth's surface in a consistent and coherent manner from space for 44 years and counting, enabling unique studies of an enormous host of slow and fast terrestrial processes. Planetary science has implemented few of these types of coherent long-term experiments. For example, between the Lunar Laser Ranging Experiment [1] and the Apache Point Observatory Lunar Laser-ranging Operation [2], lunar laser ranging has been conducted continuously for 47 years. This long-term dataset has enabled not only direct and detailed characterization of the effects of tidal interaction between the Moon and the Earth, but also unparalleled tests of fundamental theories of gravity [3]. I will discuss several classes of planetary science endeavors enabled by extremely long-term planning. Together, they motivate the development of mission efforts that operate over multi-decade to century timescales. These Centennial Missions, if flown, will be missions of inheritance, built and launched for the benefit of future generations of explorers.

Baselines For Long-Term Predictions: Discovering potentially hazardous objects is only one component of effective planetary defense; another is characterizing their current orbits and their orbital evolution. Non-gravitational forces that act to slowly alter the orbits of small asteroids are difficult to characterize without concerted astrometric characterization over long timescales; predicting and mitigating impact hazards centuries into the future relies upon this characterization. LSST will enable the discovery of order 100,000 Near-Earth Asteroids [4]; no means have been established to guarantee that these objects will be tracked with high enough precision to determine their orbital evolution. Long-term, space-based, highly autonomous platforms can enable these measurements.

Processes With Long Timescales: Many processes active today in the solar system act over timescales longer than a human lifetime. Uranus and Neptune have orbital periods of 84 and 165 Earth-years, respectively, and these long periods coupled with their high obliquities drives extremely long-term seasonal variation in their deep and complex atmospheres. Orbital missions that could persist in their observing campaigns over these timescales would provide future generations with powerful tools to understand the structure and evolution of these worlds. Similarly, the magnetic fields of the giant planets may undergo quasi-periodic reversals on timescales of centuries [5]. This timescale is intermediate between the 11-year solar polarity reversal periodicity and the much longer timescale of the Earth's geomagnetic reversals. In-situ monitoring of Jupiter and Saturn's magnetospheres over century timescales would provide valuable insight into the complex behavior of planetary dynamos.

Mission Sustainability Through Autonomy: Long-term experiments must be robust to the vagaries of human support for them. Should human events transpire that lead to loss of contact from the Earth, these experiments should endure and their data remain recoverable. This coupled with the desire to reduce operation costs over long mission lifetimes, calls for both a high degree of autonomy and open-source communication standards. A truly autonomous platform can recognize and adapt to temporary termination of communications, and continue its operations while waiting for new communication to be initiated.

A Pathway To Interstellar Exploration: In the absence of a means to travel faster than light, robotic missions that cross the interstellar void to even the nearest stars will operate in transit for many decades or centuries. Many interstellar mission development efforts focus on propulsion and communication technologies; however, developing an understanding of *operational* procedures for extremely long-duration missions is also critical for successful interstellar exploration. This development can begin without waiting for solutions to be found for the other engineering challenges that beset interstellar flight. Multi-decadal and centennial planetary missions provide an ideal avenue for building this understanding.

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NEW PARADIGMS FOR HUMAN-ROBOTIC COLLABORATION DURING HUMAN PLANETARY EXPLORATION.

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Introduction: Human exploration missions to other planetary bodies offer new paradigms for collaboration between humans and robots beyond the methods currently used to control robots from Earth (e.g., Mars rovers) and robots in Earth orbit (e.g., ISS Mobile Servicing System, ISS Dextre). Additionally, certain science objectives may lend themselves better to human operation or robotic operation, or a hybrid of the two. In terms of resource availability, EVA crew time is expected to be a dominant factor, but other factors such as communication bandwidth, command time delay, power, and robotic system availability may also affect decisions regarding the application human and/or robotic resources. Furthermore, the next several decades promise enormous advances in particular technologies affecting the human-robotic interface (e.g., autonomy, sensing) and these technology advances will almost certainly change the paradigms of human-robot collaboration.

In 2015, the Human Science Operations-Science Analysis Group (HSO-SAG) of the Mars Exploration Program Analysis Group (MEPAG) studied this issue for the case of human exploration of Mars and published its findings[1]. This paper describes the relevant findings from the MEPAG HSO-SAG report, focusing on: (1) the range of potential styles of interaction between humans and robots, and (2) the range of potential styles of control of robotic systems by humans at varying levels of separation.

Human/Robot Interactions: A human exploration mission could possibly utilize robots to more efficiently achieve some of its science objectives while other science objectives would be best accomplished by humans alone. One example might be the use of sterilized robots to explore special regions in order to minimize forward and backward contamination.

High latency rover operations on Mars (where humans are operating from Earth) are well understood (e.g.. Mars Pathfinder, Mars Exploration Rovers, Mars Sceience Laboratory), but the types of robots that would be utilized and the model of human/robot operation for human planetary exploration missions are not as clearly defined.

There are several existing models of human-robot interaction that could be useful, including (1) International Space Station, (2) subsea oil rig repair, (3) teleoperated, minimally invasive surgical techniques. These models offer significant insight into potential applications of interaction and control, but the overall concept of operations for the human planetary exploration application needs more development, including: (1) interaction during field work, (2) exploration of special regions, and (3) reconnaissance.

Style of Crew Control and Interaction with Robots: The crew and robots would have several styles of interaction during a crewed mission (Fig.1). These include: (1) crew and robots cooperating on tasks both inside and outside of a pressurized habitat, (2) crew and robots operating independently and handing off tasks between each other when appropriate, and (3) robots operating independently of crew.

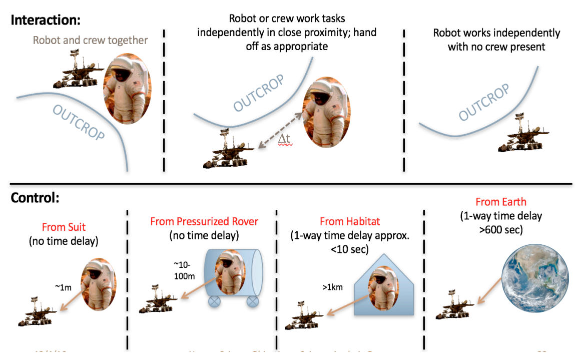

Figure 1. Range of Styles of Human/Robot Control/Interaction.

Furthermore, there is a range of styles of control of the robots by humans, including: (1) directly from an EVA suit over a few to tens of meters, with no time delay, (2) from a pressurized rover over tens to hundreds of meters, with no time delay but potentially limited line of sight, (3) from a fixed habitat over kilometers, with 1-10 second time delay, (4) from Earth over millions of kilometers, with 1-10 minute time delay. It should be noted that the current ISS robotic operations fall largely into the second class, while

Mars rover operations fall into the fourth class. The first and third classes have relatively little precedent in space operations, but other operations environments such as subsea oil well repair do offer relevant analogs.

The science objectives to be addressed during a crewed mission are influenced by robot involvement, the style of crew control and the style of crew/robot interaction that are supported by the mission architecture. Some objectives are better met by different combinations of robot involvement, crew control and crew/robot interaction.

Finding (HSO-SAG #4): The range of possible science objectives to be addressed during a crewed mission would be broader if crewed mission architecture supports the development of and an ability to routinely switch between styles of robot involvement, crew control and crew/robot interaction to achieve tasks.

Telepresence Beyond an Exploration Zone: Robots operating beyond line of sight of crew could extend the human presence beyond the edge of the Exploration Zone via telepresence. Furthermore, telepresence could be the only permissible way to explore in protected areas on Mars. Objectives to be met by telepresence operations should be identified as those that: (1) benefit from crew operation in the Mars system, and (2) support the overall science objectives of the human mission.

Finding (HSO-SAG #5): Operation of robots out of the line of sight of crew could be used to extend the human presence beyond the Exploration Zone or into protected areas.

EVA Time as a Critical Resource: Crew time during a crewed mission is a limited resource; only a fraction of the total crew time would be available for dedicated science operations**.** A main rationale for a crewed mission is to enable EVA time; as such, EVA time must be used to conduct tasks that require a crew presence**.** A critical role filled by the use of robots is an ability to ensure that crew time is dedicated to tasks that most benefit from a human presence. A useful paradigm used on ISS is for EVA worksite setup and teardown by robotic systems that “let the robot prep the patient, then have the human enter for the surgical procedure”.

Finding (HSO-SAG #6): Use of robots to support EVA-related activities could increase the number of or degree of satisfaction of a science objective(s) be enabling crew to focus on tasks that benefit from a human presence.

Summary: The style of human/robot interaction may have implications for Exploration Zone selection. In particular, remote operations outside of the Exploration Zone may expand the scope of science investigations. In this case, it is worthwhile to ask which tasks could be accomplished by robots, and how could these be integrated into the human mission to enable the completion of the broadest range of high intrinsic value science objectives.

One potential example is robotic deployment of science packages by autonomous robots inside or outside the Exploration Zone. Robots could complete tasks such as deployment of science packages to accomplish high value goals while humans complete tasks that most beneficially involve their participation (sampling, lab work field analyses). It is important that these robot-only activities support the overall science objectives of the human mission.

Finding (HSO-SAG #7): Preparation for a potential Mars surface mission requires more focus on the development and testing of operations concepts that include human-robotic interaction. This also requires development and testing of supporting technologies and systems.

References:

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Science at a Variety of Scientific Regions at Titan using Aerial Platforms, M.Pauken[1], J. L. Hall[1], L. Matthies[1], M. Malaska[1,] J. A. Cutts[1], P. Tokumaru[2] , B. Goldman[3] and M. De Jong[4], [1]Jet Propulsion Laboratory, California Institute of Technology, MS 321-550, 4800 Oak Grove Drive, Pasadena, CA 91109, Michael.Pauken@jpl.nasa.gov, [2]AeroVironment, Monrovia, CA, [3] Global Aerospace, Monrovia CA, [4]Thin Red Line Aerospace, Chilliwack, BC

Titan's low-gravity, thick-atmosphere environment lends itself to exploration by atmospheric flight. Flight on Titan can also provide science with observational opportunities that would be achieved by orbiters and rovers on other planets and moons but which are not possible on Titan because of the obscuring atmosphere and hazardous terrains. This paper reviews past work and recent developments on aerial platform concepts for Titan and the contribution of aerial exploration to Planetary Science Vision 2050.

Scientific Motivations:

Titan has an abundant supply of a wide range of organic species and surface liquids, which are readily accessible and could harbor exotic forms of life. Furthermore, Titan may have transient surface liquid water such as impact melt pools and fresh cryovolcanic flows in contact with both solid and liquid surface organics. These environments present unique and important locations for investigating prebiotic chemistry, and potentially, the first steps towards life.

Aerial platforms are ideal for performing initial reconnaissance of such locations by remote sensing and following it up with in situ analysis. The concept of exploring at Titan with aerial vehicles dates back to the 1970s [1] and NASA initiated studies of Titan balloon missions in the early 1980s [2] and JPL conducted a studies and technology development in the 1990s and early 2000s [3], but it was the Cassini-Huygens mission arriving at Saturn in 2004, that gave a new impetus to aerial exploration of Titan.

Impact of Cassini Huygens Mission

When ESA's entry probe Huygens descended through the atmosphere of Titan it determined that not only was the atmosphere clear enough to permit imaging of the surface but also the surface had a rich variety of geological features. Winds were light and diurnal changes were minimal ideal for aerial platforms

These observations reaffirmed the notion that aerial vehicles were destined to play a key role in the future exploration of Titan for 1) remote sensing since many orbital signatures were obscured by the dense atmosphere, 2) mobility, since the lakes and dunes that covered many areas of Titan of would present hazards to surface vehicles and 3) surface sampling through controlled flight near the surface [4].

Here we review the various aerial platform concepts for Titan that have been proposed since the landing of Huygens in Dec 2004, the technology development that has been undertaken and the role that these vehicles can plan in a Planetary Science Vision 2050.

Lighter Than Air LTA Concepts

: In 2008 NASA and ESA jointly developed a concept for a Titan Saturn System Mission (TSSM) which included a Montgolfiere balloon for which altitude control is provided by heating of ambient gas with radioisotopically derived waste heat [5]. TSSM competed with a concept for a mission to the moons Europa (NASA) and Ganymede (ESA) which ultimately was selected on the basis of technical maturity in Feb 2009. A joint CNES JPL technical effort on balloon development continued addressing issues of buoyancy stability and control and deployment.

: Selection of Montgolfiere balloons using RPS waste heat for Titan mission was based on their ability to float for many years in the Titan atmosphere and to change altitude with minimal energy use. However, subsequent work on helium balloons has shown that these features can also be obtained in a much more compact and easily controlled helium balloon. Life-limiting diffusion of helium through balloon envelopes at Titan temperatures was shown to be reduced by 4 orders of magnitude from that at Earth ambient [6]. Altitude control of helium balloons was shown to be feasible with very modest amounts of energy by either pumped compression or mechanical compression (Figure 1 and [7]).

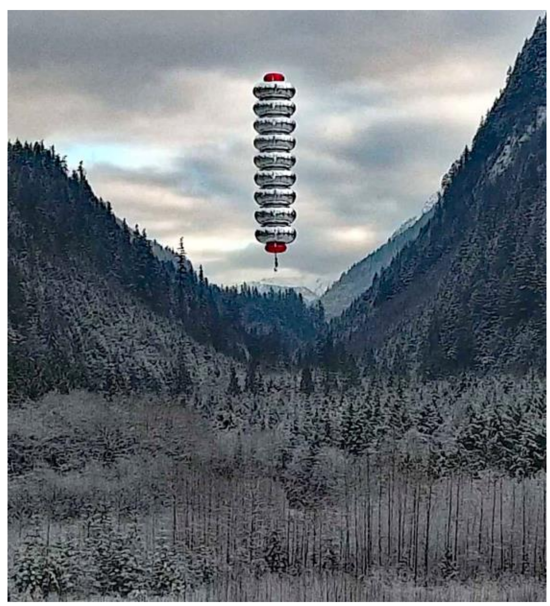

Figure 1 Mechanical Compression Altitude Control balloon is comprised of a number of segments that are compressed by shortening a tether that runs down the axis of the balloon. Release of the tether allows the balloon to rapidly ascend

Concepts for achieving lateral motion and control of the lighter than air vehicles have also been developed such as the Titan Winged Aerobot (Figure 2) was investigated in NASA's 2016 Phase 1 SBIR program.

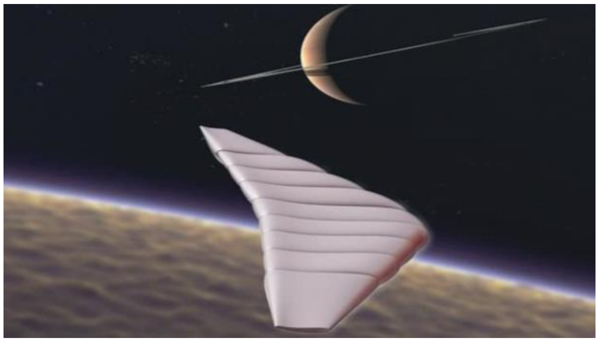

Figure 2 Concept for a Titan Winged Aerobot a hybrid balloon glider that does not require significant power either to stay aloft or to achieve lateral motion

Heavier Than Air HTA Concepts

Concepts have also been developed for both fixed wing and rotorcraft for Titan. Both take advantage of the favorable conditions on Titan for flight [5].

: Concepts for fixed wing aircraft on Titan have been developed by Lemke [8]. Despite the poor specific power of radioisotope power sources, the combination of the density of the Titan atmosphere and the very low gravity makes it practical to achieve sustained flight on Titan. The AVIATR—Aerial Vehicle for In-situ and Airborne Titan Reconnaissance [9] involved a study to fully explore the capabilities of a fixed wing aircraft.

While a disadvantage of the fixed wing aircraft is that scarce electrical power must be subdivided between the needs of staying aloft and propulsion. AVIATR addresses this by a novel 'gravity battery' climb-then-glide strategy to store energy for optimal use during telecommunications sessions. However, AVIATR cannot descend to the surface for sampling.

The dramatic expansion of drones capable of controlled descent has spurred interest in applying the same concept at the planets. A Mars Helicopter drone is currently under development at JPL targeted at flight on the Mars 2020 mission. Concepts using two coaxial counter-rotating rotors appear to provide the best thrust to weight ratio, which is crucial for feasibility in Mars thin atmosphere. In Titan's thick atmosphere and lower gravity, multicopters are feasible and offer simpler mechanical and control system designs (Figure 3 and [10]. Like the Mars Helicopter, this would be powered by a rechargeable battery which permits only short flights of the order of an hour before recharging. However, unlike Mars where the helicopter could land and recharge using a solar panel, the Titan Aerial Daughtercraft (TAD) must recharge from an RPS which is located on a Mothercraft – either a lander or a balloon.

Figure 3 Concept for a Titan rotorcraft flying over a Titan lake. The vehicle is powered with a rechargeable battery and must return to a mother craft to recharge.

Aerial Platform and Planetary Science Vision

As NASA formulates a plan for Planetary Science Vision 2050, aerial platforms at Titan should play a key role. Both LTA and HTA concepts are clearly practical and can offer unique contributions to exploration of this fascinating world. They bring the unique ability to perform synoptic coverage from altitude and in situ measurement when they descend to the surface. Aerial platform will perform a large part of the role that both orbiters and rovers have served at Mars. When the time comes for sample return aerial platforms will also perform the critical role of lifting samples from the surface to a high enough altitude from which they can be injected into space. Planetary Science Vision 2050 must include a strategy for aerial platforms at Titan.

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* IPPW is International Planetary Probe Workshop. Presentations and papers can be accessed at the IPPW archive http://solarsystem.nasa.gov/missions/ippw

Missions to special regions of Mars to find currently active Martian biosphere. A. A. Pavlov[1] and A. K. Pavlov[2], [1]NASA Goddard Space Flight Center (NASA Goddard Space Flight Center, code 699, Bldg 33, room B220, Greenbelt, MD 20771. E-mail: alexander.pavlov@nasa.gov), [2]Ioffe Physical-Technical Institute (Laboratory of Space Spectrometry, Ioffe Physical-Technical Institute, St. Petersburg, Russia).

Introduction: Finding life on other planets was and will be one of the major reasons for space exploration. Unless there is a major breakthrough in propulsion technology, Mars will remain one of the prime targets for the search of alien life even in 2050.

Current (MSL) and near future missions (e.g. Mars 2020, MSR) to Mars are focused on the search of the "extinct" life. Specifically, their approach is to find organic molecular biomarkers in ancient Martian outcrops and based on that determine if the early Mars harbored life. Although such approach is "safe" with respect to concerns of planetary protection, it has some fundamental difficulties.

Martian surface rocks are exposed to the Cosmic Rays (CRs) due to the lack of magnetic field and thin atmosphere. Recent modeling and laboratory studies demonstrate that CRs penetrate down to depth of ~4 meters into the solid rock and can either destroy or transform organic molecules. Since drilling below 4 meters is extremely expensive and there is no a priori knowledge about organic abundance at those depths, we suggest that NASA should implement a mission which will focus entirely on the search of currently active "extant" life on Mars.

Search for extant life on Mars: Ever since the successful Viking missions did not find organic molecules in the Martian soils, scientific community became skeptical about existence of an active biosphere on the surface of Mars. The interest in Martian life was re-invigorated after the controversial evidence of past life in **Allan Hills 84001** meteorite. However, it was still believed that the present Martian surface is sterile and only ancient rocks from the time of warm wet Mars could have retained tracers of the ancient life.

In the last decade, the case for Martian "extant" life has strengthened significantly. First, shallow subsurface ice was discovered during Phoenix mission at 70 degrees in the Northern Hemisphere of Mars. Laboratory studies of salty permafrost suggest that subsurface ice at such latitudes will produce liquid films of water in the soil during Northern summer months. We should expect a similar process in the Southern hemisphere. Therefore, large areas of Martian surface soil at high latitudes would have access to liquid water at least over a brief period each year. Furthermore, recurring slope linea (RSLs) have been discovered in numerous locations in the equatorial regions of Mars, suggesting a possible explanation that the liquid water can erupt sporadically in the equatorial regions as well.

Second, in the last decade there were several studies on the terrestrial microorganism which found that life can adapt and grow in the simulated Martian-like environments – low pressure, desiccation, high salt tolerance, large diurnal temperatures variations, high UV exposure etc. Given evidence of the available liquid water and the toughness of microbial life as we know it, the post-Viking assumption that shallow subsurface of Mars has been sterilized for billions of years is incorrect.

Unlike ancient biological molecules which are gradually destroyed by CRs, biomolecules from the extant life would be constantly rebuilt by life itself. Therefore, organic molecular biomarkers from the current biosphere will have a much better chance of survival against CRs exposure in the shallow subsurface of Mars. We propose that NASA should dedicate a mission to look for active or dormant Martian biosphere in the areas where liquid water is expected to be present for at least a part of the year – RSLs and shallow subsurface ice at mid-high latitudes. Such mission would require development technologies in several key areas:

1) Improve techniques of liquid water detection (including water films in subsurface soil) on Mars and adapt them for rover or balloon applications.
2) Develop new standards and controls for planetary protection protocols designed specifically for special regions research.
3) Develop in-situ "active" life detection techniques in the Martian-like conditions

In this presentation, we will introduce the basic concept of a mission to the special regions of Mars and seek feedback on its feasibility by 2050. We would like to start a discussion on the technological advancements necessary for such mission to happen in future.

MANNED MISSIONS GEOENGINEERING AND PLANETARY PROTECTION – HO SAFE IS SAFE ENOUGH
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Introduction: Sterilisation of landers, rover and other equipment sent to another world (planet or moon) can never be perfect. A sterilization process that would guarantee to kill off all life would also destroy the equipment. This is (for obvious reasons) true to an even larger extent for human astronauts. This means that if and when human astronauts eventually set their foot on potentially habitable worlds such as Mars, we have to acknowledge that if this world is habitable for earth microbes, it will be contaminated. If we ever decide to start geoengineering another world, and maybe even terraform a world that is not presently habitable for humans, it also highly probable that it will become less habigtable for any indigenous life. Making sure, or at least trying to determine the probability that a potentially habitable world is in fact uninhabited will thus be an important step before we start any geoengineering on that world, and possibly even before we let humans land there in the first place.

The questions that will be at the center of the discussion are:

* How sure do we need to be that the world in question is uninhabited before it is OK to perform certain things on that world?

* How do we connect degree of certainty to actual research setup?

* How do we balance the need for scientific certainty with the need to get on with the exploration or exploitation within reasonable time?

How certain can we be and how certain do we need to be : Establishing that a world is uninhabited is a different kind of task than showing that it is inhabited. They might sound like just opposite sides of the same coin but they are actually from a science point of view, very different. The latter task can be accomplished through one positive finding while it is not entirely clear what it takes to accomplish the former. In my presentation I will suggest that to establish that a planet is uninhabited cannot be done in the same way as establishing that it is inhabited. It will not be a matter of one amazing discovery but of successively updating the probability. In order to give green light for different kinds of activities on the world in light of this we therefore need to answer to separate questions:

* How can we determine the probability that a world is uninhabited?

* How certain do we need to be in order to give green light for different types of activities?

There is no strictly objective way of answering the second question. It is a decision we have to make based on our plans for the world in question, which in turn include science objectives, possible commercial plans and also ethical considerations.

The first question is about thow to connect degree of certainty with research setup. This is the question I will focus mostly on in my presentation. I will suggest that in this particular case, the degree of certainty that a world is uninhabited has to be decided by three factors: The number, diversity and quality of negative observations. These three factors can be measured or at least ordered with respect to certainty in a fairly objective way.

Being in time versus being right: A complicating factor is that practical decision making usually involves a time constraint. This is also true for decisions regarding exploration and even more so for decisions regarding exploitation of other worlds. This can lead to demands that we settle with a lower degree of certainty in order not to delay the missions. On the other hand, it is also very important to consider the safety of both extraterrestrial life and earth life. These obligations demand a higher degree of certainty. How can the conflict between safety and timing be dealt with in a constructive way? First of all, the fact that there is a time constraint means that we cannot postpone the answer indefinitely. If we did, it would mean one of two things. Either a death sentence to all exploration and exploitation plans of other worlds, or a carte blanche for any kind of activity on other worlds as long as no one has positively shown that it is inhabited. Both alternatives seem unrealistic.

The values (scientific, commercial or other) that can be obtained from exploration or exploitation provide us with a duty not to postpone our judgment on whether the world in question is uninhabited for too long. On the other hand, it seems equally clear that our duties to protect the life on another world as well as on our own world are at least as strong and they tell us not to be too premature in our decision.

A Bayesian approach to determining and im proving certainty: There is no objectively true answer for how to handle this dilemma. Eventually it comes down to values and the values need to be discussed by experts as well as laypeople. It is, however, also important that the discussionis are scientifically well informed. One thing we can do to help achieve this is to set the stage right for the value discussion by trying to put a number on how certaim we are that the world in question is uninhabited given what we know now and what we can do in terms of concrete sciene missions, to improve that certainty. Establishing the probability that a world is inhabited cannot be done in the traditional way by using relative frequency as a proxy for probability. If we perform 100 experiments on Mars designed to look for life and one of them provides a reliable unequivocal positive result, it does not mean that there is a one in houndred chance that Mars is inhabited, it means that Mars is inhabited. If we get zero positive results, it does not necessarily mean that Mars is uninhabited. It can just as well mean that we have not yet looked in the right place in the right way. We therefore need a way of translating exclusively negative results into a probability. This is not an easy task, but since it is important and since there will be discussions regarding how certain we are when it is time to decide how certain we need to be, it is still important to get started with this work. In order to get started I want to make two suggestions: 1. We need to base our estimates on the three factors mentioned above (the number, quality and diversity of experiments), and 2. We need a Bayesian rather than a reative frequency approach to estimating the probability, where each new failed attempt to find life leads us to update the probability based on the fact that it is one more failed test, on the quality of the test, and on whether it tests something different or in a different way than previous failed tests. I believe that if we can agree on this we have achieved something important and are at least off to a good start.

A constructive and well-informed discussion about what it takes to establish that a world is uninhabited as well as some idea about how to do it in practice, needs to be initiated as soon as possible in order to prepare for our future in space. The main purpose of this presentation is to set the stage for that discussion.

LONG DURATION SURFACE EXPERIMENTS ON AIRLESS BODIES: THE NEED FOR EXTENDED *IN SITU* MEASUREMENTS AND LESSONS FROM ALSEP.

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Introduction: Future exploration of planetary bodies, especially airless bodies such as the Moon and asteroids, will be science driven endeavors with the goal of sample return or human and/or rover-based exploration. The detailed sampling of a planetary surface, as was done during the Apollo exploration of the Moon, will drive the selection of sampling sites and the technical capabilities will drive the duration of surface stays. A critical aspect of any future exploration should be the deployment of experiments that are left behind and continue to operate long after humans leave the surface or the landed robotic or rover missions are concluded. Such long duration measurements enable additional science not possible during short duration surface explorations and afford the opportunity to measure periodic or temporally controlled phenomena.

During the Apollo program the Apollo Lunar Surface Experiments Package (ALSEP) was a multi-year geophysical and environmental monitoring station [1] that established a long baseline of measurements, which have proven to be a treasure trove of data for modern interpretation [2-11]. However, ALSEP was terminated prematurely on September 30, 1977 due to budgetary and logistical interferences, cutting short the anticipated 20-30 year lifetime [12] (with a power source of Plutonium-238, half-life of 89.6 years). Granted, the design life of the stations was 1-2 years [1], but at the time of their termination viable data were being transmitted.

Here we discuss the lessons from the ALSEP program and their implications for future long duration surface measurement packages. In addition, we discuss new approaches to such long duration experiments, an approach outside NASA's Planetary Science Division's current mode of operations.

The Need For Long Duration Surface Measurements: One of the most valuable lessons from ALSEP was that extended duration surface measurements provide critical insight into the internal (*e.g.,* seismic and heat flow), surficial (*e.g.,* dust environment), and exospheric (*e.g.,* atmospheric constituents) variability at the Moon over several years. Indeed, some experiments showed long term temporal drifts [13] that could be natural phenomena or unidentified instrument error, demanding long new term data to provide answers. The long baseline data were useful at the time in identifying, for example, variations in crustal structure as data were being collected [14, 15] but also provided, after termination of the program, a large number of events so that such data could be re-evaluated using modern techniques [6, 7].

Long baseline measurements, especially when part of a widely distributed network, provide unique opportunities to gain insight into a distinctly new dimension of the processes that act on a planetary body. An example of this is illustrated in Figure 1, where the impact of increasing spatial and temporal baselines for seismic measurements is plotted. In the case of ALSEP, the stations were distributed across the nearside and operated for multiple years. However, had the stations been left on for 10 years or more, more insight into the deep interior could have been gained.

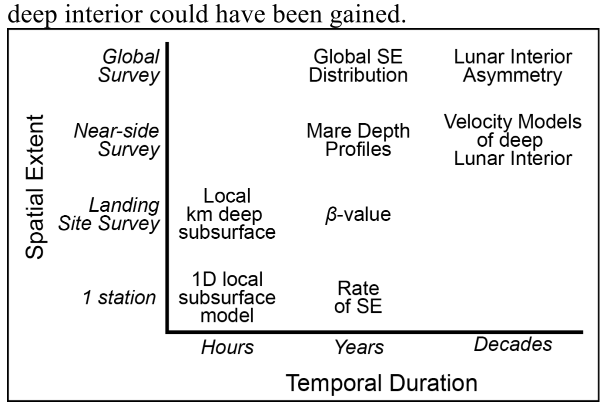

Figure 1. Diagram showing an example of the benefits of extended spatial and temporal measurements from a network of seismometers. Any other measurement on a network (heat flow, radiation environment, dust environment, etc.) would show similar improvements as a function of distribution and duration. SE= Seismic Events.

Example Measurements: While a modernized version of each of the ALSEP experiments at the Moon would be beneficial, here we identify a distinct suite of measurements. Clearly these would be dependent on the target (Moon vs. asteroid), but in general are broadly applicable. If broadly deployed to airless objects throughout the Solar System (the Moon, Ceres and other main belt asteroids, outer solar system icy moons) these packages would provide a detailed geophysical characterization of very different objects that could revolutionize how we think about interiors and surface space weathering throughout the Solar System.

In addition, future measurements should be made over as much of the lunar day as feasible, not just during lunar night as was done by several of the ALSEP experiments.

Radiation Monitoring: The CRaTER instrument on LRO has clearly demonstrated the value of extended measurements of the radiation environment at the

Moon, as a direct result of both solar and Galactic Cosmic Ray (GCR) activity [e.g., 16, 17]. A broadly distributed network of surface measurements not only would measure the entire sky for GCR radiation, but also would measure how the flux of solar radiation varies over time, interacts with the regolith to modify chemical properties, and produce secondary radiation products. The measured chemical modifications of the regolith will affect how we interpret the long-term history of space weathering and energetic particle interactions at the Moon.

Solar Wind, the Plasma Environment, and the Exosphere: Long baseline measurements of the solar wind, its interactions with the surface, and variations in the compositions of exospheric constituents [18-21] would provide important constraints on, for example, how volatiles migrate across the surface, if at all. Such measurements, especially when coupled with orbital observations [22], would provide important constraints on the influence of the solar wind and its interactions with the surface.

A long baseline system could examine the plasma-surface-volatile interaction, like that associated with solar wind hydroxylation, over a range of space plasma conditions from solar min to solar max. A local space weather station along with a local IR spectrometer could examine the dynamic effect that a strong solar storm or CME might have on surface hydroxylation. We suspect that the hydroxylation level will reach a different equilibrium during a solar storm - but given enhancements in both source protons and sputtering losses, it remains unclear if that overall level grows or shrinks. Having a space weather station with IR augmentation would also allow an examination of hydroxylation associated with meteors and meteor streams - which LADEE found to be a dominant process for driving the exosphere.

Geophysical Measurements: The seismic measurements from ALSEP have proven to be extremely useful in characterizing not only the interior of the Moon, but also for monitoring the surface and the number of impacts. The accompanying heat flow measurements show that the interior and crustal composition vary dramatically on spatial scales. This suite of measurements has yet to be improved upon on any other planetary body, and still provide for valuable data for the interpretation of the early history of the Moon. A long baseline of seismic observations, coupled with a broadly distributed array, would provide not only insight into the structure of the Moon, but also the variability in heat production from the crust and interior. When expanded to different sized asteroids and perhaps icy outer Moons, this geophysical package would revolutionize our understanding of interiors and be an incredible comparative planetology dataset.

Lessons from ALSEP: At the premature conclusion of the ALSEP program, five recommendations were made [1] that should be heeded in similar future experiments. **1**. Personnel changes should be minimized during the duration of the experiments. **2.** Ground hardware and software changes should be minimized. **3.** Data should be collected at regular intervals across the entire lifetime of the experiment. **4**. All data downlinked should be stored in as modern a method as possible, and all data need to be both time-tagged and registered to each other. **5.** During deployment, the experiments should be located as far as possible from interfering sources (launches, cabin outgassing).

We expand those lessons here, given the nearly 40 years since the termination of ALSEP. Issue 1 is perhaps the most in conflict with the current model for how planetary missions are operated. NASA should treat these experiments as facilities, with consistent funding and support over decades. In addition, where experiments are too long to accommodate a single science lead, a succession plan should be implemented so new personnel will have a seamless transition. The surface experiments must also be easily and quickly deployable. Also, where possible, surface measurements should be coupled with long-term orbital observations as well (akin to surface weather stations on Earth and orbital weather monitoring). The data from these stations should also be made available in near-real time, following an initial validation period. As such the impact to the community would be felt immediately and over a long period of time.

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It's Infrastructure!

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There have been countless workshops, conferences, meetings, and back-room discussions focusing on the need for infrastructure in exploration of the Solar System. That's not 'improving' or 'fixing' infrastructure, but *creating* an infrastructure that enables serious and safe space exploration and encourages new and innovative activities.

Why is infrastructure so essential for the future? It's simple: ultimately, lack of infrastructure is a cost barrier for progress. Currently all space endeavors (large and small) must plan and implement everything that will allow them to meet an objective: launch, navigation, communication, operations, data storage and transmission, analysis, maintenance, etc. Although a large fraction of these needs are common to all space activities, each separate space endeavor must carry the full burden of cost (including design, implementation, and oversight). The duplication and re-invention is an extraordinary high and often prohibitive cost.

What are the key needs currently envisioned? Highly interwoven components include:

1) *Physical transportation*. Cost effective launch capability from Earth is a most obvious continuing need. In addition during the decades ahead, traversing to diverse planetary bodies (e.g., the Moon, Mars and Beyond....) and effectively operating on the surface will drive technology and test efficiency.
2) *Remote communication*. We are no longer in the "Space Age" but have been in the "Digital Age" for quite some time. The current generation is no longer awed by an image of something new. Expectations are instead for high definition videos – in color as a minimum. Of course, 'color' now also includes hundreds of channels. If NASA wants to remain relevant, the dismal data pipeline needs an overhaul, including long-term plans for global communication networks at the Moon and Mars.
3) *Access to power and resources.* Assuming 1 & 2 above are met, any significant exploration activity needs power to carry out its operations and eventually resources (local) to continue and/or modify its plan.

What are the roadblocks? Again, cost and timing: establishing a stable infrastructure requires near-term commitment of resources with the return being long-term. Nevertheless, the longer such an investment is postponed, the more difficult it becomes to implement. In addition, implementing appropriate infrastructure is an excellent area where serious international joint efforts could be highly productive and cost effective.

What are examples that strong space-based infrastructure would enable for 2050? A *Modern* NASA would provide leadership in space exploration. Lower cost for individual activities allows small missions to be undertaken by new international partners or private companies. Virtual reality for activities on the Moon and near-Earth Asteroids [and through autonomous navigation, delayed virtual reality for Mars, Venus, and Europa] will relate to the current generation. Providing global access to diverse sites on the Moon allows developing serious partnerships across a broad international activity. Etc., Etc.

SOLAR SYSTEM GEOPHYSICS WITH THE SILICON SEISMIC PACKAGE: FROM EARTH TO EUROPA.
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Introduction: The current planetary science decadal survey has identified "building new worlds" as one of its three themes. Within this theme, one priority question is "what governed the accretion, supply of water, chemistry and internal differentiation of the inner planets?" [1]. The answer to this question can be addressed by studying the seismic activity and therefore internal structure of Solar System bodies, using seismometers placed on their surfaces. In this abstract, we briefly review the current state of the art, future science goals, performance requirements, and the technology development needed to meet those requirements. The 2018 InSight mission Short Period (SP) microseismometer is suggested as a suitable candidate for a low mass, low power, and high sensitivity seismometer applicable to a broad range of studies.

Current developments: The current state of the art in in-situ seismometry is the 2018 Discovery-class mission to Mars, Interior exploration using Seismic Investigations, Geodesy and Heat Transport (InSight). Its prime instrument, Seismic Experiment for Interior Structure (SEIS), consists of six seismometers: three Very Broad Band (VBB) and three Short Period (SP) units. The SPs cover the frequency range of approximately 0.5 to 25 Hz with a noise floor of 10^{-9} m s^{-2} Hz$^{-0.5}$.

Future science goals: Between now and 2050, a considerable amount of information could be gained on the internal structure of Solar System bodies through seismometry. A prime target is Europa, where seismometry may be used to constrain the geometry of the subsurface ocean [2]. Another possible destination is Venus, and seismometers can be adapted to perform as gravitometers for use on, for example, a Ganymede orbiter. These destinations present a range of challenging requirements, particularly in terms of temperature and ionizing radiation.

Performance requirements: The desired long-term level of seismometer performance is outlined in NASA technology roadmap *TA 8: Science Instruments, Observatories, and Sensor Systems*. The requirements are summarized as a 10^{-10} m s^{-2} Hz$^{-0.5}$ noise floor over the frequency range 0.01 to 10 Hz with a resonant frequency of 0.03 Hz and Q of 1000. Such a seismometer must operate over a temperature range of −220°C to 100°C, and tolerate up to 10^{17} fast neutrons cm^{-2} [3].

Technology developments needed to meet these requirements include "electrostatic zeroing" of the resonant frequency, "tunnel diode readout" and "force feedback" [3].

Our current work in improving the SP's performance indicates an alternative approach to achieve this performance. Reducing the resonance of our suspension using a non-linear design rather than electrostatic zeroing allows an improvement by a factor of 30 to 100 in the noise floor in our next generation Silicon Seismic Package (SSP).

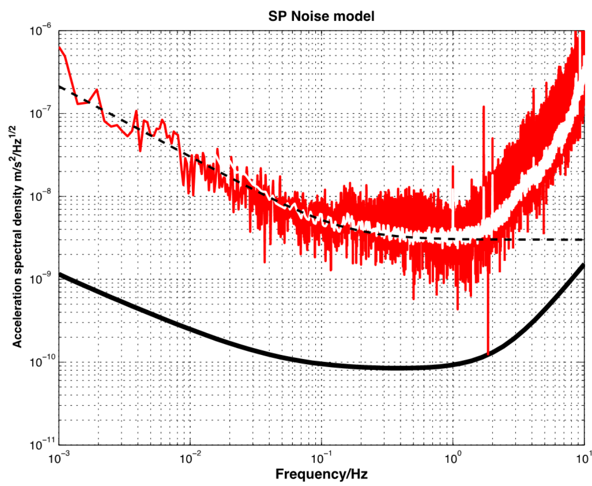

Fig. 1. The current performance of the SP (red), and the modeled performance of the SSP (black).

The SSP design remains within the existing resource envelope of 600 g for a three-axis instrument, drawing 270 mW of power, whilst being robust to shock (up to 2000 g) and vibration (30 g rms), and includes a self-leveling capability. This allows the inclusion of SSP in non-dedicated geophysics missions whether as a drop-off module from a rover or as part of a payload as for Europa.

Environmental conditions impose further material properties limitations on the SSP: some typical values of relevant parameters are listed in Table 1, along with their values on Earth for comparison. Cross-referencing these parameters with the properties of materials used in the SP microseismometer yields Table 2. Green indicates adequate, yellow uncertain, and red inadequate performance for each material under the environmental conditions of the bodies considered. For example, the surface temperature of Venus, 740 K, is above the melting point of the two solder alloys, eutectic Sn-Ag-Cu (SAC) and eutectic Au-Sn (AS) which are 493 K and 551 K respectively. Alternative solder and/or bonding methods are required.

Parameter	Earth	Moon	Mars	Venus	Europa	G'mede
Typical max. diurnal surface temperature (K)	290	390	240	740	130	150
Typical min. diurnal surface temperature (K)	280	100	180	740	90	90
Mean surface temperature (K)	295	250	210	740	100	130
Diurnal temperature variation (K)	10	290*	60*	0	40*	60
Typical ionizing particle flux (cm^{-2} s^{-1})	0	1	1	0	10^7 – 10^8	10^3 – 10^7
Acceleration due to gravity at surface ($m\ s^{-1}$)	9.81	1.62	3.70	8.90	1.31	1.43
Ambient surface pressure (kPa)	10^2	10^{-13}	1	10^4	10^{-10}	10^{-4}
Global magnetic field?	Y	N	N	N	N	Y

Table 1. Environmental parameters relevant to the SP microseismometer for Solar System bodies of interest. Particle flux is in the approximate energy range of 10^1 to 10^5 keV; Moon and Mars flux for Galactic Cosmic Rays (GCRs) only. *Diurnal temperature variation at low latitudes [4-12].

Parameter	Earth	Moon	Mars	Venus	Europa	G'mede
Silicon						
Silicon dioxide						
Sn-Ag-Cu (SAC) alloy						
Au-Sn (AS) alloy						
Pyrex						
Gold						
Titanium						

Table 2. Suitability of materials used in the SP microseismometer for various bodies of interest.

Possible missions: With the further development of SP microseismometer technology, this instrument will be suitable for missions such as those listed in the TA 8 technology roadmap: a Flagship mission to Europa and a New Frontiers Lunar Geophysical Network with notional launch dates in 2022 and 2029.

Such missions would greatly increase our understanding of the internal structure of these bodies and the processes that created them, helping to answer subsequent decadal surveys' questions on the origins of the Solar System.

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CAPABILITIES TO ENABLE FUTURE PLANETARY SCIENCE. J. B. Plescia[1], [1]The Johns Hopkins University, Applied Physics Laboratory, MS200-W230, Laurel, MD 20723 (jeffrey.plescia@jhuapl.edu)

Introduction: Since the launch of Explorer 1 in 1958, scientific satellites have grown in capability and complexity and provided a wealth of data for numerous scientific disciplines for bodies across the solar system. The program of robotic exploration has followed the general pattern of flyby, orbit, land, rove and eventually returned samples. As the capabilities of exploration have increased, our understanding of different planetary bodies has increased; numerous questions have been answered and many more have been raised. With the exception of Mars, the exploration of other solar system bodies has been intermittent although the capabilities have steadily increased with time.

While early on the objectives were simply to understand the basic characteristics of a body (e.g., Mariner 2 at Venus, Mariner 4 at Mars, Pioneer 10 at Jupiter), later mission objectives became much more specific and quantitative. The list of outstanding scientific questions is perhaps longer today than it was in 1958, although the questions now are more detailed and complex.

We have characterized the surface, and in some cases the shallow sub-surface, of the terrestrial planets and the Moon as well as the icy satellites, small bodies and dwarf planets of the outer solar system. In some cases orbiting spacecraft have provided global coverage over long periods of time, in other cases only partial coverage has been accomplished (e.g., New Horizons at Pluto). The interiors of all of the solid bodies, with the exception of the Moon, remain largely unexplored, and even for the Moon the data are limited. While orbital geophysical data have been modeled to provide insight into interior structure, such models are somewhat non-unique.

In order to make major progress on the complex outstanding questions, a set of capabilities that either are currently limited or do not exist as flight hardware will be required.

Power: Missions to the outer solar system, areas of permanent shadow (e.g., lunar polar craters) and energy-intensive surface mission (e.g., rovers) are difficult or impossible to accomplish with solar power. While schemes have been devised in some cases to conduct missions within the context of solar power alone, higher energy sources are required to efficiently conduct such missions. Nuclear power is typically considered the non-solar option. Fully developing advanced power system such as the Sterling engine as well as ensuring sufficient nuclear fuel are critical to expanding exploration capabilities and enabling missions. These systems must be available on a routine basis. While nuclear-fueled missions carry an administrative overhead that solar missions do not, the scientific return typically outweighs the administrative cost.

Communications: Communications between a spacecraft and the Earth can be limited by spacecraft resources such as power and size of the spacecraft antenna and by visibility of the spacecraft from the Earth.

Missions in solar orbit or in orbit around a planetary body can typically be observed either continuous or intermittently from the Earth via the Deep Space Network, except during periods of opposition when the spacecraft is close to or obscured by the Sun or when the spacecraft is hidden from view by the planet.

Spacecraft on the surface of planet can experience periods when they are not in direct contact with the Earth (e.g., Mars rovers). Gaps in communications on the surface are typically much longer than for orbiting assets (e.g., more than 12 hours for Mars). Surface assets can also be located in areas that never have direct contact with the Earth (e.g., lunar polar craters and the lunar farside).

To facilitate greater data return at high rates, improvement to the communications strategy are needed. Improvements to the spacecraft side include increased power and larger antennas for increased signal strength and data rate. A significant increase in data rate is possible with laser communications. Laser communication has been demonstrated on a number of missions, but has not yet been employed as the baseline system. Such a system has the capability to increase the link between the Earth and the spacecraft by orders of magnitude relative to radio transmission.

For surface rovers, the landed mass is best devoted to the mobility and science systems. Communications with the Earth can be handled by an orbiting communications infrastructure thus minimizing the requirements of the rover. Areas such as lunar polar craters and the lunar farside that are never visible from the Earth will require an orbital communications infrastructure to enable the missions. Continuous communications with an asset on the martian surface would also require an orbital infrastructure and could significantly increase the data return.

The current set of Mars orbiters has been used to communicate with rovers on the surface. But these orbiters have their own mission objectives and limitations. To fully exploit surface systems in particular locations, an orbital communications infrastructure is required.

Network Systems: Geophysical information regarding the interior of a planetary body can only be obtained by instrument networks on the surface that operate continuously. This was demonstrated by the Apollo seismic network that provided information about lunar seismicity and internal structure. Monitoring surface meteorological conditions (e.g., Mars, Titan) or solar wind / surface interaction (e.g., Moon, Mercury) also require dispersed stations that operate continuously.

While the Apollo network provided data on the interior of the Moon, its lifetime and the station locations limited its usefulness. Long-lived (decadal) systems will need to be deployed on the surface of the terrestrial planets, the Moon, satellites of the outer planets and dwarf planets, all of which probably have complex internal structure and some level of internal seismic activity. These systems can all be passive in the sense that they simply detect natural events. However, active experiments can provide critical information for large bodies and are probably required for small bodies (e.g., asteroids) that lack natural events. The impact of the Apollo SIVB and Lunar Module Ascent Stage on the Moon clearly demonstrated how such high-energy events reveal details of the interior structure. Such active experiments need not be large like the SIVB, but can employ small simple energy sources such as the Apollo 17 explosive charges and the thumper and mortars on Apollo 14.

Such network systems must operate continuously such that events are not missed and to allow the highest quality data. Continuous operation thus requires either a solar power system with sufficient battery capability or nuclear power to operate at night. Network systems need not have continuous communications, data can be stored and returned intermittently.

***Subsurface Access*:** The surface of a planetary body is composed of material that has been altered from its pristine state, in some cases by extensive physical disaggregation (e.g., lunar and asteroid regolith) and in other cases by weathering processes (e.g., Mars). While understanding the degradation processes is important, fresh, unweathered samples are required for many questions. To obtain fresh material, the sample must be acquired from depth; that depth may be only cm for hard rocks or it can be many meters for soil- or regolith-covered bodies.

Subsurface samples from depths of up to several meters were acquired by the Apollo and Luna missions. In case of Mars, subsurface samples have been acquired to depth of a few cm. These samples all represent altered material. To obtain appropriate material, drilling will have to be done to greater depths and into hard rock. This will require drilling capability similar to the Apollo Lunar Surface Drill. However, in the absence of an astronaut, the system must be mounted on a spacecraft platform that has sufficient mass and power to allow stable drilling and systems to process the material.

In Situ Science: Instrumentation used on planetary surfaced has advanced significantly over the radiation densitometer deployed on Luna 13. A variety of instrumentation has been flown to analyze the atmosphere and surface materials of different bodies. There has, however, been a sentiment that many types of analysis can best be done on Earth with a returned sample than in situ - radiometric age dating for example.

There is no question that better analyses can be done on a sample in a terrestrial laboratory than a spacecraft. However, sample return missions are complex, risky, expensive, and are not likely to be frequent because of those issues. Using the age dating example, several major questions for both the Moon and Mars could be satisfied with radiometric ages of key surfaces that would provide important information about the cratering rate and the volcanic and geologic history of the bodies.

In situ analyses could be used to provide a range of data that would allow a sample return mission to find the appropriate samples and ensure that the primary science question for that sample is indeed answered. Sample return should be a mission of last resort when it is clear that the science can only be advanced by a returned sample

Summary: Our understanding of the processes and events that have occurred within the Solar System over the last 4.5 Ga grow with time. Every planet (including an ex-planet) and many smaller bodies have been visited. We have basic knowledge about each of them and the simple questions have been answered. Now, the questions being posed are complex and will require not only additional missions, but capabilities and approaches that have not been used in the past, or used in only a limited fashion. Having all of these capabilities would be an incredible boon to robotic missions. However, even a few of them would allow faster and deeper progress than the current capabilities.

PROSPECTS FOR DETECTING CRYOVOLCANIC ACTIVITY IN EXOPLANETARY SYSTEMS.
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Introduction: "Ocean planets" are a class of H_2O-rich exoplanets [1-7] roughly resembling larger versions of the satellites in our outer solar system [2-3, 8-9]. Geophysical processes operating on these cold, low density worlds may therefore be similar to processes operating on our solar system's icy moons. Explosive cryovolcanism has been observed on several of our solar system's icy moons [10-14] (Fig. 1). Cryovolcanic activity on icy satellites may indicate the presence of a subsurface fluid reservoir, possibly, an internal ocean.

By analogy, surface venting on cold ocean planets could be indicative of fluid reservoirs within. Given the limits of current instrumentation, spectroscopic detection of H_2O and other molecules that are explosively vented onto planetary surfaces may be the the only way to infer the presence of subsurface oceans in these bodies and indirectly assess their habitability. Detections of cryovolcanism on cold, H_2O-rich worlds could therefore be used as a proxy to constrain their habitability. Here, we discuss the prospects for detecting these dynamic processes using next-generation telescopes. Our results suggest that a search for plume activity on icy exoplanets should be a priority in the coming decades.

Approach: To determine whether geyser-like plumes would be detectable in exoplanetary systems, we apply the physics underlying ballistic eruptions [15-17] to frozen ocean planets to estimate possible plume characteristics. We consider a low-density (ρ = 2 g/cm^3), 2.5 Earth-mass planet with a 270 K surface temperature orbiting an M-dwarf star. We assume the planet has a negligible atmosphere, so that temporary excesses in H_2O vapor, CO_2, and other molecules associated with explosive cryovolcanism [13,18] can be easily detected.

We estimate plume particle eruption velocities, plume height, width, and particle number densities, under the assumption that water vapor, CO_2, and SO_2 serve as the volatiles driving the eruptions. Water vapor and CO_2 have been detected in plumes on Enceladus [18]. Water vapor is also the primary plume constituent on Europa [13], but CO_2 and SO_2 have been detected on the surface [19]. We follow the approaches of Fagents et al., [16] and Quick et al. [17] to estimate plume parameters, assuming an initial eruption temperature T = 273 K. The eruption velocity, V, of the plume particles is:

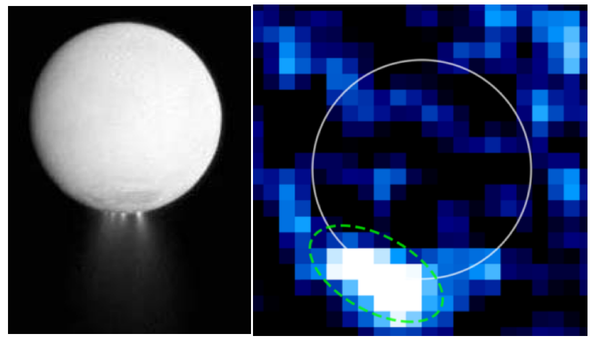

Figure 1. Explosive cryovolcanism in the outer solar system. **Left:** Geyser-like plumes erupting from the south pole of Enceladus (Credit: NASA/JPL-Caltech/SSI). **Right:** HST UV observations of putative plumes at Europa's south pole from [13].

$$V = \sqrt{2nR_G T\kappa/m(\kappa-1)} \qquad (1)$$

where n is the mass percentage of gas in the plume, R_G is the gas constant, κ is the ratio of specific heats of the entrained gas, and m is the molar mass of the entrained gas in kg/mol. The maximum height that a plume with a 45° ejection angle will extend above the surface of the planet, $H = V^2/2$g. Here, g = 6.95 m/s^2 is the acceleration due to gravity. The plume's particle number density is:

$$P_N = \frac{V_{Plume}}{V_{particle}} = \frac{R^2 H}{16 r_p^3} \qquad (2)$$

where according to [17], R_p = R/2 = H sin(2θ), θ = 45°, and $V_{Plume} = \frac{\pi R_p^2 H}{3}$ is the volume of the cone-shaped region of the plume that will be observed by telescopes (Fig. 2). The quantity $V_{particle}$ is the volume of a spherical icy particle with radius r_p = 0.5μ [17].

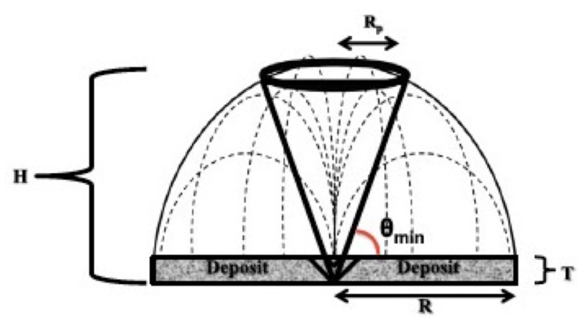

Figure 2. The central, densest portion of a plume has been modeled as an inverted cone. Figure from Quick et al., 2013 [17].

Results: Plumes with H_2O as the primary volatile constituent will reach higher above the planet's surface than plumes composed of CO_2 or SO_2, and may therefore be more easily detected by space telescopes. For example, plumes consisting of ~ 90 wt% H_2O will extend approximately 54 km above the surface, while those consisting of CO_2 and SO_2 in the same proportions will extend only 30 and 20 km above the surface, respectively (Fig. 3). The estimated particle number density, P_N, of a plume containing 90 wt % H_2O vapor is 4×10^{21} N/m^2, while $P_N = 2.2 \times 10^{21}$ N/m^2, is a factor of two lower, for a plume containing 90 wt% CO_2. The particle number density, $P_N = 1.5 \times 10^{21}$ N/m^2, for a plume containing 90 wt% SO_2. In the next iteration of this model, we will explore detection limits for plumes erupting on cold ocean planets with masses between 0.5 and 5 Earth masses.

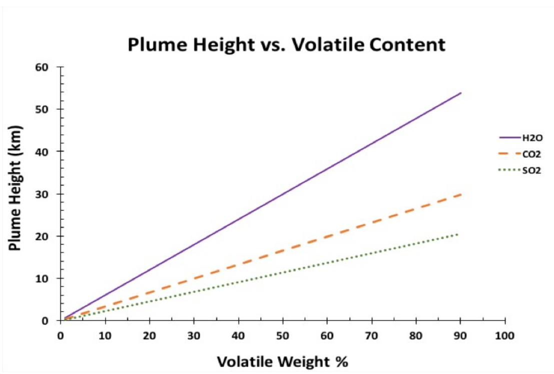

Figure 3. Plume height as a function of mass percentage of gas for H_2O vapor, CO_2, and SO_2.

Detection Possibilities: Direct detection of explosive cryovolcanism during transit may be possible with a next-generation, 10-meter class, *Kepler*-like space telescope. Plumes that are concentrated in one hemisphere on a planet with no atmosphere (e.g., Fig. 1) would block extra starlight during the ingress or egress of the planetary transit. Of order a hundred geyser-like plumes may be currently erupting at Enceladus' south pole [20]. For similar conditions on an ocean planet, if each plume is at least 40 km high by 50 km wide, with an opacity = 1, then 100 plumes would cause an extra decrease of 0.5 ppm in the integrated transit light curve. For reference, the smallest transit detected by the *Kepler* telescope is 12 ppm deep. Conversely, if H_2O and CO_2 are the dominant plume constituents [e.g., 18], resolving the transit with spectroscopy will lead to higher signals and easier detectability if we observe H_2O and CO_2 emission lines. In near-infrared wavelengths, JWST has been estimated to be barely able to detect H_2O and CO_2 features of 2-6 ppm when transits are binned over a 5 year period [21].

Exoplanet Interiors: Each of the icy bodies in our solar system that exhibit explosive cryovolcanism are thought to harbor subsurface liquid. Europa likely has a subsurface ocean six times the volume of Earth's ocean beneath an ice shell tens of kilometers thick [22]. Enceladus also contains substantial internal liquid reservoirs, which may or may not form a single, globally interconnected ocean [23]. The balance between radiogenic heating and convective/conductive heat transport also permits an ocean on Triton [24]. Similar to the bodies in our Solar System, it is likely that 2.5 Earth mass, water-rich superearths that have geyser-like plumes will also have subsurface liquid water oceans and perhaps even ice tectonics [25]. If plume activity were detected at a cold ocean planet, it would therefore provide strong support for the presence of subsurface pockets of liquid water.

Each of our Solar System's cryovolcanically active bodies has also experienced an episode of tidal heating, during which their orbital energy has been dissipated in their interiors as heat [26]. In addition to providing a source of energy, tidal forces also provide a means of opening vents for explosive eruptions: Plume eruptions on Enceladus correspond to times in its orbit where vent source regions experience extensional stresses [e.g., 27]. For exoplanets that are close to their parent stars and harbor liquid oceans, tidal heating can generate TW heat flows, comparable to the present-day heat flow of the Earth [28]. The potential powered by radiogenic heating alone in the absence of tidal forces has not yet been addressed for ocean planets; this is a subject for future work.

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Scientific and Technological Approaches to Searching for Extant Life in the Solar System. R. C. Quinn[1], A. J. Ricco[1], A. Davila[1] , J. E. Koehne[1], C. P. McKay[1], C. E. Dateo[1], M. L. Fonda[1], [1]NASA Ames Research Center, Moffett Field, CA 94035 [Richard.C.Quinn@nasa.gov].

Introduction: Future directions for investigations and measurements identified in the decadal survey Vision and Voyages for Planetary Science in the Decade 2013-2022 include direct methods to search for extant life. Within the framework a 35-year science vision for future decades extending into the 2020s and beyond, "Ocean Worlds" of the outer Solar System (e.g., Enceladus and Europa), as well as Mars, represent accessible targets that likely provide habitable environments that may support extant life. NASA Ames Research Center (ARC) is currently developing a multi-dimensional approach, led by astrobiology scientists in the ARC Space Sciences & Astrobiology Division, technologists in the ARC Exploration Technology Directorate, and small payload engineers in the ARC Mission Design Division, to enable the definitive detection of extant extraterrestrial life in future NASA missions.

Science Approach: While no definitive definition of life exists, a living organism can be described as a "self-sustained and self-enclosed chemical entity capable of undergoing Darwinian evolution" [1]. In a biochemical context, self-sustenance requires the use of catalytic molecules to transform energy and drive the metabolic processes responsible for growth, reproduction, maintenance of cellular structures, and response to the environment. Earth life uses amino acids to build catalytic polymers (i.e. enzymes, a subset of proteins). In order to contain their metabolic machinery, organisms must be self-enclosed, and on earth this requires the use of lipid membranes that separate the intracellular space from the exterior environment, regulating the traffic of chemical substances in and out of the cell even as they "sense" and respond to external stimuli. When faced with environmental challenges, populations must be capable of undergoing Darwinian evolution, and this requires that genetic information be encoded and stored in a manner that is reliable and stable but at the same time mutable. Lovelock (1965) first pointed out that biochemistry at its most fundamental level occupies a relatively narrow chemical space, because life only utilizes a selected set of organic compounds to build larger, more complex molecules. Our approach to the development of methodical searches for extant life places biochemistry at the center, and focuses on aspects of life that are likely to be universal across the entire biochemical space.

Technology Approach: Our multi-dimensional technology approach leverages ARC nanosatellite space biology and astrobiology technology development and fabrication capabilities including stringent sterility and cleanliness assembly approaches, as well as microfluidic design, development, fabrication, integration, sterilization, and test approaches. Technical constraints will inevitably limit robotic missions that search for evidence of life to a few selected experiments. Our approach includes the search for simple building blocks, more complex biomolecules involved in basic biochemical functions and information storage; and structures that are required for cellular life to exist. This strategy allows us to cover a broad biochemical space and maximize the chances of a (true) positive result, even as the chances of a false positive result are minimized. This approach not only offers complementarity, but also reinforces the interpretation of the data and minimizes ambiguity.

Key to enabling this approach are ARC advances in the development of automated microfluidic handling and manipulation technologies for use in microgravity. These technologies have been successfully demonstrated through a series of small-sat NASA missions including GeneSat (3U cubesat), PharmaSat (3U), O/OREOS (3U), SporeSat (3U), and the upcoming EcAMSat (6U) and BioSentinel (6U). Currently at ARC, these fluidic processing technologies are being coupled, as front end systems, with measurement technologies to enable the search for extant life in the solar system. The measurement technologies in development at ARC, among others, include luminescent imaging for identification of microscopic biological structures, and chemical sensors for the detection of molecular biological building blocks and complex biomolecules. The combination of microfluidic systems with chemical and biochemical sensors and sensor arrays offer some of the most promising approaches for extant life detection using small-payload platforms. These systems can provide high sensitivity with limited power, mass, and volume requirements making them a logical choice for small payload implementation and an attractive alternative to traditional analytical instrument approaches. These microfluidic approaches also allow for in situ chemical synthesis of active sensor interfaces at time of use. Through in situ synthesis, shelf-life limitations of sensors that utilize detection mechanisms that rely on highly reactive chemical interfaces (e.g. enzyme, membranes, thin-films etc.) can be overcome providing viable technologies for long-duration space missions. **References:** [1] Benner, S.A. (2010) *Astrobiology, 10,* 1021–1030. [2] Lovelock, J.E. (1965) *Nature*, 207(997), 568-570

ADDRESSING POTENTIAL CHALLENGES AND OPPORTUNITIES IN THE YEARS BEFORE PSV 2050: ANTICIPATING REVOLUTIONS STILL TO COME IN SCIENCE, TECHNOLOGY AND SOCIETY.

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Introduction: As we undertake strategic planning for long-duration science exploration, it is also important to anticipate and address potential future challenges and opportunities, many of which lie outside the usual planetary science disciplines. Various groups in the astrobiology and space mission communities have already begun to focus on these 'other' topics and areas that will need to be addressed if we are to realize our long-term multidisciplinary visions in planetary sciences in the coming decades. Among the important R&TD areas that have been recognized include: a) planetary protection knowledge gaps and requirements, especially in event of detection of life elsewhere in the Solar System; b) multidisciplinary R&TD needs for accomplishing long-duration human flight and developing science-supportive infrastructure beyond Earth orbit; and c) considering the revolutionary effects of advances in IT and robotics that approach human-level capabilities.

This proposed panel presentation will identify recognized science & technology concerns related to human missions to Mars and other locations beyond Earth orbit. Speakers will map and prioritize the R&TD gaps and indicate their importance for making incremental progress towards realizing PSV goals. Addressing these R&TD challenges as part of long range planning is essential not only for overall mission success, it will also help fulfill policy requirements, ensure the integrity of science investigations, and answer potential societal concerns about human activities on planetary surfaces as well as upon return to Earth.

The invited panelists will provide overviews and summary findings from several recent US and international workshops involving scientists and mission planners from government agencies and commercial entities alike.

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OBTAINING AND USING PLANETARY SPATIAL DATA INTO THE FUTURE: THE ROLE OF THE MAPPING AND PLANETARY SPATIAL INFRASTRUCTURE TEAM (MAPSIT). J. Radebaugh[1], B. J. Thomson[2], B. Archinal[3], J. Hagerty[3], L. Gaddis[3], S. J. Lawrence[4], S. Sutton[5], and the MAPSIT Steering Committee. [1]Department of Geological Sciences, Brigham Young Univ., Provo, UT, janirad@byu.edu; [2]Department of Earth and Planetary Sciences, Univ. of Tennessee, Knoxville, TN; [3]USGS, Astrogeology Science Center, Flagstaff, AZ; [4]NASA Johnson Space Center, Houston, TX; [5]Lunar and Planetary Laboratory, Univ. of Arizona, Tucson, AZ.

Introduction: Planetary spatial data, which include any remote sensing or *in situ* data or derived products with sufficient positional information such that they can be projected onto or associated with a planetary body, continue to rapidly increase in volume and complexity. These data are the hard-earned fruits of decades of planetary exploration. Maintaining these data using accessible formats and standards for all scientists is essential for the success of past, present, and future planetary missions. The Mapping and Planetary Spatial Infrastructure Team (MAPSIT) is a group of planetary community members tasked by NASA Headquarters to identify and prioritize the spatial data infrastructure needs for research and analysis using NASA's past, current, and future planetary science missions.

Planetary Spatial Data and MAPSIT: The extraction of scientific knowledge from planetary mission data relies on several steps of refinement of the raw data from instruments. One of the most important steps is to place the data into a recognized spatial framework. Creating scientifically useful information is often a major research and development effort in itself. To complete this process, goals need to be identified, missions need to be properly designed, and instruments need to be appropriately developed and calibrated. The software tools and content distribution platforms required for scientists to obtain, process, and analyze planetary mission data require continuing development and maintenance. For these reasons, community coordination and strategic planning for the use of planetary spatial data are essential for the success of planetary exploration.

To address the critical lack of a community-wide organization driving strategic spatial infrastructure planning for planetary science and exploration, the Planetary Science Subcommittee of the NASA Advisory Council (NAC) endorsed the formation of a group to coordinate NASA strategic planning needs for planetary spatial data. To this end, NASA and the USGS have worked together to establish MAPSIT, which has steering committee membership drawing from most aspects of planetary spatial data expertise and solar system bodies. MAPSIT's mission is to ensure that ***planetary spatial data are readily available for any conceivable investigation, now or in the future***. MAPSIT has several functions: (1) Provide community findings concerning the scientific rationale, objectives, technology, and long-range strategic priorities for geologic mapping [1] and spatial software development (e.g., [2]); (2) Encourage the development of standards for present and future planetary missions and research activities, coordinate systems, mapping, geologic mapping, cartographic methods and nomenclature; (3) Help define community needs for critical research and planetary mission infrastructure, particularly software tools and content archival and delivery systems; (4) Provide findings on the accuracy and precision required for spatial technologies and products; and (5) Coordinate and promote the registration of data sets from international missions with those from US missions to optimize their combined utility.

MAPSIT will help enable the broad spectrum of planetary spatial data and programmatic capabilities required to effectively execute robotic precursor and human exploration of the Solar System. These include (but are not limited to) the science analysis of planetary surfaces, the identification of safe landing sites, the down-selection of sample acquisition locations, hazard assessment, and the spatial characterization of *in situ* resources [3,4,5].

Immediate Goals: There are numerous, high-priority goals that the MAPSIT-represented community is focused on addressing in the near future, including:

- How should the current, unprecedented influx of high-volume, planetary mission data (e.g., Mars Reconnaissance Orbiter, Lunar Reconnaissance Orbiter, MESSENGER) be geodetically controlled and integrated to enable science and operation of current and future missions?
- How should global, regional, and local topographic models be created from multiple data sets?
- What requirements should be developed for missions to follow during the formulation and definition stages to mitigate subsequent growth of costs?
- How can research and analysis programs support strategic development of mapping procedures for new and complex products?
- How should community input be obtained and used to prioritize product development on near-term time scales?
- How can planetary spatial data products be used to enable and facilitate future human exploration and *in situ* resource utilization? [6]
- When and how should geodetic analysis and mapping tools be developed and be tested for accuracy and usability?

- How can training in planetary spatial data be established or encouraged so that existing expertise is passed on to next-generation workers?
- How can we fully leverage the vast and continuing increases in computer capability as well as the larger software-driven "Big Data" community to further planetary science goals?

One example of in-depth assessment that MAPSIT can facilitate includes addressing the needs for software tools to handle the increasingly complex instruments and vast data volumes of current and planned missions. Such software needs include: (1) faster and more robust matching between disparate data types, enabling new types of data fusion; (2) the ability to simultaneously adjust data from different platforms (e.g., orbital, descent, lander, and rover) and data types (e.g., images, radar, and altimetry); and (3) new tools to combine different methods for generating topographic information.

Planetary Data in 2050: By 2050, we anticipate that extensive planetary science mission activities will have driven NASA and its international partners to make great advances in the tools and practices necessary for planetary spatial data. Following current computing trends, it is likely that artificial intelligence specifically and heuristic algorithms generally, coupled with improvements in computing power and user interface design, will have dramatically decreased the computational and personnel overhead required to derive useful data products. There will be a need to stay in touch with new technologies and standards that will be developed for similar terrestrial work.

A New Strategic Plan: MAPSIT's first task is to synthesize a new cohesive Planetary Geospatial Strategic Plan (PGSP). To build the strategic plan, MAPSIT will solicit broad stakeholder input through community surveys and town hall meetings, such as at LPSC and at a MAPSIT community meeting in conjunction with the June 2017 Planetary Data Workshop. A partial goal is to recommend and prioritize the needed data products and infrastructural developments, following a process much like that of the Lunar Exploration Roadmap [7], the 2015 SBAG Goals Document [8] and in part the OPAG Roadmap for Ocean Worlds. The roadmap will build on the Planetary Spatial Data Infrastructure (PSDI) document [9], which outlines and defines all aspects of planetary spatial data and lays out the needs, capabilities and tasks of the community. This builds on a similar document for Earth Sciences, the National Spatial Data Infrastructure (NSDI) document [10]. It is envisioned that the roadmap will be a living document that evolves over time as milestones are met and the state of the art advances.

A Future Using Planetary Spatial Data: One component of planetary spatial data infrastructure is the assumption that there are foundational data sets. For planetary exploration, these could be identified as geodetic control or reference frames, topography, and orthoimages [9]. All data sets have value, but these can be the underlying framework for the registration and understanding of all others. Collecting such data sets and making such products at the highest resolution practical for each body in the Solar System should be planned for and could even be feasibly accomplished over the next three decades. In limited cases, some of these data products exist already at moderate resolution (e.g., topography for the Moon at ~100 m resolution or better). In many cases the data exist but have not yet been processed (e.g., early 1970s Apollo data is only now being processed into topography and orthoimages [11]), so a fundamental goal in the coming decade would be to control all existing data sets and make appropriate fundamental products.

For the 2030s to 2050, we should look forward to new missions, instruments, algorithms, software tools, and skilled personnel that will allow us to make a set of such meter-scale products for all Solar System bodies of major interest, which would be enabling for a wide variety of scientific studies and exploration operations to be performed on those bodies. It would include the capability to land safely anywhere on bodies such as the Moon, Mars, Venus, Mercury, the Galilean moons, and Titan and the icy Saturnian moons. Other capabilities include 4D mapping and continuous change detection, and the identification of volatiles and resources at the same meter spatial scale.

Conclusions: The planetary science community faces numerous issues relating to NASA strategic planetary spatial data infrastructure planning, particularly as the US and international partners aim to carry out ambitious planetary missions throughout the Solar System. By involving key stakeholders in the process and by inclusively building an active and productive community, MAPSIT will help NASA drive future discovery and innovation. Just as this type of planning was required starting 50 years ago during human exploration of the Moon and our initial forays into the Solar System [12], we can be sure it will be even more necessary in 2050 and beyond.

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A LONG TERM APPROACH ON QUANTUM COMPUTING FOR DEEP SPACE EXPLORATIONS

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Introduction: A long term approach to effectively develop and use quantum algorithms in order to replace classic computation usage and to attack certain optimization areas in space exploration and replace with a far better alternative of quantum computation or at the very least, a Quantum-Classical approach. As future space explorations are clearly targeted far away from Earth, there is a very logical reason that these explorations will have to be conducted by autonomous rovers and unmanned spacecrafts that will have to make split second decisions with little to no human intervention. We will target different applications like Asteroid mining, image processing where pattern matching plays a major role, quantum simulations and take a look at each of them and assess how quantum computation will help and what are long term targets to achieve them. We will also look at a framework so to speak for the achieving the same. Emphasis will also be laid on quantum algorithms that will have to be developed. Current advancements on the topics will be discussed and extrapolated to arrive at a better model.

We will also review the applications of quantum annealing algorithms in satellite image processing and planetary object identification in an unsupervised condition. Asteroid mining and colonizing will need swarm of robots with a higher AI and decision making abilities. Also, the decision making will have to be true realtime and cannot afford a turn around communication time as the robots will be that much farther from Earth. In other terms, the missions will have to be pre-planned for all posibilities arising and thats exactly the realm where quantum computing shines and so it makes sense to employ them. One example would be the travelling salesman problem in picking the shortest and best path between asteriods. One has to keep in mind that unlike conventional shortest path algorithm, the distance between nodes(asteroids) may keep changing due to collisions within asteroids or external space object and each node has a weighted value as to the minerals that they contain, the effort needed to mine each mineral and also the battery usage that will have to be traded as a result. All these will have to be added into the algorithm developed.

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THE PLANETARY SCIENCE WORKFORCE: GOALS THROUGH 2050. J. A.. Rathbun[1], B. A. Cohen[2], E. P. Turtle[3], J. A.. Vertesi[4], A. S. Rivkin[3], S. M. Hörst[5], M. S. Tiscareno[6], F. Marchis[6], M. Milazzo[7], S. Diniega[8], E. S. Lakdawalla[9], N. Zellner[10], [1]Planetary Science Institute (1700 East Fort Lowell, Suite 106, Tucson, AZ 85719-2395, rathbun@psi.edu), [2]NASA Marshall Space Flight Center, [3]Johns Hopkins Applied Physics Lab, [4]Princeton University, [5]Johns Hopkins University, [6]SETI Institute, [6]USGS, [8]JPL, [9]The Planetary Society, [9]Albion College.

Introduction: The planetary science workforce is not nearly as diverse as the society from which its membership is drawn and from which the majority of our funding comes. The most recent survey (2011) of the planetary science workforce [1], showed that only 25% of responding planetary scientists were women; while by ethnicity, while 87% were white, 7% were Asian, and 1% each Black and Hispanic. The US population in 2010 was 51% women and 64% white, 13% Black, 16% Hispanic, and 5% Asian [2]. The curent planetary science workforce has an overrepresentation of men, particularly white and Asian men.

Diversity and inclusiveness along gender, ethnicity, ability, sexual orientation, generational, and other axes is a business as well as a social imperative. Organizations that embrace diversity as a vehicle for approaching complex tasks and processes succeed in increasing creativity and innovation, and diversity in leadership positions encourages recruitment and retention of top talent [3-5].

By 2050, demographics in the US will shift further, resulting in 47% whites, 29% Hispanic, 13% Black, and 9% Asian [6]. Hence, if no action is taken there will be a growing discrepancy between the representation of the US diverse communities in the planetary science workforce.

Why diversity: *Innovation:* Diverse workforces are proven sites of innovative and interdisciplinary thinking. Places where invididuals come together from different backgrounds offer new solutions to intractable problems, leading to both technological and scientific breakthroughs [7]. By contrast, places with high levels of homogeneity in their workforce are subject to groupthink and risk [8,9]. Investment towards evening the playing field for female scientists and scientists of color is an investment in NASA's innovation.

*Funding***:** The planetary science workforce survey showed that 72% of planetary science research is supported by US public research funds (NASA and NSF) [1]. Since funds are from the public, ensuring public support of our scientific endeavors is particularly important for planetary science. As our workforce threatens to become increasingly less diverse than the US population, it will become difficult for the US public to see themselves engaged in planetary science, and public support will likely wane.

Barriers to entry: In industries that pride themselves on meritocratic advancement, one might suggest that the best junior participants will rise like cream to the top. But the notion that well-qualified minorities fail to make it in science because they are not good candidates has been disproved by a barrage of sociological studies of the sciences and technical domains.

The role of culture: Being reminded of minority status negatively affects people's performance [10]. Also, minorities who attempt to take leadership roles acquire negative reputations because they are perceived as deviant [11]. Experimental studies that change the name on a resume have shown the tremendous effects of implicit bias at play in evaluation of female and minority candidates for promotion, support, or hiring [e.g. 12], more so during economic hard times [13]. Meanwhile, women who are judged "competent" are typically held back in their careers instead of offered opportunities to advance [14] – or hold themselves back so as to remain in-line with gendered expectations [15].

Masculine work cultures can create self-fulfilling prophecies, where the right person for the technical or scientific job can only be white and male [16]. Peer networks and mentor relationships are also essential for the advancement of young scientists [17]; these relationships may arise naturally for certain young men with their senior colleagues but are unavailable to women and minorities.

The role of demographics: In addition to cultural barriers, studies of organizations demonstrate that environments with fewer than 30% minorities are subject to devastating interpersonal dynamics that punish those same minority individuals for their participation. 15% or fewer minorities invokes a tokenist environment, where individuals are negatively impacted by their heightened visibility [18].

Demographics and measures of success: Insufficient data exists to evaluate the impact of the situations described above in planetary science. Considering involvement in a spacecraft mission as one possible measure of success as a planetary scientist, Rathbun et al. [19,20] determined the percentage of women participating in the original science teams of 26 NASA robotic missions over a 41-year period. They found that since 2001 the participation of women has remained constant at about 15%, substantially less than the overall percentage of women planetary scientists, dramatically different from the US population, and more likely to trigger poor outcomes. Rathbun et al. were unable to quantitatively study the number of scientists of color on spacecraft teams, but concluded that the number remains very low.

Suggestions for equity: The above data suggest that there are barriers in place within planetary science which prevent equal participation from certain groups.

Step 1: Determine who is currently affected by the barriers. The demographic data indicate that white women and people of color are not only finding barriers to entering planetary science, but, once participating, they are finding barriers to funding success and inclusion on teams. We do not know which structural factors are at play, nor which determine how other groups are affected, i.e. those with minority statuses such as sexual orientation and disability.

NASA has recently begun to collect data on demographics information for people submitting research applications through the NSPIRES system. This is a welcome change, but data collection is only the first step to understanding the problem. NASA must fund analysis of these data and distribution of the results. Studies to address this issue must start immediately to enable positive impacts through 2050.

Step 2: Determine the nature of the barriers. The AAS Committee on the Status of Women in Astronomy conducted a survey on workplace climate and found that 8% of respondents had been harassed because of their race, 5% for sexual orientation, and 32% because of their gender [21], indicating that harassment is one barrier to success in planetary science.

Step 3: Invoke policies to remove barriers. Data will help to establish which issues are at play. But policy changes can yield immediate effects. For instance, the AAS recently released a statement encouraging universities to limit the use of Physics GRE scores in graduate admissions in the astronomical sciences after studies demonstrated that the GRE scores were not correlated with success but were correlated with demographic information [22]. Such policy change is expected to have an important effect on their community.

An implementable policy that could be enacted immediately would be to use more participating scientist programs on spacecraft missions, since those programs have a greater participation of women than the originally selected teams [20]. Mentorship networks, specialist conferences, and scholarships have also been implemented in other fields such as physics [23] and computer science [24]. NASA should also consider implementation of implicit bias training for all review panels. Since NASA is currectly collecting demographic information, we hope to find data on whether the demographics of funded proposals match that of the submitted proposals and whether implicit bias training changes the outcome.

We require more data than are currently available to have sufficient guidance on how to remove the barriers that prevent minority groups success in planetary science. However, current policies are not reversing the trend. Therefore, fearing and delaying changes to current practices will continue the disadvantages to minority groups, and the advantages of majority groups. We encourage NASA to make bold, straightforward, visible policy changes now and to collect the data necessary to determine whether implemented changes have the desired effect on our community. Development and and implementation of a concrete long-term strategy will show that NASA leadership are committed to improving the situation for underrepresented minorities, and making Planetary Science inclusive of the society whom we serve.

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Remote Sensing Science and Instrument Development Paradigms will Radically Change as Deep Space Optical Communications Infrastructure is Standardized. K. D. Retherford[1] and C. D. Author[2], [1]Southwest Research Institute (6220 Culebra Rd., San Antonio, TX 78238; kretherford@swri.edu), [2]Affiliation for second author (full mailing address and e-mail address).

Introduction: The advent of Deep Space Optical Communications (DSOC) systems in this and the coming decade ensures that this technique will surely become the norm, given the inherent advantages of high data rates and volumes for achieving the science of the future [1]. Present day mission design concept proposals describe the data sufficiency to achieve goals in terms of the constraint/bottleneck in data volume returned, as opposed to the inherent data gathering capabilities of instrumentation and spacecraft operations. Likewise, remote sensing instruments designed for planetary missions could readily include the latest 4k x 4k mega-pixel detector formats or larger, but opt not to owing to the inability to return the full amount of data collected within such capabilities.

The present complexity of such DSOC systems and the relative lack of ground-based infrastructure compared to traditional radio communication systems have perhaps slowed the pace of this sea change compared to earlier predictions. The next Decadal Survey is likely to discuss a telecommunications orbiter relay system for Mars, currently under study by MEPAG and others. Such a Mars orbiter would have a science focus but would also resemble elements of the Mars Telecom Orbiter concept briefly studied back in the mid-2000's, which included a Mars Laser Communications Demonstration [2]. Notably the Discovery missison Phase A competition has 3 of 5 mission concepts that chose to include a DSOC technology demonstration component (i.e., Psyche, VERITAS, and NEOCam).

The LADEE Lunar Laser Communication Demonstration (LLCD) [3] achieved long-range uplinks at 10 and 20 Mbps, with downlinks in the 39 Mbps to 622 Mbps. A 0.10 m reflective telescope is coupled by optical fibers to a modem transmitter. Its primary ground station terminal, located at White Sands, NM, was composed of four 40-cm telescopes for downlink and four 15-cm telescopes for uplink. Alternate sites were located at NASA/JPL and ESA's OGS telescope in Tenerife, Spain. The successful demonstration of key technologies such as pointing, acquisition, and tracking from lunar orbit enables the progression of demonstrations at further distances on upcoming missions throughout the solar system in the next decades.

MRO/HIRISE's 0.5 m diameter mirror and the 0.30 m diameter telescope on Deep Impact/EPOXI's High Resolution Imager (HRI) are two of the largest telescopes flown on planetary missions, for examples. In 2013 McEwen presented a "Mars Orbiting Space Telescope (MOST): Advancing Planetary Science (+Astrophysics, Heliophysics), Space Technology, and Human Spaceflight" concept for using the Hubble-class 2.4 m diameter telescopes provided to NASA by NRO [4]; McEwen similarly identified the ideal use of this telescope at Mars for optical communications technology demonstration.

Planetary Mission Payload and CONOPS Architectures in 2050: Our primary argument is that once 0.5 m class telescopes and larger are contemplated for DSOC systems on interplanetary missions it is inconceivable to not attempt to add remote sensing science instruments at the focal plane to take advantage of the mass, complexity, and cost invested in this spacecraft capability. Furthermore, the DSOC system drives requirements on spacecraft attitude control systems for exquisit pointing knowledge, control, and stability that, in addition to the telescope structure, adds even more mass, complexity, cost, and power resources.

An architectural approach that uses one common telescope to conduct science investigations across multiple spectral ranges is the logical driving direction that planetary mission payload concepts will be increasingly pushed into in the next three decades. A clear precedent for this observatory approach is the Hubble Space Telescope (HST) example of using one as-large-as-possible telescope to conduct experiments from far-UV (~105 nm on the Cosmic Origins Spectrograph) to the near-IR (~2.5 μm on NICMOS). Certainly the James Webb Space Telescope (JWST) and other astrophysics missions have followed this successfully demonstrated strategy. This approach typically uses a Cassegrain type telescope with different alignments of detectors and fields of view within the focal plane, and often include the implementation of pick-off mirrors, beam-spitters, and grating/filter wheels to achieve multi-wavelength capabilities.

Future work in the coming decades should identify the particular complications and unique challenges that incorporating both DSOC and science remote sensing instrumentation on the same telescope will entail. Obvious complications arise from needing to slew from planetary target to the Earth, but many spacecraft with fixed pointing arrays already solve these operational complexities satisfactorially. Bigger challenges reside in finding mirror materials, coatings, and temperature control properties, but many enabling advances in such areas are already underway. Adding mechanisms to block off potentially intense laser light from Earth from entering and damaging highly sensitive spectrographs and cameras seems unavoidable in at least some cases.

Instrument Design Challenges for the next 3 Decades: New instrument technologies will need to be implemented within the framework of a DSOC optimized telescope plus spacecraft system (i.e., an observatory approach rather than a "probe" approach). The continued imperative to reduce mass and power resources in technology developments should proceed in parallel in any event, but perhaps with an even more enhanced focus. Power supplies, C&DH electronics, and interfaces are likely to become even more standardized within a given observatory framework in order to be accommodated more harmoniously within individual mission designs. Hence the development of these subsystem technologies is likely to even more rigoursly push industry wide and NASA-wide standardization of requirements and specifications.

A notable drawback for planetary measurements from Hubble and JWST type observatories where one instrument field of view cannot overlap another by design is that they preclude simultaneous time and/or spatial coverage of interesting features or time-variable phenomena. Individual back-end instruments are more likely in this case to implement beam-splitters or other innovative optical designs to shunt light of different wavelenghts onto different detectors simultaneously. This multi-purpose approach to multi-wavelength instrument design would be a radical deviation from present designs that focus on optimizing all aspects of instrument performance to their specified bandpasses.

An interesting area for study and further thought exists when contemplating the inclusion of both in situ and remote sensing experiments within one observatory+probe mission. In situ (mass spec, fields, particles, active radar, etc.) experiments will no doubt want to take advantage of the higher data rates afforded by a DSOC subsystem. Whether or not a dedicated DSOC telescope system provides a cost savings in this type of investigation will answer the question on whether individual planetary missions will face segregation by measurement techniques. For remote-sensing only type observatory missions another potential exists to optimize the telescopes for the band-pass of interest, from x-ray to far-IR and all combinations in between.

Summary: The future advancement of DSOC will greatly impact the paradigms we invoke for conducting planetary missions and combining different payload instrument elements. Will there be a heighted specialization of measurement types per mission? Or will technologies converge to better enable multi-wavelength remote sensing platforms? What complications are included when in situ measurements are also needed by a particular mission? These practicalities will both constrain and enable opportunities for defining the hypotheses able to be address by future planetary missions.

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SmallSat Spinning Landers for Ocean Worlds Exploration Missions – Future ESPA-class Hitchhikers.

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Introduction: The spinning lander concept is a novel adaption of a classic dual-spin spacecraft architecture. A spinning module provides robust gyroscopic attitude stability, a relatively benign thermal environment (by evenly distributing heat loads) and centripetal acceleration (for effective propellant settling and flow control); it is connected to a despun module *via* a rotor/bearing assembly, and this despun module also accommodates a landing leg system. Most subsystems for a spinning lander—power, telemetry and command, RF telecommunications, attitude control, despun rotor control, propulsion, etc.—are nearly identical functionally to those included on over a hundred successful dual-spin spacecraft missions in the past [1-3]. What converts this proven, robust, scalable spacecraft architecture into an effective small lander [4, 5] is the addition of landing legs to the despun section, a landing radar and dedicated science instrument payloads that are commensurate with CubeSat volumes, *e.g.,* spatial heterodyne Raman spectrometer [6, 7]. It is envisaged that a constellation of spinning landers (each spinning lander carring a dedicated payload) would be ejected and deployed from an Evolved Expendable Launch Vehicle Secondary Payload Adapter (ESPA). Fig. 1 shows an ESPA-class spinning lander concept with a 1U CubeSat avionics enclosure volume.

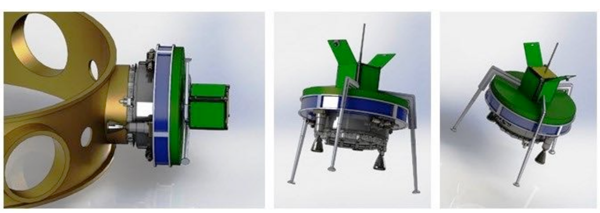

Figure 1. ESPA-class spinning lander concept (only one spinning lander shown). There is an 8” Lightband interface with the ESPA ring port and ~1U CubeSat-sized avionics electronics enclosure on the despun side.

Fig. 2 shows a notional spinning lander mission concept. Control of spacecraft velocity, spin rate and attitude is accomplished *via* relatively simple and independent sets of thrusters: axial (parallel to spin axis), radial (normal to spin axis) and tangential (to spinning section rim). In free space, bulk spin rate of the spacecraft is controlled with the tangential thrusters, while relative spin rate and azimuth phase control between the despun and spun sections is accomplished with the rotor/bearing assembly, which also passes power and signals across the interface *via* a series of slip rings. Telecom antennas, scaled to meet mission objectives, can be mounted to both sections, though the higher gain antenna(s) are almost always on the despun section.

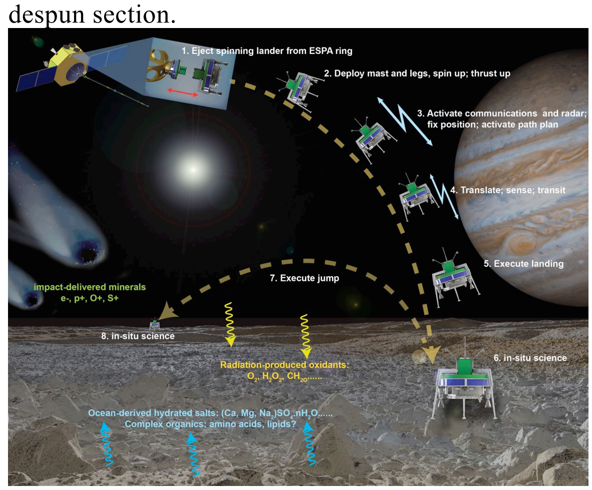

Figure 2. Cartoon of stowed spinning lander in an ESPA ring and subsequent ejection and concept of operations. For example a dedicated Raman spectrometer science payload on a Europa Mission will provide surface and near-surface spectroscopy while the lander is stationary or hovering. Europa’s surface composition is derived from a mixture of processes, which must be unraveled to understand the ocean below.

During the terminal landing phase, with despun section and legs set at zero spin, the spinning portion of the lander continues to spin until touchdown, providing significant gyroscopic stability to the entire landed system. Importantly, this system essentially can’t tip over during landing, but will rather ‘bounce’ or ‘stick’ depending on the leg system design. Depending on mission goals, once on the surface the spacecraft’s spinning section can either be stopped or left to spin at any desired rate *via* rotor/bearing control. In the spinning mode, the entire lander becomes an excellent hopper as well, providing extended range/coverage options, onboard propellant permitting. Selected instruments on the despun section can be controlled independently in azimuth and elevation during all mission phases using typical pan-tilt assemblies. Instruments and components on the spun side can be positioned in azimuth by rotation of the entire spun module.

The mass-efficient, cost-effective spinning lander system designs can, for relatively low total mission costs, address mission objectives for planetary exploration, resource utilization and commercialization at various solar system destinations. Solar system mission capability is enabled primarily by how much onboard Δv capability is incorporated (*via* some combination of liquid monopropellant and/or bipropellant and/or solid kick motor systems) and available power (*via* spun- and despun-mounted solar arrays, batteries).

Issues to address by 2050: Apart from issues of landing leg design, spun-despun bearing design, lander dynamics and control system design and analyses, propulsion subsystem design, *etc.*, adapting the small spinning lander concept to Ocean World exploration missions brings into play some additional challenges not yet addressed:

- Lander Δv requirements will be different for specific missions. These differences will likely drive propulsion subsystem sizing and technologies in significant ways, and perhaps other subsystems.
- Communication relay operations will be much more challenging.
- Landing targeting will inherently come with significant uncertainties.
- Solar arrays will not be a practical option for lander power generation. Miniaturized RTG's and primary batteries are anticipated to be far superior in 2050 leading to longer mission duration. However focused science objectives must be accomplished in hours to days.
- Outer planet and moon surface environments are extremely cold, and subject to extreme radiation so temperature-control and radiation hard subsystem designs need to be addressed..
- Two-way light times from Earth to target and back combined with a short mission duration will likely lead to the requirement that all lander operations be conducted in a fully autonomous mode.

The lander mission will be architected to reduce the total radiation dose incurred on critical flight elements while maintaining reasonable mass margin on the lander element. The unknown surface terrain on the planetary target at lander scales will drive the architecture to deploy all means feasibly available to ensure a precision landing and hopping on safe terrain. Studies have to be performed for obtaining pre-deployment orbital reconnaissance, precision deorbit maneuver execution, altimetry-guided soft landing, and estimate the performance of the high-stability landing system with energy attenuation. Most of these technologies exist but need to be matured and tested, and all of these techniques will be required to ensure a safe landing and completion of the primary science objectives in a single mission. In scouting missions we assume that there is no precursor reconnaissance mission.

It is recommended that concept studies should proceed in the next few years so that the necessary technologies can be matured and demonstrated by 2050. To do this we will first baseline some assumptions about battery technology, propellant type, radio frequency, class of onboard avionics and spinning lander-to-primary spacecraft mechanical interface. Next, the Δv requirements for descent and initial landing will be estimated based on likely initial flyby or orbiting conditions. Mission scenarios involving a primary lander which carries one or more spinning landers to the surface of a solar system body would also be considered. These Δv will drive sizing of the thrusters and propulsion tank, and to some extent the spun-despun bearing interface sizing. Post-landing hopping (whether after direct descent from an orbiter or flyby spacecraft or from a primary lander) will increase tank sizing from their baseline sizes and thus may also drive the sizing of other subsystems.

Assessing the thermal environment during lander descent, initial landing, surface operations and hopping combined with one or more notional operations scenarios will inform heat-balance analyses, which will drive battery sizing.

All of these analyses should lead to some good estimates of overall lander size, with which assessment of science instrument accommodation and landing leg design can proceed.

Some workable lander system configuration options should derive from this process, with which various mission and system design trades can be conducted, especially lander system initialization, guidance and control details, and related thruster sizing and placement details.

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CERES AND ITS COUSINS IN THE POST-DAWN ERA A. S. Rivkin[1], J. C. Castillo-Rogez[2], C. A. Raymond[2], [1]JHU/APL (andy.rivkin@jhuapl.edu), [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

Introduction: Our understanding of the largest asteroids has flowered in the last decade. A combination of new telescopic capabilities, improved mass and size estimates, dynamical and collisional modeling, and updated solar system formation theories all lead to an emerging recognition of the importance of the large, low-albedo, water- and organics-rich objects of the asteroid belt.

Recent studies of the dwarf planet Ceres have been central to this recognition. A decade of work including ground-based and HST observations and interior/thermal history modeling, and culminating in the ongoing Dawn rendezvous, has shown Ceres to be more interesting than even the most optimistic boosters had expected. Carbonates, first discovered in ground-based spectra of Ceres, have proven to be pervasive on its surface and its famous "bright spots" have been found to have very high concentrations of carbonate. Spectral features that have been the subject of decades of back-and-forth debate are currently interpreted as due to ammoniated minerals by the Dawn team De Sanctis et al (2015) argue that this points toward a possible outer solar system origin for Ceres or at least some of its starting material.

Along with these findings about Ceres, we have come to realize that the similarity between Ceres and many other large asteroids can be deeper than simply sharing low albedos. When we look at the largest objects (200+ km diameter) in the asteroid belt, we find a population with infrared spectra dominated by hydroxyl- and organics-rich minerals, and ice frost in some cases. Spectrally, several of these large asteroids have the same spectral features as Ceres in the 3-µm region, where features due to hydroxyl, organics, and other volatile species are found. In addition, they appear to have densities consistent with Ceres. Surprisingly many of the largest asteroids, including Ceres and objects with similar 3-µm spectra, appear to to be unsampled in the meteorite collection. Collectively we refer to this group of large objects with similar reflectance spectra over the 0.5-4 µm region as "Ceres' cousins" below for convenience.

Collisional models tell us that objects over ~100-200 km in diameter are very difficult to disrupt (Bottke et al. 2005), and are likely to be intact from the time of their formation. The most recent models of planetesimal formation suggest that objects of that size accreted directly from cm-size pebbles. These planetesimals are beyond the detection capabilities of even the most optimistic planned exoplanet search plans, and therefore they must be studied in our Solar System for their role in planetary accretion and in delivery of prebiotic materials to the inner solar system, to be understood.

The Question of Location: As noted, the interpretation of ammoniated clays on Ceres' surface has led to speculation that it formed in the outer solar system where ammonia is stable and was delivered later to the asteroid belt. This is an intriguing idea, and an origin for Ceres among the other dwarf planets could qualitatively explain some of Ceres' properties. However, the necessity for Ceres' ammonia to be obtained from the outer solar system has not been demonstrated. Furthermore, the existence of Ceres' cousins suggests that Ceres' history was repeated more than once—Ceres' presence in the main asteroid belt cannot be a low-probability fluke. If Ceres and other large low-albedo asteroids can be shown to have formed among or beyond the ice giants, they would be the most accessible representatives of that region, and their study would improve our understanding of large TNOs directly (and tremendously).

Ocean Worlds Where the Tide Is Out: With the Dawn spacecraft rendezvous with Ceres, we have additional insights into that body and its history. The best current data suggests that Ceres is partially differentiated, with a mixed ice-rock mantle (<40% ice) above a rocky core. This was a surprise, as models suggested Ceres should be fully differentiated with a very high ice fraction in its subsurface. While new models are still being developed, one suggestion is that Ceres' near-surface ice was steadily lost to a combination of impacts and sublimation. We might easily imagine that other spectrally-similar objects may share Ceres' history and are either partially differentiated or fully differentiate into an ice shell over a rocky core.

Early in its history and prior to this ice loss, however, there is evidence that Ceres would have had many features of astrobiological interest: an abundant subsurface layer of liquid water, organic materials, and energy to drive aqueous alteration reactions. As such, it can serve as an important data point showing the conditions under which astrobiological processes (presumably) stall out (Castillo-Rogez et al, this workshop).

Recurring Ceres? In addition to the objects with Ceres-like mineralogies mentioned above, other large outer belt asteroids show spectral evidence of ice frost at their surfaces, along with organic signatures [ref]. It is not obvious whether these bodies are undifferentiated, primordial mixtures of ice and rock or if they were differentiated like Ceres, disrupted after large impacts, and reaccumulated into the ice-rock mixtures we see today. Given expectations that the early asteroid belt was 150-200 times more massive than today's and that objects in this size class have impacted the terrestrial planets, Ceres-like objects could have been important vectors for delivery of prebiotic material.

Proposed Roadmap: The specific questions we have about Ceres and its "cousins" can be broadly grouped into a few overarching questions*: Where did they form? How far along the path to habitability did they progress? Are they active today? How commonly shared is Ceres' history?* As is fitting for objects with such importance to planetary geochemistry and geophysics, astrobiology, and exoplanet studies, a full understanding of Ceres and its cousins will require a range of studies from modeling, laboratory and astronomical measurements, and in-depth and reconnaissance-level missions.

Progress over the next several years will be made through continued study of data in hand and use of Earth-based facilities. Spectral mixing models have thus far largely made use of inputs that were found in public databases—measurements of candidate minerals in vacuum at relevant temperatures can be straightforwardly made using lab spectrometers. The release of Dawn Ceres data to public archives will allow the full extent of compositional variation to be determined.

Planetary astronomy will play a continuing role in understanding this group of asteroids. Observations in the UV and mid-IR, spectral regions where Ceres is known to have spectral features that were not within reach of Dawn's payload capabilities, will allow discrimination between multiple compositional hypotheses. Current and near-term observations by JWST, ALMA, and ground-based optical telescopes can be used to extend Dawn's results and monitor Ceres for activity. In addition, observations of other asteroid groups will mutually support advances in Ceres science. Adaptive optics/JWST observations of Hygiea and other large Ceres-like asteroids will be necessary to test the extent of their similarity to each other and to Ceres.

In addition to the largest asteroids, members of asteroid families should be targeted. Hygiea sits near the edge of a group currently thought to be ejecta from an oblique impact, and while Ceres has no identified family there are arguments that one could exist in particular restricted areas of dynamical space. In both cases, infrared observations would demonstrate whether the dynamical links to Hygiea or Ceres are real. All of this work, and the attendant theoretical work, will require consistent support from R&A programs.

Beyond the astronomical observations, missions are also warranted to these objects. A lander (ideally a rover) on Ceres could measure the geochemistry of its surface and test models of its formation. Techniques being developed hold the promise of in situ radiometric dating of surface minerals, important to determine whether Ceres is still active. Additionally, landers could directly determine whether outgassing is still underway at production rates consistent with observations made by the Herschel Space Observatory. Recognition of Ceres' place in the Solar System menagerie should lead to its inclusion among the Ocean Worlds, with a New Frontiers-level mission concept studied (and ideally advocated) by the next Decadal Survey. Eventually, depending on results from and comparison between Hayabusa-2 and OSIRIS-REx, sample return from Ceres may be deemed particularly scientifically valuable.

The experience learned from Dawn can also be leveraged for missions to Ceres' cousins. Visits to these objects will eventually be necessary to understand the full extent of their similarity. Are they also partially differentiated bodies? Do they also have carbonate-rich bright spots? Rendezvous missions carrying Dawn-like payloads to Hygiea, Patientia, or other cousins of Ceres will allow direct comparison of gravity, morphology, and composition.

Looking beyond the near term, Ceres and the icy asteroids appear to be natural waypoints for ambitious missions to Europa and the icy satellites. Their icy nature, short travel times, and lack of radiation makes them obvious proving grounds for the technology needed to drill on Europa, and a natural next outpost for human exploration beyond Mars. Such missions would not only set the stage for further exploration, but return incomparable datasets to further address the issues mentioned above.

Summary: Over the last decade, we have discovered that Ceres has experienced intense aqueous alteration and partial or full differentiation in its history, it maintains an ice-rich subsurface, and has many ingredients of interest to astrobiologists. We have also learned that several other objects in the asteroid belt are consistent with Ceres within observational uncertainties, with Hygiea (for instance) a compelling match in its 0.5-4 µm spectrum, albedo, size, and density.

With the recognition of Ceres' nature and its importance for understanding Solar System formation, the origin of life, and ongoing geological processes, its further study is more than justified. Along with Ceres itself, significant insight can also be gained by investigating these Ceres-like objects in order to provide context for Ceres itself and for the Ocean Worlds in the outer solar system.

ASTEROID STUDIES: A 35-YEAR FORECAST A. S. Rivkin[1], B. W. Denevi[1], R. L. Klima[1], C. M. Ernst[1], N. L. Chabot[1], O. S. Barnouin[1], and B. A. Cohen[2], [1]JHU/APL, [2]NASA MSFC.

Introduction: Asteroids are of central importance to space science. They are surviving witnesses to the earliest solar system history. They have been credited with delivering water and organic materials to the inner solar system, making life possible here (and elsewhere?). The microgravity of small asteroids amplifies the importance of tiny forces, allowing observations of processes that are unobservable on larger objects. Asteroids of various sizes on Earth-crossing orbits commonly rain down on us, affecting the evolution of terrestrial life and inspiring efforts to mitigate future impacts. The proximity of some asteroids has led an emerging set of asteroid mining companies to work toward making use of their resources.

Our knowledge of asteroids has undergone a revolution in the past 35 years, and practically everything we know about asteroids has been learned in that time. Forecasting forward 35 years is thus a fraught exercise, even ignoring the fits and starts in the pace of progress that are likely ahead. Nevertheless, we can look forward and discuss the likeliest or highest-priority advances before us, with the recognition that in 2050 today's undergraduates will be entering their late career and most newly-minted PhDs are still awaiting their births.

The Diversity of Asteroids: Asteroids cover a wide range of sizes, compositions, orbits, and histories. At this writing, two asteroid missions are in progress (Hayabusa-2 and OSIRIS-REx), two others are in planning (HEOMD's Asteroid Redirect Mission (ARM), and the Double Asteroid Redirection Test (DART)), and three others are finalists for the ongoing Discovery Program competition (of which zero, one, or two might be chosen). In the best case, these missions will collectively return pristine, carbonaceous material to Earth and to lunar orbit, and investigate in detail a large asteroid thought to be metallic, fly by several Trojan asteroids, and/or conduct a telescopic survey to obtain albedos and sizes for a significant number of asteroids. In addition to this set of missions, ground- and space-based facilities (including JWST and LUVOIR) will be used to make a mixture of population studies and focused investigations.

These efforts will enable significant progress on the science questions they are designed to address. However, broad and important questions of asteroid diversity will still be unaddressed without further efforts including: What is the nature of the transition from gravity-dominated to strength-dominated targets? How do the cohesive and non-gravitational forces on asteroid surfaces at small sizes interact? What were the original formation locations of the asteroid classes? *Are the handful of asteroids we know well representative of the vast population of which we know so little?*

Future Investigations: While the round of missions discussed above is still reaching its scientific prime, the thrust of the next round of missions seems reasonably clear. We will have fewer than ten objects whose properties we will know very well from spacecraft. Radar shape models will be available for a hundred or so objects, primarily NEOs. Finally, we will have tens of thousands of asteroids for which we have only disk-integrated albedo, size, and perhaps color data. *Our ultimate goal should be to understand the connections between composition, size, surface, system, and interior properties, and orbital properties such that researchers can quickly and reliably estimate properties of an unknown asteroid from a minimal set of telescopic measurements. This will have not only science benefit but also be of great benefit to the planetary science and asteroid mining communities.*

A set of missions designed to fill the middle ground between comprehensive knowledge and cursory information will be required to allow the point-source data, radar data, and rendezvous/sample return data to be best integrated. An asteroid flyby tour with current technology can provide imaging and other data on par with early rendezvous missions. If sufficient propulsion can be developed, frequent SmallSat tours could augment occasional Discovery-class tours. These tours could provide imagery and spectral data for hundreds of targets, and with particle analysis instruments like SUDA or Hyperdust compositional data can also be obtained.

In parallel, in-depth study of select targets should continue. Dawn has helped cement Ceres' place as an erstwhile ocean world and site of astrobiological interest. Similar missions to other large, low-albedo objects (some of which share Ceres' spectral properties) will be needed to establish how unusual or common Ceres-like histories were in the Solar System. Further visits to Ceres itself are certainly warranted to better understand its history and the nature of its prebiotic inventory. In-depth studies of smaller asteroids will also be necessary to further understand the connections mentioned above. Key "high leverage" targets can be identified for in-depth rendezvous/landed/sample return missions in much the same way that key locations on the Moon and Mars are identified and targeted for investigation.

Ceres and the icy asteroids of the outer belt also appear to be indispensible waypoints to the icy satellites. The technology needed for ambitious missions like drills through Europa's ice shell can be tested on an icy asteroid without long travel times to the outer solar system or the complicating challenges of Jupiter's radiation. Similarly, when humankind has walked on Mars and begins to look for additional challenges, Ceres provides an obvious next outpost with its abundant water.

Future Capabilities: We can already imagine the capabilities that will be available for asteroid studies by the end of the 2020s if current and planned missions move forward. Multiple sample return techniques will be available for "particle sizes" varying from typical regolith (OSIRIS-REx and Hayabusa) to multi-meter blocks (ARM). The studies for ARM and DART show how asteroids can be manipulated and orbits changed with current or near-term technology. The following decades could see such capability expanded, perhaps by allowing larger masses to be moved or by allowing more precise placement of perturbed asteroids. For instance, a mission to divert a PHA to cause a lunar impact could simultaneously provide data for a future lunar seismic network, asteroid samples for geochemical study, and a large-scale test of impact models, as well as remove the asteroid as a threat to future generations.

As instruments become more miniaturized and capable, as communications become better, and as AI and telerobotics mature, we might also expect a flowering of *in situ* asteroid studies. Indeed, combining the above points to the utility of a robotic science facility orbiting in the main asteroid belt, with a fleet of reusable probes visiting targets and returning samples of interest to the central facility, where sample analysis is done telerobotically.

We can expect surveys for PHAs larger than 140 m to be completed before 2030, with some fraction of smaller objects also discovered during the process. Surveys designed to provide days-to-weeks warning of impending impacts will likely be in place, potentially turning bolides and fireballs into predictable events. Those PHAs that are most dangerous can be targeted by flyby tours of the sort mentioned above in order to obtain first-order physical characteristics to provide a head start in case future mitigation is ever deemed necessary. The technology used to extract blocks from asteroid surfaces could also plausibly be put to use emplacing long-lived transponders to allow precise tracking of PHAs, as warranted.

Astronomical facilities will also become more capable in coming decades. Observing time on 30-m-class telescopes will be difficult to obtain, but will be enabling for studies of objects too dynamically difficult to reach conveniently with missions. Asteroid studies will continue to benefit from the need to identify moving targets in all-sky astrophysical surveys, as they have benefitted from the massive databases created by the Sloan Digital Sky Survey, IRAS, WISE, Gaia etc.

Commercial and International Aspects: In addition to science-driven and hazard-driven investigations, asteroids have been identified as sites for economic development. The United States has been enacting laws to make asteroid mining more economically feasible, and the nations of Luxembourg and the United Arab Emirates have followed suit or are planning to do the same. Multiple asteroid mining companies have formed, and aim to begin operations well within the time frame considered here. Asteroidal resources have been touted as potentially enabling for human exploration and outpost creation on the Moon and beyond. As a result, asteroid studies will have aspects of basic science, trade secrets, and applied engineering.

There will potentially be a lot of overlap between the data desired by mining companies and asteroid scientists in the 2020s and beyond, even if the goals of the data analyses differ. This raises opportunities for public/private partnerships, but also the need for clear expectations from each side as to what is being paid for in terms of public vs. proprietary data. The USGS is in the process of an exercise as to how they might go about assessing asteroidal resources, and the government should play a role in ensuring all Americans benefit from use of space resources.

In addition to Americans, the asteroids provide potential targets for many other nations. The Europeans, Chinese, and Japanese have all had successful asteroid encounters, as the Russians and Indians presumably could if so moved. Other nations could support asteroid missions in this timeframe as well. Their interest will likely increase if asteroid mining companies establish themselves. Again, this offers both opportunity and peril, depending on how the legal framework for asteroid mining is established and enforced: if expansion of humanity off of the Earth is seen as benefiting only a few wealthy nations (or individuals), it will inevitably run into opposition. Similarly, if perhaps beyond the scope of this report, the United States will be very different demographically over the next few decades compared to the last few. For American space studies to succeed, its participants must be seen as reflecting and representing our nation. It is not too soon to take steps to help the science community of 2050 look like the United States of 2050.

STRATEGIES FOR PROSPECTING AND EXTRACTING WATER ON MARS FOR LONG-TERM HUMAN EXPLORATION.

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Changing the Paradigm of Human Exploration: Since the Apollo era, human spaceflight missions have operated under a paradigm of supplying all required consumable resources from Earth. Materials such as propellant, oxygen, and water have traditionally been shipped along with crew and other cargo to destinations such as the Moon and the International Space Station. However, the use of local resources to produce consumables that the crew needs to carry out the mission, known as in-situ resource utilization or ISRU, can be an enabling factor for human exploration missions beyond low-Earth orbit. ISRU can help reduce the overall consumable mass sent from Earth to support human crews, significantly reducing mission cost and risk while enabling long-term or permanent habitation of other solar system bodies.

Water on Mars: The horizon goal for human space exploration is a crewed mission to the surface of Mars in the 2030s [1]. Sending humans to the Martian surface will enable real-time sample acquisition and analysis using sophisticated instruments, allowing for an adaptable exploration campaign that can dramatically increase science return compared to orbiter and robotic lander missions. Current studies conducted by NASA as part of the Evolvable Mars Campaign are considering a 500-day mission on the Martian surface [2]. The use of ISRU will be vital to support the crew in long-duration mission scenarios such as these and to enable permanent settlement.

One of the most critical resources for a human crew is water. Besides its use for human consumption, water can be used to produce oxygen for the crew as well as propellant for a Mars ascent vehicle and other surface systems. It can also be used for crew hygiene, food production, and radiation shielding. Because of the immense versatility of water as a resource, the extraction and use of water from the surface of Mars can play a key role in the development of human mission architectures to the surface of the red planet.

Current data obtained from orbital spacecraft and landed rovers has indicated the presence of a significant quantity of water at or beneath the Martian surface, as seen in Figure 1 [3]. Water on Mars is expected to be present in various forms, including subsurface glaciers, hydrated minerals, and trapped in regolith [4].

Goal and Scope of Work: To date, work has been performed by NASA at a conceptual level to classify the water reserves present on Mars and to design systems to prospect for and extract water [4].

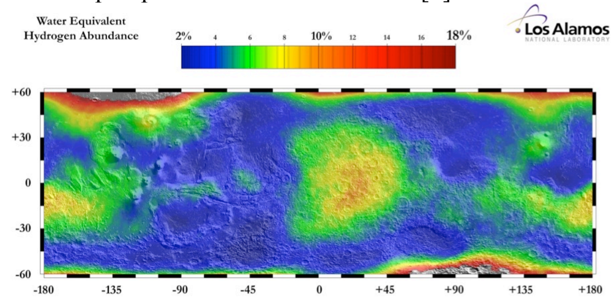

Figure 1: Water Equivalent Hydrogen Abundances on Mars [3].

The goal of the work proposed in this abstract is to expand upon the results of previous studies. We aim to develop a specific set of criteria to classify water reserves on Mars, and to design water prospecting and extraction systems for various human landing sites using a requirements-driven framework. Specific steps to achieve this goal are as follows:

- Identify a representative amount of water needed for human missions to the Martian surface
- Study analog infrastructures for prospecting and extracting resources on Earth, including the mining and petroleum industries
- Classify water reserves and quantify environmental characteristics of potential human landing sites and exploration zones
- Design water prospecting and extraction systems based on the water reserves and environmental characteristics of each site

Each of these steps is explained in greater detail in the following sections.

Water Usage: Water can be used by a crew of astronauts in several different ways, including: crew hydration, food and beverage rehydration, personal hygiene, medical usage, EVA usage, oxygen production, radiation shielding for both a surface habitat and nuclear fission power systems, and propellant production. To gain an understanding of the mass of water required for a human Mars mission, parametric models of each of these usage types will be developed based on the number of crew and duration of the mission. A minimum and maximum use case will be identified to constrain the quantity of water needed.

Water usage can also be classified to better understand its impacts on mission architectures. We propose to classify types of water usage as enabling vs. enhancing, fixed vs. variable, and recyclable vs. non-recyclable. A metric of marginal water per capita will be produced, identifying how much additional water is needed to support one additional crew member.

Earth Analogs: All of the materials we use in our daily lives can be considered the end result of 'ISRU' on Earth. In particular, the mining and petroleum industries have employed and refined methods of identifying, classifying, and extracting resource reserves for centuries. Studying how these industries classify resource reserves and investigate and extract mineral ore and oil deposits can provide valuable insight into how such a process might be carried out on another planet such as Mars.

Reserves at Landing Sites and Exploration Zones: The first human landing site workshop identified nearly 50 potential landing sites and exploration zones that could be selected for the first human missions to Mars, shown in Figure 2 [5]. In order to accurately design surface systems to prospect for and extract water at these locations, the water reserves at each site must be classified and the environmental factors of each site must be quantified. Water reserves at each site will be classified according to a specific set of criteria based on resource availability (demonstrated, inferred, speculative) and feedstock type (glaciers, hydrated minerals, regolith). Environmental characteristics including average slope, rock distribution, temperature range, elevation, and availability of sunlight, will be quantified for each site.

Prospecting and Extraction Systems: A detailed understanding of the water reserves and environmental characteristics of a landing site can help identify whether the site has the potential for water ISRU, and if additional prospecting is necessary to provide greater knowledge of available reserves. If a site contains sufficiently demonstrated reserves, this information can drive the design of optimal extraction and processing systems to minimize overall mass and power. Several systems will be designed to support water prospecting and extraction needs at selected landing sites. This will provide a more detailed, quantitative, and practical approach to planning human Mars exploration missions utilizing water ISRU.

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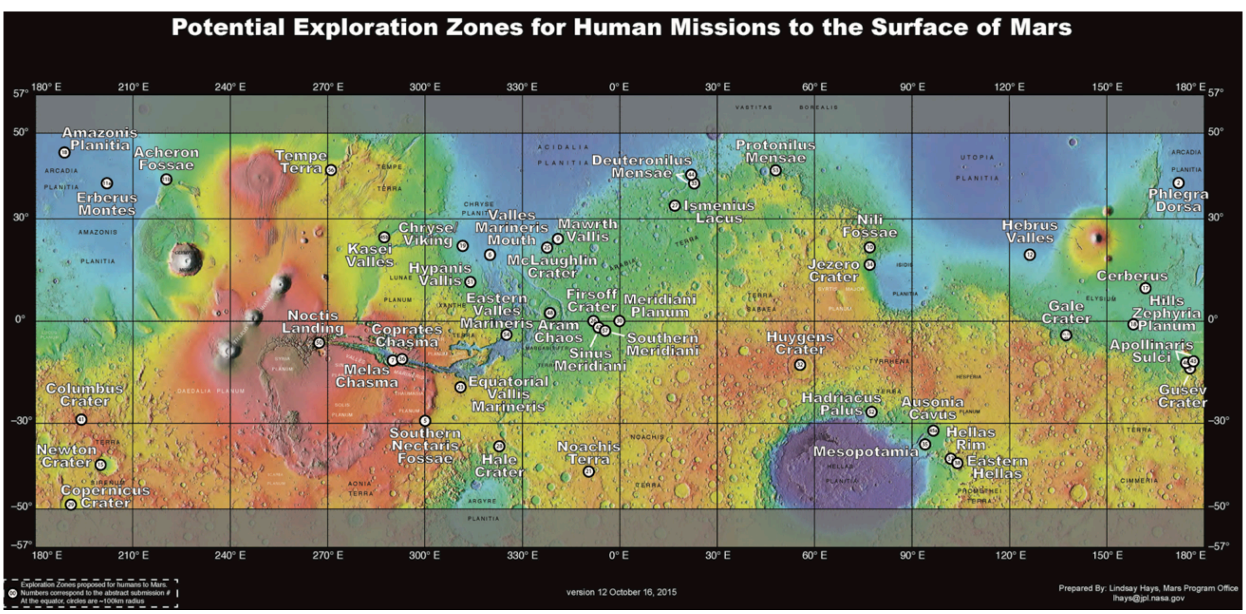

Figure 2: Proposed Landing Sites and Exploration Zones for Human Mars Missions [5].

"BE CAREFUL WHAT YOU WISH FOR": THE SCIENTIFIC, PRACTICAL, AND CULTURAL IMPLICATIONS OF DISCOVERING LIFE IN OUR SOLAR SYSTEM. J. D. Rummel, SETI Institute, Mountain View, CA 94043, USA

Introduction: The 'Search for Life' is, for some in the planetary science and astronomy communities, as much a marketing strategy as it is a serious scientific pursuit. Astrobiologists are in it for the critters, but many others are happy to have the "life" brand speak for them when it comes time to attract public and private funding, but have not seriously contemplated the implications of a successful search for extinct AND extant life The hypothesis that the presence of life on Earth indicates that there should be evidence of life elsewhere in this solar system (and beyond) may not be directly relevant to the characterization of gamma-ray bursts or the measurement of the topography of Venus—but that is no condemnation. Sure, a case can be made that such results are of interest to the overall potential for life elsewhere in the universe, but it is clear that neither microbial or macro-life will have much to say about them. As such, it should be no surprise that many (if not most) space scientists—and a surprising proportion of astrobiologists—have not fully considered the implications of discovering life in our own planetary neighborhood.

The following is a projection that looks back at those discoveries from the vantage point of 2050.

Success Has a Thousand Fathers . . . and Many More Brothers and Sisters (Mars): Upon the return of humans to the Moon in the mid-2020s, *in situ* sampling of former Apollo landing sites demonstrated new techniques for the use of highly sensitive instruments in a laboratory setting to search for biologically derived organic compounds (and dead organisms) to assess the contamination of the Moon by previous lunar spacecraft [1, 2]. Such studies, and the technology and technique-development that went with them, later provided a strong basis on which to build a similar crew-tended laboratory on the surface of Mars in the mid-2040s. This turned out to be an important contribution to the discovery of life on Mars, as the work in that laboratory proved the existence of extant (and, of course, extinct) life there. Life on Mars has a rough time of it between obliquity changes that favor warmer, wetter conditions, so a large percentage of Mars life goes extinct on a regular (if extended) basis—but not everywhere on Mars, all at once.

The really shocking news to the scientific community, and (eventually) to the uninvolved public, was that the work of the Mars surface laboratory proved that life on Mars was not *first* discovered in the mid-2040s, but had been been "discovered" in the late 2020s, when the first robotically returned samples from Mars were brought to Earth for scientific analysis. That was the first time that Mars life (seemingly, the spore of a small lichen) was seen. Unfortunately, it was judged by the sample analysis/biohazard team to be one of the numerous contaminating organisms from Earth that had made the round-trip journey with the sample. The true significance of this organism, which shares DNA, RNA, and proteins with modern Earth organisms, was not understood at that time.

It was the experience gained with degraded organics and organisms in the lunar-surface laboratory, transported to Mars with the first human landings, that allowed scientists on Mars to conclusively prove that the "lichen spore" first discovered in the robotically returned Mars sample was actually a martian organism no longer under containment on Earth. Those Mars samples had been released from rigorous containment in the late 2030s after "false" positive indications of life were all that were detected in containment.

Naturally, the US National Institutes of Health, the Centers for Disease Control, and the Environmental Protection Agency had linked their public obligations to a major increase in funding, and even before the first human-crewed scientific expedition to Mars had returned, they had recovered all of the robotically returned samples from investigator laboratories and had asserted the right to do their duty by conducting their own quarantine of the Mars samples collected by the first human mission, as well as the human crew themselves. By 2050, NASA and its international partners were trying to rearrange the scientific study of the robotically collected samples, and to understand how future astrobiological studies of a Mars lichen could be done under the conditions present in containment facilities provided by the Earth's public health authorities.

What's a Universe Good For (Europa)? The space agencies involved in the first human mission to Mars, as well as those that participated in the first robotic sample return mission, could be forgiven for their acceptance of a negative result for two basic reasons. In the first place, the Mars lichen really did look a lot like Earth contamination, both genetically and structurally, as might befit an organism whose ancestors could have come from either planet. The second reason was that NASA was distracted elsewhere. The space agency had become focused on Moon and Mars distances and cruise times in the late 2010s and early 2020s as it (and most of its international partners) had signed agreements with commercial companies to conduct scientific exploration and (eventually) tourism as partners. These agreements were forward-looking with respect to the overall movement of humanity into space, but they focused attention, time, and money on short missions that were intended to build up capabilities on nearby planetary surfaces. Accordingly, new missions to the outer planets and their satellites were in short supply. Imagine the dismay of strategic planners at NASA when their one-and-only (well-sterilized) Europa lander mission, launched in the early 2020s, discovered a second source of extraterrestrial life just beneath Europa's icy surface. The solar system, rather than being cold, dry, and dead, was starting to feel a little crowded. Eventually, when the Mars-life realization was added, it would seem that the universe exists for the express purpose of generating life.

Before the Mars discovery was understood, however, much time and effort in the early 2030s had been exerted to follow-up on the detection of this second genesis of life from Europa. Despite a demonstration of the motility of cells recovered from melted Europan ice, the lander had conducted tests for DNA, RNA, and their degradation products, as well as for proteins and lipids. There were equivocal results regarding proteins and lipids, but DNA and RNA had not been detected.

None of the material detected by the Europa lander had yet been returned to Earth, but what consumed the attention of NASA astrobiologists was the renegotiation of commercial agreements originally focused on missions to the Moon and Mars, but now being rescheduled and modified to include licensing agreements regarding the possible commercial benefits of the life discovered on Europa. The pharmaceutical industry had joined the tourism and space resources companies in their enthusiasm for future spaceflight opportunities.

Good News, Bad News: Some of those same agreements would have to be negotiated again in the late 2040s once it was discovered that the Mars lichen was actually from Mars. Mars agreements would reflect the need for the US and its international partners to consider the ethical and practical implications of continuing human exploration (and eventually tourism) on Mars. Agencies shared a reticence to expose a human crew to a demonstrably uncharacterized biosphere with possible implications to crew health and the safety of the Earth. Likewise, the Mars exploration partners had been challenged by other treaty signatories under the surviving Article IX of the 1967 UN Outer Space Treaty [3], which prohibits harmful contamination of other worlds and seeks to protect against "adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter." That same treaty had been altered to encourage space resource development only 20 years previously.

Elsewhere, the discovery of two forms of life in our own solar system had, by 2050, greatly expanded public interest in efforts to completely characterize the signs of life that could be read in the atmospheres of planets orbiting other stars. Funding had grown, accordingly. While sending humans to Mars seemed to becoming more risky, should the Mars lichen have nasty relatives. Clean rover technology with artificial intelligence and autonomy were considered to be safer and nearly as competent (with virtual reality video). The characterization of life on extrasolar planets seemed both safe and possibly leading to a future real estate boom, which for most people seemed as likely to happen as their own move to Rakitu Island—highly entertaining to consider an exotic change in locale, but not a practical necessity for most taxpayers.

Solar System Values: From a cultural perspective, and despite the fervent hopes of ethicists and political scientists, there were almost no major surprises regarding public attitudes after the discovery of life in our solar system. Government (e.g., NASA) had managed to "hide" the discovery of life on Mars for almost 20 years. That the pertinent mistakes were made almost 10 years earlier than the final sample-return mission didn't alter a skeptical view of the government and its candor/competence. But the attitude that there could (and should!) be aliens living in our solar system had been accepted by the vast majority of people with the first Star Wars film. The fact that the new aliens were likely to be microbes had turned out to be a large disincentive for most of the public to care about them. Of course some were interested in the potential for pharmaceuticals developed from this new life, and those interested in such things were also interested in investing in such things, but by-and-large the public's view of the universe would need to change only if a particularly clever alien were to come into the room and either entertain or threaten, or sell real estate that someone could actually visit. Until that time, the Earth's cultural norms would not be threatened nor modified.

Such is the nature of scientific progress.

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Pioneering Outer Planet Ocean Exploration at Europa and Beyond.

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Introduction: A mission to explore Jupiter's moon, Europa, has been enthusiastically supported by both of the last two Planetary Decadal Surveys. Europa is one of the most astrobiologically interesting worlds in the solar system, and future exploration of Europa will serve as a model for exploration of other ocean worlds. Europa is a challenging target, orbiting close enough to Jupiter to be continuously bathed in damaging radiation and dynamically taxing due to the constant influence of Jupiter's gravity. Here we describe the pioneering NASA mission to Europa [1] and envisage the future of planetary ocean exploration and search for life missions that it will enable.

A new age of space exploration: Use of NASA's Space Launch System would allow direct transit of the Europa Multiple Flyby Mission to Europa in only ~ three years [2]. This innovation creates the possibility for exploration of the outer solar system with a cadence comparable to the two-year window for launches to Mars that has been exploited in recent decades to rapidly advance our understanding of the red planet and its habitability. Follow-on missions will be able to take advantage of the experience of the Europa mission to address the challenges of operation in the distant space environment and particularly the strong radiation near Jupiter, as well as leveraging improvements in data transmission bandwidth (laser communication), position knowledge (deep space atomic clock), biosignature investigations, and radiation-hardened electronics.

Motivation: Based on multiple consistent lines of evidence provided by the Galileo mission at Jupiter, a compelling case was made for the existence of a liquid ocean at Europa [3], beneath the famously beautiful cracked icy surface. The most definitive evidence comes from measurements of magnetic field data near the moon; humanity has a long history of making and interpreting magnetic field data, going back to at least the original ocean faring clippers, and these measurements represent a gold standard in remote sensing. The Galileo magnetometer measured an induced magnetic field at Europa consistent with a 100-km-thick layer of a conducting material with a density around 1000 kg m^{-3} [4, 5]. Liquid salty water is the only geologically plausible material.

Gravity measurements are consistent with a layer of water that is between 80–170 km thick [3, 4] (although existing gravity measurements cannot unambiguously confirm a liquid ocean). The ocean is overlain by an ice shell, which, based on analyses of crater morphology and other landforms is expected to be between 3 and 30 km thick [6–9].

Among icy worlds, Europa is potentially the most energetic and shares common features with other ocean worlds (but not found on Earth)—in particular a geologically flexed and fractured ice covering that may be undergoing solid-state convection [10] and a deep global ocean with unknown circulation [11]. Understanding the workings of Europa's ice, ocean, and deeper interior will inform exploration of other ocean worlds.

Pioneering exploration of solar system ocean worlds: Initial mission concepts for a dedicated Europa spacecraft that would precess to a circular orbit around the moon were found to be expensive and short lived [12]. The currently planned Europa Multiple-Flyby Mission would provide an innovative solution that allows for multiple flybys of the moon via numerous targeted flybys as well as providing important context on the local environment that Europa is immersed in during its orbit of Jupiter.

The planned Europa Multiple-Flyby Mission would follow up on the Galileo mission to provide a full orbital survey of the magnetic field perturbation, perform global mapping, and sound the subsurface to unambiguously characterize ocean depth and salinity. Compositional and geophysical instruments are expected to further characterize Europa from orbit, and the long-baseline mission will enable assessment of ocean dynamics and variability as well as any plume activity, which has been suggestively observed by HST [13]. The comprehensive instrument suite and numerous close flybys would provide needed mapping of Europa's surface and subsurface in preparation for future landed missions.

Future exploration of Europa: Completion of the robust reconnaissance provided by the current Europa Mission would enable characterization of potential landing sites based on composition, recent activity, subsurface structure (for example shallow water), terrain roughness and stability, optimizing the potential for the detection of life, as well as ensuring mission safety by assessing surface properties (such as roughness and slope) that are currently unknown at the scale needed by a landing system.

Having identified appropriate landing sites a lander mission equipped to sample the surface and subsurface directly would be the logical next step. The primary focus of a lander mission would likely be astrobiology.

This should be followed by rover-style missions which could travel to multiple interesting surface locations to sample the subsurface and perform visual and compositional analysis of materials that come from Europa's near-surface – informed by results from the lander such a mission would aim to search directly for life on a planetary body.

Notional future missions would hopefully include more capable landers, rovers, and lead eventually to a submersible or melt probe that would directly sample the subsurface liquid ocean layer and areas of shallow water.

Results from life detection searches on Europa will be compared with the results of characterization of habitable environments and the search for life on Mars. Environments for life, past or present, on ocean worlds provide one endmember in the characterization of potential past life on Mars. Such comparisons are necessary for informing future astrobiological exploration.

Enabling technologies: Enabling technology for future missions include long-distance rovers capable of traversing multiple kilometers of uneven, icy terrain as well as devices which are able to descend into cracks or plume vents to access subsurface melt lenses and other near surface liquid water regions.

Advancements are also needed in the design of life search instruments. An integrated strategy should be developed to include multiple instruments and complementary techniques. The "Ladder of Life" initiative [14] helps us identify the path from habitability to biosignatures to life and should be used to direct investment. Future techniques may include chemical analysis as well as direct imaging. Investment to incubate innovative technology development will be needed.

The ultimate goal of Europa exploration would likely be a cryobot or autonomous underwater vehicle, which would melt or drill through the surface ice layer to access the ocean directly. Such a probe could enable observations of potential Europa life in situ, in arguably the most habitable environment in the solar system for an extant ecosystem beyond the earth. While such a mission might be beyond the 2050 time horizon for the current study, the precursor missions described here pioneer exploration of alien oceans, continuing humanity's search for life beyond Earth.

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'It Takes a Village.' Collaborative Outer Planet Missions. A. M. Rymer[1], E. P. Turtle[1], M D. Hofstadter[2], A A. Simon[3], and G B. Hospodarsky[4]
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Introduction: A mission to one or both of our local Ice Giants (Uranus and Neptune) emerged as a high priority in the most recent Planetary Science Decadal Survey [1] and was also specifically mentioned supportively in the Heliophysics Decadal Survey [2]. In 2016, NASA convened a science definition team to study ice giant mission concepts in more detail [3]. Uranus and Neptune represent the last remaining planetary type in our Solar System to have a dedicated orbiting mission. The case for a Uranus mission has been made eloquently in the Decadal Surveys. Here we summarize some of the major drivers that lead to enthusiastic support for an Ice Giant mission in general, and use the example of a Uranus Mission concept to illustrate opportunities such a mission might provide for cross-division collaboration and cost-sharing.

Context and Motivation: The Cassini spacecraft has been able to make unprecedented observations of the heliosheath during its tour of the Saturnian system, due to a fortuitous combination of the capabilities of its instrumentation and the vision of a small group of plasma physics experts who recognized the opportunity post launch [4]. Future missions might not include such a comprehensive instrument suite without deliberate prior planning.

Opportunity: A mission to the outer solar system provides numerous opportunities for cross-disciplinary science and collaboration, including, but not limited to:

1) Heliophysics. Studies of the heliosphere via inclusion of energetic neutral atom (ENA) imaging technology could be performed during cruise and, like Cassini, make observations of both planetary and heliospheric ENA emission during an orbital tour.

2) Exoplanets. Exoplanetary studies would certainly benefit from *in situ* study of Uranus and Neptune since the majority of exoplanets that have been discovered are also Ice Giants [*e.g.,* 5]. Measurements at infrared to millimeter wavelengths of dust in the inner solar system, looking inward from the outer solar system, could also be compared with what is seen when looking at proto-planetary and planetary disks around other stars to help put observations of distant solar systems in context.

3) Interstellar Probe. It is conceivable to combine an Ice Giants mission with the long desired follow up to the two Voyager spacecraft in the form of an "Interstellar Probe" to investigate the structure of the furthest reaches of our solar system and its interaction with the interstellar medium [6]. In this scenario, Ice Giant orbiter(s) and probe(s) could be dropped off en route to the intergalactic medium.

4) Astrophysics. Instrumentation could be specifically designed to make useful long-wavelength radio observations of the cosmic microwave background during interplanetary cruise to an Ice Giant planet and then to perform deep sounding of the atmosphere and satellites of the Ice Giant itself.

5) Interagency collaboration. Other agencies (*e.g.,* ESA, JAXA) are pursuing many of the same overarching goals [*e.g.,* 7] and there is much that a combination of agencies could achieve that a single agency alone cannot. However, different timelines and mission development processes can hamper coordination. As an example of one strategy to foster collaboration, NASA missions of opportunity have helped US participation in missions being developed by other agencies. The 'directed good fortune' represented by NASA MoOs is an excellent model which we suggest can be more broadly applied.

These examples highlight how cooperation across NASA Divisions and between space agencies furthers the specific goals the Planetary Science Division has identified for this workshop. Most strongly, the "Origins" theme is addressed, using observations of solar system planets and the Sun's magnetosphere to connect our mature solar system to young and forming exoplanetary systems. (Cosmological studies would also address "Origins" in the most inclusive sense.) And interagency collaborations can enhance or enable investigations in all the Workshop's themes, by either expanding the scientific payload possible compare to a NASA-only mission, or in the extreme by enabling a mission that would not be feasible for budgetary or other programmatic reasons.

Recommendation: Future missions, including a long anticipated voyage to Uranus and Neptune should consider not just the directed mission, but also ways to make the most of other logistical and scientific opportunites along the way. In this presentation we will provide examples of what has been achieved through both fortuitous and directed collaboration and suggest strategies to enable cross-division collaboration and cost-sharing to improve collaboration over the upcoming decades.

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Over the decades, there have been many studies that have clearly demonstrated how we can study the planets using thermodynamics and the available astrophysical data [1-3]. Such studies have been successful in estimating the chemical compositions and density of planetary interiors which are in conformity with seismic data. An example can be reproduced below which shows that condensation of solar nebular gas yields species which after self- compression mimic the interior structure of the earth very well [4].

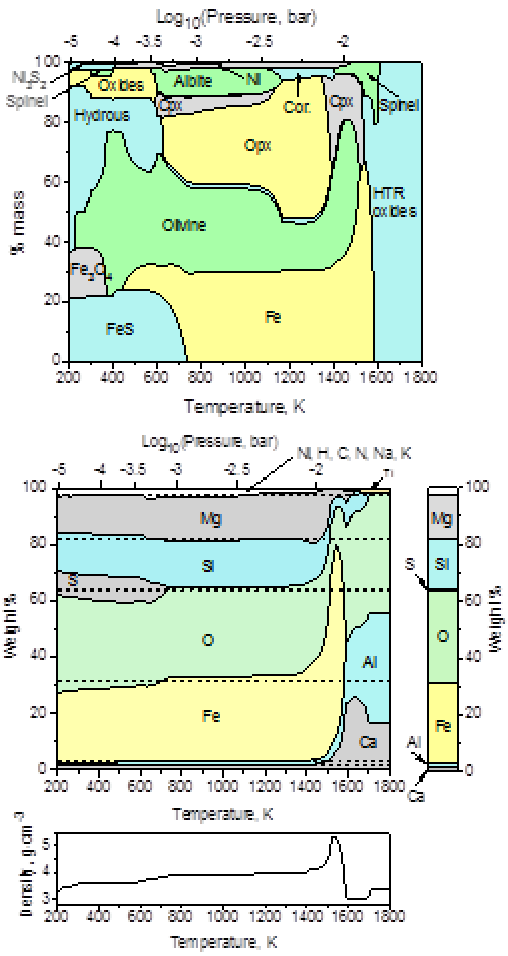

Fig.1, Solid phase proportions along the high adiabat[4]. Element proportions of the condensed phases along the high adiabat, the side bar shows the elemental composition of Earth according to Allegre et al. [5], c. Density of condensed solids along the high adiabat.

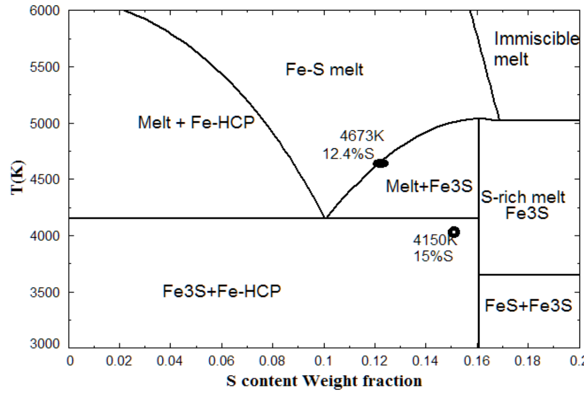

Fig.2 shows the binary system Fe-S at 360 GPa. The light element in the core is taken to be S.[4]

The databases which if robust could give us invaluable information on the nature of the celestial body and plan our missions at lower risks and costs. There are, however, large uncertainties associated with the thermochemical data. Some data on important species that are known to form in meteorites are missing or not robustly known. Other significant problems with our databases are:

a). The existing formulations of Equation of state are either theory based such as the Mie-Gruneisen or the hybrid models such as the high temperature Birch-Murnghan (or Vinet). The latter can be quite robust if only pressure and volume are to be considered at 300 K but run into problem if the temperature effect needs to be considered. Current alternatives proposed are by Brosh (6) and by Jacobs and Fei (Dorogokupets, 7).

b). Another critical issue is the problem of modeling the excess Gibbs energy of multicomponent solid solutions. Most minerals contain many-cations mixing on nonequivalent crystallographic sites and require complicated formulations with fictive end members. Databases which seem to be internally consistent are not consistent with each other and there is an urgent need to adopt a database format which could bring all the databases in a form such that they can be used interchangeably for testing against experimental data. The format should permit inclusion of data on the mechanical properties of materials for geophysical modeling.

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Critical Issues

:There are numerous thermochemical database compilations available (such as NIST, JANAF etc)) but those that can be used specifically by planetary scientists are few.

: complete integration of the data on thermochemistry and physical data in a single database for use by the planetary science community,.

Software for calculation of phase equilibria has to support various chosen models and it must be possible to use it as a subroutine.

We need to provide basic tools and techniques for search, retrieval and analysis of the data. The tools will be motivated by the fundamental questions raised by the research community.

The sub-lattice model (commonly used in ceramics and metallurgy) requires many parameters and fictive components. A major difficulty, we anticipate is that the properties of many solids (end-member components) in the currently assessed databases depend on the solution model used. Any change in the solution model would require a reassessment of the associated end-member data..

There is a need to reevaluate the basic approach to incorporating the PVT data in calculation of Gibbs free energy.. For semi-empirical models such as the Birch-Murnaghan or the Vinet, we need to use large number of experimental data to ensure compliance with the polynomials chosen for extrapolation. The EOS for liquids may need a separate consideration.

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Belonoshko discussed the PVT fluid model with 13 species in the C-H-O-N-S system as proposed by Belonoshko and Saxena (22) and its use in considering the solid-fluid equilibrium in earth's mantle. This model needs experimental support.

The melt model of Ghiorso (Ghiorso and Sack, 6) on modeling magmas has been widely used by petrologists and geophysicists. There has been considerable amount of work on modeling binary and ternary systems in ceramics and the use of such data and building of a multicomponent model for the geologically relevant compositions is quite desirable.

Since the accuracy of the ab-initio calculations of the physical properties of solids (volume, compressibility) is now widely accepted, we must plan calculations of critical data missing from our data bases. Furthermore a combination of ab-initio and molecular dynamics calculations can be used to obtain P-V-T data for solids. Such computed data will save us time and efforts and let us complete the high pressure database much faster.

Geophysical data

We need to combine the phase equilibrium calculations of the planetary systems with geophysical data for modeling the mantle dynamics. It is required that we include in the thermochemical database all physical properties of the solids.

Planned work for the ne t decade

Once the necessary improvements have been made in out databases and software, we need to explore the planet formation systematically. The multielement multiphase system should contain all major and possibly minor and trace elements for modeling the chemical composition of the planetesimals, asteroids, exoplanets and planets and all physical and mechanical properties of the materials for dyamic modeling.

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On the need for Artificial Intelligence and Advanced Test and Evaluation Methods for Space Exploration.
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Introduction: The romantic view of artificial intelligence (AI) is the study of thinking machines, specifically machines that are equivalent to, and think like, humans. Robots embodied with AI have been a romantic element of space exploration through influential films including Fred Wilcox's Forbidden Planet (1956) and, using a much darker tone, in Stanley Kubrick's 2001 a Space Odyssey (1968). While it is true that many of the reasoning methods being pursued by the AI community are anthropomorphic, artificial intelligence has a more pragmatic side, which is the study of algorithms that allow machines to produce answers to complex, multifaceted problems. To understand the difference between an artificial intelligence system and "unintelligent" computer systems, we should first consider how software is normally developed. The software development process begins with the specification of requirements, followed by design where software engineers rigorously determine the appropriate machine response to each and every combination of inputs that might be encountered. Sometimes the appropriate responses to system stimuli are defined mathematically by using control theory, and sometimes software engineers use brute force by exhaustively enumerating all possible stimulus-response pairings. Traditional software engineering works well for the vast majority of software systems; however, when system requirements demand that machines make decisions in a world that is too complex or too uncertain for engineers to solve during software design, AI is required.

The design process for AI, necessitated by the need to have machines address intractable problems during execution, is a radically different approach to developing control software. When developing artificial intelligence, software engineers do not program explicit responses to situations encountered by the machine, but rather write software that provides machines with an ability to solve problems during program execution, allowing the AI software to produce a decision that was not explicitly encoded in the software. All major forms of AI research, which includes deductive, inductive and abductive reasoning, search-based algorithms, machine learning and neural networks, exhibit the property that the machine's answers to specific problems are not explicitly encoded within the AI software; rather methods for devising answers to the problem are encoded. This subtle distinction between AI and unintelligent controller provides the power and promise of AI and AI's greatest risk. The promise of AI is an ability to solve important problems that cannot be solved through traditional programming means. The risk of AI is the potential to produce unvetted responses to situations that run counter to the designer's wishes.

On the use of Artificial Intelligence: When is it useful to have a machine use AI to make a decision? After all, after millions of years of evolution and roughly 10,000 years of civilization, humans are (usually) quite good at making decisions in complex, uncertain environments. Through our research in AI-enabled systems, Johns Hopkins University's Applied Physics laboratory has identified three general use cases for AI: first, for some tasks AI is more cost effective than humans; second, AI is better suited than humans at solving some, but not all, problems; third, AI allows us to develop machines that are capable of responding faster than when a human is in the decision loop. [1]. Each of these three strengths is potentially relevant to future NASA mission architectures.

AI's ability to allow machines to respond more rapidly than when a human is inserted into the decision chain is significant for NASA because communications between Earth and extraterrestrial spacecraft or rovers dramatically lengthen operational response times. The speed at which AI-enabled machines can react has several benefits. First, it allows diagnosing and repairing faults within complex systems to prevent measurement (instrument) or mission failure through timely diagnosis and management of unexpected anomalies. Secondly, it allows responding to unexpected, ephemeral science opportunities and the exploration of high-temporal phenomena. Finally, AI can accelerate the cadence at which science is conducted.

The use of AI to enable science by observing the pace of rapidly evolving phenomena was demonstrated spectacularly with the Jet Propulsion Laboratory's 2006 discovery of dust devils and clouds on Mars. [2] Both JPL [3] and APL [4] have demonstrated that AI can accelerate the pace of science by more effectively coordinating and utilizing space-based sensors. As an example, the intelligent fault management system *Livingstone* was developed by NASA AMES and flown on NASA's Deep Space One mission in 1998. [5]

The current risks of AI: Today, AI is immature and requires further development to reach its potential. For instance, the AI algorithms that detected the dust devils could not have identified whether the Martian weather represented a threat to the rover. Also, AI can not yet use instrument input to determine what, where, and how to autonomously make the next science measurement. An equally important factor limiting AI's deployment is that we lack the methodology and technology to effectively test AI. We have explored emerging requirements for testing aspects of terrestrial autonomous systems [6] and these needs are reflected in space-based AI testing.

Path to AI in 2050, Testing: The greatest risk associated with AI is the risk of undesirable detrimental, consequences from decisions emerging from unintended combinations of legitimate rules and/or patterns. Traditionally, system test and evaluation requirements define the desired system response for all anticipated operating conditions. Requirements-driven design is problematic for AI-enabled systems because the size of the condition-response matrix is intractably large, preventing test engineers from fully enumerating system requirements. In addition, autonomous systems, by their very nature, determine responses at run time, a control technique that is itself antithetical to an a priori system response matrix. The first challenge with testing AI-enabled systems is: how can AI performance be measured? The National Institute of Standards and Technology (NIST) autonomy levels for unmanned systems ALFUS [7] codify the degree to which a system is, or is not, autonomous; standard metrics on autonomous system performance are not codified. It is clear that AI-enabled system metrics must include measurements of the decision made by the system; and a subset of any autonomous system metrics should be derived from mission performance. Relying solely on mission-based metrics for AI-enabled systems can be problematic as the decisions made by the AI may have unintended consequences that are unrelated to mission objectives, yet very detrimental to the larger objectives of the operator. How can the test team provide performance assurances given that it is impossible to test all circumstances?

Because AI-enabled system performance is dependent upon the complex interactions between the AI-enabled system and artifacts in the real world, it is vital that tests be conducted in environments that mimic the complex interactions between actors in the real world and the AI-enabled system. This need presents us with our final challenge to testing AI-enabled systems: how can we provide a complex, *interactive* test environment that, from the point of view of the AI, mirrors the diverse interactions experienced in real-world operations.

Path to AI in 2050, Technology Advancements and Distributed Systems: Complex algorithms are often synonymous with power hungry electronics. As technology advances, the realization of low power computing becomes viable in space. An example of this new technology is neuromorphic computing. Influenced by how the mammalian brain processes and communicates data, neuromorphic computing is a new class of non von Neumann machines that is showing excellent performance in neural network applications. One such system, the IBM TrueNorth, has packed a million spiking neurons into a chip consuming on average less than 100 mW [8] and recent work has been demonstrated on deep learning datasets [9].

The combination of distributed autonomous systems [10] with low power yet high computing resources provides a bridge to fully autonomous mission concepts. Imagine a swarm of dispensable autonomous explorers that can intelligently investigate large areas and provide reconnaissance and surface exploration prior to the main spacecraft arrival. Mission success is robust against individual unit failure, as the aggregate is more capable than the sum of the parts.

Advances in algorithms, testing, sensor technologies and packaging is beginning to make possible the concept of complete autonomous space systems. The realization of fully autonomous systems enables new solutions for planetary exploration.

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DON'T INVENT THE WHEEL: SEEKING LIFE IN THE SUBSURFACE OF MULTIPLE ICY OCEAN WORLDS BY 2050. B. E. Schmidt[1], [1]Georgia Institutte of Technology (britneys@eas.gatech.edu).

Introduction: Icy ocean worlds such as Europa, Enceladus and Triton are compelling targets for exploration, not only for understanding how solar system formation has occurred and the vast range of possible forms that arise, but also for the potential detection of a second (or more) origin of life within our solar system. Indeed these worlds are unique, as different from each other as they are from terrestrial planets. However, these planets present together a similar challenge for future exploration and the search for life. With no appreciable atmospheres and astrobiologically relevant environments separated from the surface by kilometers of ice, these worlds have different science questions, different engineering challenges, and different priorities than the Moon and Mars. Most importantly, the most critical and potentially impactful questions must be answered NOT at the surface, but deep within the subsurface in aquoues environments. We must not use our experience with Mars as an intuitive guide for how to approach their exploration. Rather, we require a hollistic approach to the science of these bodies and the way that we envision exploring their subsurfaces.,

Get to the Surface: These worlds present many challenges for engineering to overcome, but I focus on two: 1) the lack of an atmosphere and 2) unforgiving surfaces. At present, landers to Europa or Enceladus are (nearly) prohibitively expensive since landing systems grow exponentially depending on landed mass. The existing landing systems for Mars, hybrids of the sky crane design, are the best solution currently available, but it is not clear that this is the optimum solution for such planets. In addition, while it is convenient to assume (or perhaps hope is a better word) that a safe landing site is accessible to our landers, there is little evidence to suggest that compelling places to investigate on theses worlds, such as the SPT on Enceladus and chaos on Europa, are likely to be safe—we will need a new way to approach lading site selection and EDL systems. Significant, multi-center investments and collaborative work with defense and private industry in entry, descent and landing (EDL) systems for these worlds are needed. The present pace of technological advance in launch capability made possible by competition and collaboration between private and public entities suggests that broadening our perspective on other technologies could provide similar improvements to exploration strategies.

Kick the Tires: At the end of the day, our questions about life's orgins and its discovery on these worlds requires getting into water. Roving the surface would be myopically limiting and likely waste significant time and funds. This is a bold assertion, but I liken it to the continued debate between returning to the lunar surface or going straight for Mars—there is limited overlap in the technology, mission planning, and scientific questions for these two scenarios. Surface mobility on icy worlds could be effective for adjusting the location of a subsurface accessing platform, but should not be thought of as the end goal. For each of these worlds, thermo-mechanical drilling is an enabling technology with little investment thus far by NASA. Thermal drills have been in development, with a wide range of designs, as have mechanical drills, but coupling these technologies could provide the required tool to deal with any environment one would encounter on these planets (chaning composition, salt deposits, impace-derived silicate debris layers). Importantly, such a flexible system would be the same, or scalable, for each of these similar worlds.

Suggestions for the Future: I suggest several steps are needed to realize the goal of multiple moon subsurface exploration by 2050.

0) Adjusting terrestrial world based intuition for exploration and science questions

1) Dedicated Icy World technology programs are needed for EDL, navigation, and subsurface access. PSTAR and such programs are great ways to make progress, but they do not result in institutional investment in these technologies without help.

2) Dedicated life detection instrumentation programs ground tested on Earth in real laboratories.

As I write this abstract, I am 34. In 35 years I hope I will see us land on Europa. If we invested in these technologies for ten years, we could launch a subsurface accessing mission to Europa or Enceladus as step one in a program to explore the icy ocean worlds with scalable technologies to lower cost and improve the likeliness of mission success in scientifically compelling regions of these planets. Flyby. Orbit. Land. Drill. Swim. Find Life.

MARS IS THE EARTH'S ONLY NEARBY EARLY LIFE ANALOG, BUT THE MOON IS ON THE PATH TO GET THERE. H.H. Schmitt[1], [1]University of Wisconsin-Madison, P.O. Box 90730, Albuquerque, NM 87199

Introduction. Mars provides a geological integration of the early solar system impacts recorded by the Moon and the contemporaneous water-rich pre-biotic period on Earth. Consideration of human missions to Mars logically would include an evaluation of the successful implementation of a comparable space effort, namely Apollo. The keys to the success of the Apollo Program included the existence of:

- A sufficient base of technology,
- A reservoir of young engineers and skilled workers,
- A pervasive environment of national unease,
- The catalytic event of Yuri Gagarin's orbital flight,
- An articulate, persuasive and patriotic president and congress,
- A commitment of a ~100% management reserve of funding, [1]
- Tough, competent, disciplined and courageous managers, [2]
- The a goal that could be accomplished in a decade, and
- A working environment of liberty.

All these keys to success must accompany a Mars Program with the following additions:

- Improved education in STEM, engineering skills, and critical thinking,
- Given the advance of technology, a ~30% management reserve through systems' CDRs may be adequate, and
- China's rapid progress substitutes for the Cold War I stimulus,
- An indefinite national commitment to deep space exploration,
- Maintenance of an average workforce age of <30 years, and
- Elimination of the political aversion to taking necessary risks.

Major Mars Program Requirements. The catalysts for initiating a Mars Program include all of the following: geopolitical reality with respect to China, economic need to stimulate future technologies, and addressing the crisis in engineering and science education facing the United States. Also, deep space operational experience must be regained by continuous generations of young implementers. Finally, there must be a permanent public and political commitment to deep space exploration and development on a par with, and related to a commitment to National Security.

A focused Apollo-style management system will be needed, possibly involving a new national space exploration agency. This system must "stay young-stay lean-stay risk takers." Once the decision to go to Mars is made, the sole focus should be to just that. With such a decision, early tradeoff studies will be needed on interplanetary propulsion development, consumables requirements and sources, specialized technology development, and human spaceflight planning and operations. Additionally, first landing mission decisions will drive development and operations, specifically, crew size and capabilities (one or two crews with one or two landers), desired exploration science returns, and space resources delineation and use.

Management Requirements. The success of Apollo depended on the evolution of a management system that, with hindsight, includes many common sense attributes. NASA and its contracting corporation had access to the best engineers and engineering managers available. Because of the short duration of the program, the average age of the workforce remained below 30 years, a characteristic that has been maintained by an equally complex nuclear Navy with similar success. (Youth provided the motivation, stamina, patriotism and courage to see projects to successful conclusions.) The bureaucratic newness of NASA meant that management was minimally layered so that decisions could be made quickly and good ideas could move rapidly to implementation. NASA also supported an internal, independent engineering design capability that gave managers alternative viewpoints to those of contractors on major issues. Finally, Administrator James Webb persuaded the White House and Congress to provide a management reserve sufficiently great to maintain schedule in the face of unexpected engineering issues and accidents.

These management lessons and requirements should be embedded in the enabling legislation for a Mars Program, along with providing the Mars implementation agency with the hire, fire and re-assignment personnel authority necessary to maintain the vigor of the program.

Moon in the Context of Mars. Consideration of missions to Mars should include the value of returning to the Moon. The Moon lies only three days away in regard to Mars mission development, simulation and training versus the many months required to reach Mars. Flying to the Moon and working there require similar deep space operational discipline that new generations of space managers, engineers and flight controllers will need to assimilate. Also, many of the same deep space technological capabilities will be needed.

The Moon remains geopolitically critical in its own right. The existence of space consumable resources and potential energy sources [3] of importance to Earth have not been lost on other international players. Accessing these resources presents the possibility of cost reduction through private-government partnerships. Further, evaluation of the effects of 1/6 earth's gravity on physiological re-adaptation will answer the question, for better or worse, concerning the consequences of re-adaptation requirements in the 3/8 earth's gravity of Mars.

Important new and unique science will come from a return to the Moon. Whereas Mars will give new insights into pre-biotic and, potentially, early biotic history, the Moon provides insights into the extraordinarily violent impact history in which life's precursors formed. [4]

Mars Transit Hurdles. Missions to Mars will not be easy for many years to come. Transit alone presents the issues of radiation protection, micro-gravity countermeasures, consumables supplies, spacecraft redundancy and maintenance, crew proficiency for landing and return, crew composition and crew compatibility, and challenging in-flight work. Solutions to some of these issues may relate to solutions to others; however, many potential solutions require consideration of a return to the Moon to stay.

Water, oxygen, nitrogen, hydrogen, methane and other possible consumables provided by lunar resources can significantly reduce the required Earth launch mass of Mars-bound spacecraft. Among those other possible consumables is helium-3, a potential fuel for fusion-powered propulsion that could shorten transit time.

Mars Landing Hurdles [5]. Mars has enough atmosphere (~1/100th of Earth's) to cause entry, descent and landing (EDL) problems, but not enough to help much in kinetic energy dissipation. It is generally calculated that a Mars Lander will have a mass of at least 40 metric tonnes, so this is not a trivial issue. Further, EDL must be accomplished without real-time assistance from Mission Control. Landing, whether automated or not, likely will utilize a beacon operating from a previously landed, un-crewed habitat-supply precursor, necessitating a rover-assisted, surface rendezvous after landing.

Whatever approaches to EDL ultimately are developed for operational testing, such tests probably will take place at appropriate altitudes in the Earth's atmosphere. Also, operational technologies and procedures will need to be developed to support consideration of aborts to a landing in contrast to aborts to orbit. Future lunar landings offer the best means of testing abort-to-land concepts along with doing so with simulated Mars communications constraints.

Related to abort-to-land considerations will be evaluation of whether each early Mars mission should consist of two landers and two full crews. The cost, time and risk inherent in Mars missions argue for steps to maximize landing and exploration success. In the likely event that both landers reach the surface successfully, the science return from two separate landing sites will be an added benefit to adopting this approach. An additional potential benefit of having two crews is that the orbiting crew can provide real-time mission support during landing and ascent and during other nominal or off nominal events. This latter activity compensates, in part, for the absence of real-time Mission Control input.

Major Mars Exploration Hurdles. Exploration of the surface of Mars will have many similarities to future lunar exploration. Lunar preparatory missions provide the means of testing, operating and maintaining Mars-consistent equipment such as mixed-mode rovers, sampling and analytical tools, analytical equipment for return sample selection, bio-containment systems for drills and sample packaging, dust mitigation concepts, food production concepts, and nuclear power systems.

Of particular importance will be the evaluation of Mars extravehicular mobility units (EMU). Whereas, Apollo EMUs were designed for use over a few days, Mars EMUs will need to be designed for long duration use and maintenance. Lunar exploration provides an unique opportunity for testing such systems over extended cycles of use.

Simulation of a variety of operational issues that will arise during Mars exploration can be conducted on the Moon. These include variable communication delays that can be integrated into lunar exploration, providing real-world operational experience with this form of crew-earth interaction.

Although consumables production (water, oxygen, nitrogen, helium, fuels and food) on the Moon begins with processing regolith rather than the more chemically variable Mars surface materials, the operational experience with such processing, as well as volatiles refining, will provide invaluable experience in the design of consumables production systems for Mars.

Conclusion. A return to the Moon appears to be essential to significantly increasing the probability of success of a Mars program and to maximizing the scientific return from such a program. Such a return to deep space exploration, however, requires the unequivocal and sustained commitment of the Nation, even more so that was required for the Apollo Program.

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THE VENERA-D CONCEPT, SCIENTIFIC EXPLORATION OF VENUS IN THE POST-2025 TIME FRAME. D. Senske[1], L. Zasova[2], T. Economou[3], N. Eismont[2], L. Esposito[4], M. Gerasimov[2], N. Ignatiev[2], M. Ivanov[5], K. Lea Jessup[6], I. Khatuntsev[2], O. Korablev[2], T. Kremic[7], S. Limaye[8], I. Lomakin[9], M. Martynov[9], A. Ocampo[10], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, [2]Space Research Institute RAS, Profsoyuznaya 84/32, Moscow 117997, Russia, [3]Enrico Fermi Institute, University of Chicago 933 East 56th Street, Chicago, IL 60637, [4]University of Colorado 1234 Innovation Drive Boulder, Colorado 80303, [5]Vernadsky Inst. RAS, Kosygin St., 19 Moscow, Russia, [6]Southwest Research Institute 1050 Walnut, Suite 300 Boulder CO 80302, [7]Glenn Research Center, 21000 Brookpark Rd, Cleveland, OH 44135, [8]Univ. of Wisconsin, 1225 W Dayton St Madison, WI 53706, [9]Lavochkin Assoc. 24, Leningradskaya Str. 141400 Khimki, Russia, [10]NASA Headquarters, Washington, DC.

Background: Because the Earth and Venus were formed in the same region of the inner solar system out of the same protoplanetary material and have nearly the same size, mass, and density, they are considered "twins". Yet Venus' atmosphere and climate are dramatically different from that of the Earth. The Earth hosts water dominated clouds, its atmosphere is N_2 rich with trace amounts of CO_2, and its near-surface temperature is a comfortable 25° C. In contrast, the climate of Venus is fueled by a massive CO_2 atmosphere resulting in an enormous greenhouse effect that has produced a surface pressure of 90 bars and a near-surface temperature of 470°C. The Earth, shielded from the solar wind by its magnetic field, contains abundant water supporting an active biosphere. In comparison, Venus lacks both an intrinsic magnetic field and any surface water. The surface has been sculpted by volcanism and deformed by faulting and folding, forming belts of mountains and rifts, geologic activity more directly coupled to mantle processes rather than plate tectonics. The lack of an intrinsic magnetic field suggests that Venus' interior structure may also be different than that of the Earth.

Why did Venus take an evolutionary path so different from that of the Earth? Currently, the Earth stands as our only example of a planet hosting life. We are therefore compelled to understand when the evolutionary paths of these twin planets diverged, as well as understand how and why the divergence occurred. Answers to these questions can help us determine if conditions ever existed on Venus that could have fostered the origin of life and in turn help us understand what makes a planet habitable.

Venera-D baseline concept: To address the overarching scientific questions regarding the evolution of earth's nearest neighbor, the coming decades offer the opportunity for the comprehensive exploration of Venus--from orbit, in the clouds, and on the surface. Envisioned for the post-2025 time frame, the baseline Venera-D (Venera-Dolgozhivuschaya (long-lasting)) concept, consisting of an orbiter and lander with advanced, modern, instrumentation, would be the next step in the highly successful series of Venera, VEGA, Pioneer Venus, and Magellan missions carried out in the 1970's and 1990's [1,2,3] along with the more recent Venus Express mission [4].

Venus science goals: To establish the science goals and priorities, mission architecture, and technology needs of the Venera-D concept, NASA and IKI/Roscosmos established a Joint Science Definition Team (JSDT). A key task of the JSDT was to codify the synergy between the goals of Venera-D with those of NASA. To this end, the group established traceability to the NASA Planetary Decadal Survey [5] and the VEXAG goals, objectives and investigations [6]. Specific areas of investigation would address questions about the dynamics of the atmosphere with emphasis on atmospheric superrotation, the origin and evolution of the atmosphere, and the geological processes that have form and modified the surface with emphasis on the mineralogical and elemental composition of surface materials, and the chemical processes related to the interaction of the surface and the atmosphere. For each Venea-D baseline mission component, the following goals would be addressed:

***Orbiter Goals*:**

- Study of the dynamics and nature of super-rotation, radiative balance and nature of the greenhouse effect;
- Characterize the thermal structure of the atmosphere, winds, thermal tides and solar locked structures;
- Measure composition of the atmosphere; study the clouds, their structure, composition, microphysics, and chemistry;
- Investigate the upper atmosphere, ionosphere, electrical activity, magnetosphere, and the escape rate

***Lander Goals*:**

- Perform chemical analysis of the surface material and study the elemental composition of the surface, including radiogenic elements;
- Study the interaction between the surface and the atmosphere;
- Investigate the structure and chemical composition of the atmosphere down to the surface, including

abundances and isotopic ratios of the trace and noble gases

- Perform direct chemical analysis of the cloud aerosols;
- Characterize the geology of local landforms at different scales

The JSDT concluded that, *in situ* measurements, both at the surface and aloft made over an extended period of time would be enabling, especially for understanding the processes that drive the atmosphere. Mobility within the atmosphere was also deemed to be of high priority in terms of understanding the location of the UV absorber and identifying its composition. Augmentations to the baseline concept could include (1) an aerial platform (balloon) to address science focused on atmospheric superrotation (UV –absorber), chemistry, and trace species in the middle cloud layer and (2)a small long-lived station for studying superrotation, meteorology and chemistry in the near surface layer.

Technology assessment: The extremes of temperature and pressure make the operation of a spacecraft in the Venus environment a unique challenge. Key areas where technology maturation is required are: (1) the lander sample handling/processing system, (2) the need for facilities to test and qualify a full-scale lander, and (3) maturation, testing, and validation of instruments that would need to operate under Venus conditions.

To ensure scientific success, laboratory experiments will be fundamental to validating scientific results. Among the high priority analyses needed to be performed include studies of (1) spectral line profiles under high pressures and temperatures (orbiter), (2) optical properties of the lower Venus atmosphere in the visible to near infrared (lander), (3) evaluation of the compositional change of the trace gas components due to temperature and pressure drop during atmospheric sampling (lander); (4) trace and noble gas enrichment procedures (lander); (5) atmosphere (pressure/temperature) effects on remote sensing instruments (lander) (6) supercritical properties of Venus-like atmospheres (lander); (7) UV absorption experiments to aid in constraining the identity of the unknown UV absorber and identify insolation energy deposition (aerial platform).

JSDT findings and recommendations: The JSDT identified priorities for the science goals and objectives for a comprehensive scientific exploration of Venus. Based on these priorities, a baseline mission would consist of a single highly capable orbiter and a single highly capable lander. Each would address science questions regarding the composition and dynamics of the atmosphere. In regard to surface and surface-atmosphere interactions, the lander would be the primary mission element to address these objectives while the orbiter, making surface observations in the near-infrared would provide global-scale data to address questions related to recent volcanic activity and compositional variability of terrains.

In formulating a strategy for the development of Venera-D, the JSDT identified areas where investments would need to be made to bring the mission concept fruition. For an anticipated launch in the post-2025 time frame, activities of the following nature would be needed to ensure mission success:

- The types of instruments, including lander sample collection and handling, to achieve the Venera-D science require various levels of validation and maturation to ensure robust and successful operation in the Venus environment
- Laboratory work to characterize the chemistry of the Venus atmosphere at high temperatures and pressures
- Development of capable facilities to test mission enabling instruments and the spacecraft at the component and system level in a simulated Venus environment
- Continued development regarding aerial platforms and long-lived surface stations

Framework for future work: The next phase of development of the Venera-D concept would focus on a deeper examination of the science measurements and potential instrumentation along with the definition of spacecraft requirements. Within this context, specific areas that deserve attention include the following:

(1) Definition of a focused mission concept
(2) Definition of the concept of operations for the lander including a timeline of science observations, strategy for sample acquisition, handling and analysis, data flow and downlink
(3) Refinement of instrument capabilities relative to the ability to achieve the science goals
(4) Refinement of the envelope (mass, power, volume) for a potentially aerial vehicle or long-lived surface station
(5) Maturation of the small station concept; instrumentation and concept for targeting and deployment
(6) Aerial platform accommodation and deployment optimization along with science priorities and instrumentation

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SAMPLING THE SOLAR SYSTEM. A CRITICAL EXPLORATION COMPONENT FOR FUTURE PLANETARY DISCOVERY. C. K. Shearer, Institute of Meteoritics, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131. (cshearer@unm.edu).

Introduction: Sample return from a wide range of planetary bodies provides valuable insights into the origin and evolution of the Solar System and identifies potential hazards and resources for future human activities on planetary surfaces. Sample return is a valuable exploration tool as it increases the value of both orbital and surface observations. In 2007, the Curation and Analysis Planning Team for Extraterrestrial Materials was requested by the Director of the NASA Planetary Science Division (PSD) to conduct an analysis of potential linkages between simple and complex sample return missions and to identify those critical investments that would best reduce risk and cost for increasingly complex sample return missions over the next 20 years. Results of this analysis are available at http://www.lpi.usra.edu/captem/sampleReturnWorkGroup.pdf. Here, we expand this analysis to 2050 in light of the most recent PSD decadal survey, observations from previous and ongoing planetary missions, new planetary discoveries, and current NASA goals for human exploration.

Sample Return Mission Styles: There are a variety of mission styles for implementing sample acquisition. *Flyby style missions* acquire samples of material from a planetary body without touching its surface. Most recent missions of this type include Stardust (comet) and Genesis (Sun). These missions used passive collecting approaches, whereas future missions could potentially use more interactive systems. With increasing complexity and durability, this type of mission style could be used to collect materials (e.g., dust) from upper planetary atmospheres (e.g., Mars, Venus) and explosive eruptive and outgassing events on several outer Solar System bodies (e.g., Io, Enceladus). In the *touch-and-go mission style*, samples are acquired by the spacecraft by briefly touching the surface of the body, quickly collecting the sample, and moving to another sample collection site (or body) or returning to Earth. This type of mission is ideal for sampling the surface of small bodies where the gravitational force is negligible, obviating the need for elaborate and expensive descent and ascent systems. Previous and on-going missions such as Hayabusa, Hayabusa 2, and OSIRIS-REx demonstrate this style of sample return. Taken to more complex levels, these styles of missions could incorporate components to better preserve collected samples (e.g. volatiles), subsurface samples, higher sample mass, deploy more sophisticated instruments on the surface, and tour multiple and more distant bodies (e.g., asteroid belt). *Landed surface sampling style missions* require safe landing on a surface, and spending sufficient time on that surface. These missions have the capability of collecting higher sample mass, collecting over a range of sites, landing on a variety of planetary bodies (e.g., comets, asteroids, Moon, Mars, Venus, Mercury, Phobos, Deimos), and deploying surface instrument packages. This style of mission has the capability of returning regolith, rocks, ices, organics, and atmosphere. Collecting many of these materials will require advance collection, contamination prevention, preservation, and curation technologies. Previous sample return missions of this style include the Luna missions carried out by the Soviet Union and the Apollo missions in the 1970s. The Luna missions were the only successful robotic sample return missions of this style.

Within and between each style of mission there are different levels of complexity. There are common technological linkages among mission styles and among planetary destinations. Technological overlap also exists between robotic and human exploration.

Examples of the increasing complexity of mission styles: NASA has a recent heritage of *flyby sample return missions*. The success of these missions provides a foundation for increasing complexity and destinations between 2017 and 2050. For example, a mission of intermediate complexity may involve sampling in the inner

Solar System using a projectile fired from the spacecraft and collected from the resulting plume. An intermediate mission could provide the capability to preserve volatile elements. A flyby mission of much higher complexity may involve sampling the atmosphere of Venus or Mars, plumes from the moons in the outer Solar System, or rings of the giant planets.

NASA does not have a heritage of *landed surface sampling style missions.* However, landed missions on Mars, developing technologies for the Mars ascent vehicle, rovers, sample manipulation capabilities (e.g., scoop, sieve, corer, rake), and orbital rendezvous, feed forward to other sample return missions. Simple missions may involve sampling outside gravity well from a static lander with direct return to Earth (small bodies). Missions of intermediate complexity may involve sampling of the surface of moderately hostile environments/planetary bodies (Moon, Mercury, Mars) with a static lander, simple sample selection and manipulation, and either direct to Earth or rendezvous return. More complex missions may involve higher sample mass, roving capabilities, a variety of sample manipulation and selection tools, more sophisticated sample preservation capabilities, and operation in highly hostile environments (e.g., Venus, planetary cold traps).

Commonality among missions: To efficiently reduce risk and cost of increasingly more complex sample return missions in the next decades, it is critical to advance technologies that have overlap among missions. There are several types of technology/capability linkages that are either appropriate for several missions with minor modifications, or feed forward to more complex missions. There are linkages between sample return and non-sample return missions such as precision landing and hazard avoidance. There are linkages among different styles of missions (flyby, touch-and-go, surface landing) such as reentry and hard-landing on Earth, reducing contamination, and preserving environmentally sensitive samples. There are linkages with a single style of mission to a variety of planetary bodies such as sample collection, manipulation, and storage on a planetary surface or sample collection and verification of success during a touch-and-go mission. Finally, there are linkages between sample return and human exploration such as rendezvous around a distant planetary body and return to Earth.

There are technologies that are specific to a single planetary body (i.e. Mars Ascent Vehicle, Mars rendezvous). Investment in these technologies will substantially reduce risk to a single sample return mission and perhaps will feed forward to more complex missions to sample this body (e.g., human missions) and reduce both cost and risk.

Initial conclusions for the future of sample return: Sample return is a vital component to any future planetary science exploration program. A variety of mission styles have application to most Solar System bodies. Higher risk and cost is commonly associated with sample return missions relative to other types of Solar System exploration missions. This is a result of sample return missions commonly being more complex and the necessity for the spacecraft to return to its point of origin. However, sample return has many important attributes. First, it is the closest approximation to a human exploration mission. Second, samples provide a unique perspective of a planetary body that cannot be obtained by any other mission approach. The mitigation of cost and risk of the mission and its development puts an even higher priority on early technology development than for more conventional mission types. Technology linkages among different types of planetary missions feed forward to increasingly complex sample return missions. Investing in developing and flying these technologies will increase the rate of success of future sample return missions and lower the overall cost in the decades to come.

FOLLOW THE (OUTER SOLAR SYSTEM) WATER: PROGRAM OPTIONS TO EXPLORE OCEAN WORLDS.
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Motivation and summary: Based on emergent findings from the past two decades of planetary exploration missions, the US Congress now requires NASA to implement a virtual Ocean Worlds Exploration Program (OWEP) using a mix of flagship, New Frontiers, and Discovery class missions [1].

Discovery-class (roughly half-$B) missions have not been found feasible: in 2010 and 2014, respectively, Discovery proposals to explore Titan and Enceladus were rejected for too-high cost risk. NASA is currently developing a moderate-cost flagship mission to assess the habitability of Europa; this may be accompanied by an essentially simultaneous flagship mission that would land on Europa to search for biosignatures. In 2016, NASA took three steps responsive to the Congressional direction: added an ocean-worlds theme to the New Frontiers-4 opportunity currently open [2]; solicited COLDTech proposals to mature relevant technologies [3]; and chartered the Roadmap for Ocean Worlds (ROW) team to catalogue potential ocean worlds and articulate key science questions for them [4]. New Frontiers (roughly $1B) is NASA's intermediate cost class for planetary missions, and multiple proposals are in preparation. The next planetary Decadal Survey will be chartered by 1QFY20, and its results reported out to NASA in 2QFY22 [5]; its deliberations will be informed by the outcome of all these initiatives.

Despite the current activities, opportunities, and interest, lack of a formal program structure precludes rapid progress for an OWEP. Nothing akin to what has been delivered by the Mars Exploration Program (MEP) over the past 15 years can occur with the current model. The strategy analysis presented here treats the governing programmatic constraints, technical uncertainties, and policy gaps that cause this to be so. Then it lays out technical constraints for results-based OWEP decision making, and multiple options for making progress in this environment. It derives and presents candidate technology investments and policy decisions that would have high leverage over the viability and velocity of an OWEP.

Not like MEP: The MEP has been able to make rapid progress just since the early 2000s because: 1) Mars-distance missions are technically moderate; 2) the 26-month synodic cadence of half-year transfers to Mars allows mission formulation to be responsive to emergent findings; 3) NASA controls project new-starts within a single Congressionally funded program budget line; 4) NASA is thus able to direct New Frontiers-class missions that implement key steps of a progressive investigation; and the multi-mission program accommodates both 5) program-dedicated technology investments and 6) operational infrastructure that simplifies individual missions. Not one of these six key conditions exists for the virtual OWEP envisioned by Congress.

The technical challenges for an integrated OWEP are formidable. Missions to the Jovian and Saturnian ocean worlds are intrinsically power-challenged: sunlight at Saturn is only 1% as strong as at Earth. When limited to the type of expendable launch vehicles standard for NASA planetary exploration, missions require half-decade (to Jupiter) or decade-long (to Saturn), transfers with multiple gravity assists: a single one-way mission to explore Enceladus or Titan would take as long as has the entire MEP to date. Key pieces of the overall scientific puzzle of ocean-world phenomenology are found at multiple moons distributed across interplanetary distances, rendering shared in-space operational infrastructure (e.g., MEP's telecommunication relays and observational assets) moot. And the oceans themselves are inside the moons, beneath kilometers of cryogenic ice.

In addition to these endemic physical challenges, a "virtual program" imposes severe handicaps to progress: development of OWEP-enabling technologies must compete for priority with other solar system objectives; and every mission requires individual new-start approval. The selection process for PI-led, competed missions (New Frontiers and Discovery) is semi-stochastic: selection depends on what is proposed, and how the proposals fare under independent evaluation by SOMA (the NASA Science Office of Missions Assessment). Ocean-worlds missions compete directly against other science objectives identified by the current Decadal, and NASA cannot directly "put its thumb on the scale" to assure selection of ocean-worlds investigations. Thus New Frontiers and Discovery can never be useful for strategic planning: the "program" could end up comprising only the Europa mission and concept currently in work. NASA's Planetary Science Division has no class of mission opportunity comparable to the MEP backbone (MGS, Odyssey, MER, MRO, and the potential NeMO, all of which are directed medium-class missions). Without a genuinely strategic program plan, the great promise of an OWEP is highly likely to remain unfulfilled.

Strategic options: The solar system serves up almost a dozen diverse ocean worlds [6]. By various counts there are 2-3 relict ocean worlds, including Mars, Ceres, and possibly even Venus. At least five Jovian and Saturnian moons have global subsurface salt-water oceans; three of these are already known to be in contact with silicate rock, a key to chemical habitability. A few implausibly tiny moons (e.g., Dione and Mimas) show tantalizing signs of interior liquid; and even the three Kuiper Belt Objects visited so far (Triton, Pluto, and Charon) evince dynamic geology caused by eutectic mixtures of water and ammonia. By systematically exploring this large set of targets, humanity can learn the limits of life's ability to appear, evolve, and survive.

The provisional assessment that Enceladus may be habitable is based on hard evidence – multiple lines of evidence more diverse and quantitative than we have so far for any other extraterrestrial ocean world. Some of the most compelling findings have been published even since the current Decadal Survey was issued, energizing this dynamic field. Although Enceladus' unique geophysics makes it the most accessible place for a direct search for biosignatures, a stepwise roadmap to find and then characterize life in this ocean world [7] can in some ways serve as a template for other ocean worlds as well.

OWEP progress would be accelerated if NASA could adapt a few key characteristics that have made the MEP so successful: 1) cross-cutting investments in enabling technologies not tied to or funded by individual mission projects; 2) directed, New Frontiers-class missions to conduct strategically pivotal investigations on a roadmap; and 3) common, multi-mission technical infrastructure. In the case of missions to distributed moons of Jupiter and Saturn, a primary example of such infrastructure could be the use of SLS (the Space Launch System) for launch onto direct-transfer trajectories into the outer solar system, which would halve trip time.

By comparing the default constraints with various options for a multi-decade, multi-world program, we frame high-leverage choices that NASA and its stakeholders could consider.

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A VENUS ATMOSPHERIC SAMPLE RETURN MISSION CONCEPT: FEASIBILITY AND TECHNOLOGY REQUIREMENTS. E. Shibata[1†], Y. Lu[2†], A. Pradeepkumar[3†], J. A. Cutts[‡], and S. J. Saikia[4†], [1]eshibata@purdue.edu, [2]yelu@purdue.edu, [3]apradee@purdue.edu, [4]ssaikia@purdue.edu, [†]School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Ave., West Lafayette, IN, 47907, [‡]NASA-Caltech Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA, 91109, james.a.cutts@jpl.nasa.gov.

Earth's "Twin" Planet: Of all the rocky planets in the Solar System, Venus and Earth come the closest to being similar—at first glance. Both are about the same size, have approximately the same mass, and have orbits that are close to each other. Similarities end there: whereas Earth has a habitable 1 atm pressure and 15°C average temperature on the surface, Venus has an atmosphere at 92 atm and 464°C; Earth has a life-friendly mixture for its atmosphere, while Venus has corrosive clouds.

Figure 1: Venus photo from the Magellan mission. [http://photojournal.jpl.nasa.gov/catalog/PIA00104]

Venus Science Goals: However, exploring Venus will help in understanding how our planet has formed. Considering the similar volumes and orbits, understanding how Venus came to be may lead to a better understanding of how planets are formed. In the Venus Exploration Analysis Group (VEXAG) Goals, Objectives, and Investigations study [1], three goals were identified for future Venus exploration:

- understanding the atmosphere's origins and its evolution, as well as the climate history,
- determining how the surface and interior evolved,
- and understanding the interior-surface-atmosphere interactions over time, as well as if liquid water was ever on Venus.

By measuring the isotopes of nobles gases and oxygen, the origin of the atmosphere can be found. Additionally, the mid-altitude range of Venus (~55 km) has a pressure of approximately 1 atm and 20°C, which has the conditions for habitability and might potentially harbor life forms or evidence of biological processes [2]. The second goal of the VEXAG study looks at the divergence of Venus and Earth from a geological point of view. Although Venus seems to have a young surface, tectonic plates are thought not to exist on Venus. Measuring the outgassing that occurs at the surface, as well as the composition of the surface, can help us understand how Venus's core works and how it has evolved to its current state. Looking into the interactions between the atmosphere, surface, and interior, the third goal cements in place how all three have changed throughout Venus's existence. Surface composition may show some record of hydrated minerals, or volatiles from the interior.

Grabbing Samples from Venus: Future Venus missions should accomplish several of the science goals through in-situ or remote measurements. An atmospheric sample return would accomplish the first and third goals, while a surface sample would accomplish the latter two. Although any samples returned would have a relatively small mass compared to in-situ measurements, having a physical sample in a laboratory has its advantages [3]. Within a lab setting, more accurate and powerful equipment can be used without having to worry about the mass penalties on the spacecraft. With proper storage, these samples could be used again and again with new generations scientists and technologies. Taking advantage of nondestructive techniques, the same sample can be analyzed multiple times through a variety of equipment on the ground; an in-situ science lander rarely has the chance to analyze a sample that has been analyzed by another instrument. With samples returned to Earth, any results can be verified or rejected by reanalyzing the same sample, avoiding some of the issues that have plagued previous missions. As seen with lunar samples, any samples returned can be retested with new hypotheses, without having to send another spacecraft to perform more science measurements.

Price of Thick Atmospheres: Sample returns missions from the Moon and comets were successful, but to return samples from Venus, technology developments and some precursor technology validation missions are essential [4]. These include high-temperature ascent balloons that can be inflated at a temperature of 460°C, guidance and control technology for a Venus ascent vehicle that would be launched from a balloon, and thermal control for a Venus ascent vehicle and lander that is also compatible with the required sample retrieval activities.

Atmosphere Samples vs. Surface Samples: Retrieving surface samples from Venus is notoriously difficult due to the technology development required for the extreme surface conditions. While atmospheric samples can be captured and retrieved with relatively low cost [5], some of the science goals rely on the return of surface samples. Numerous studies have investigated the feasibility of both atmospheric and surface sample returns.

Atmospheric Samples. Two types of atmospheric sample return missions are considered depending on altitude: (1) a single spacecraft can perform a high altitude flyby over Venus and collect samples from the upper atmosphere; (2) lower altitude flyby uses an additional element that dives deeper into the atmosphere to collect gas samples from lower atmosphere and exits the atmosphere to rendezvous with a spacecraft returning to the Earth. The latter concept allows for the collection of particles and aerosols from the clouds in the lower altitudes. Another concept [7] considers a single spacecraft on a free return trajectory and a propulsion burn of 700 m/s at a periapsis altitude of 110 km to compensate for the drag loss.

Surface Samples. Surface sample return missions would require a surface ascent vehicle. Collecting surface samples at the aforementioned extreme environment is complicated enough; the operation becomes even more demanding when one tries lifting the samples off the surface. Three approaches of lifting surface samples were studied and compared [6]. The first approach of using conventional solid rockets has been concluded as unfeasible for Venus Ascent Vehicle (VAV) due to the thick atmosphere. A second approach is to deploy the VAV in the upper atmosphere, which is suspended on a blimp, and using the blimp to rendezvous the VAV with a balloon that lands on the surface and lifts the sample. The third approach is similar to the second but uses an airplane to suspend the VAV and to rendezvous with the balloon carrying surface sample. Figure 2 shows five sample return architectures that have been analyzed for Venus.

A Venus Atmospheric Sample Return Mission: The goal of this work is to 1) reevaluate the feasibility of Venus sample return mission with state-of-the-art or near-term technologies, and 2) propose a new atmospheric sample return strategy. The previous Venus sample return missions have been done with then-current state-of-the-art technology. By revisitng these with modern technologies and other near-term technologies, those mission proposals can be updated and improved. Missions are look at the mid-altitudes, where conditions for habitability exist, will be concentrated on. Revisting the previous architectures proposed, a new Venus atmospheric sample return strategy will be investigated, which can be done using existing technologies or planned in near-term for Earth and other planetary applications. One such technology is a Cubesat launcher. Since Venus and the Earth are similar in size and mass, similar vehicles could be applicable to be launched from the atmosphere. An Earth launcher designed for Cubesats may be useful for raising a Venus cloud sample to low-Venus orbit, which is then retrieved by an orbiter before it propels itself back to Earth.

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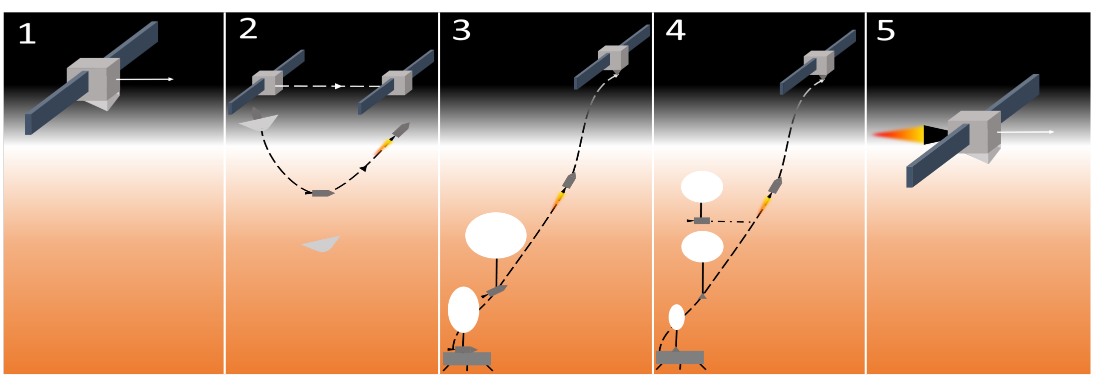

Figure 2: Five architectures that have been analyzed. Architecture 1 is the atmospheric skimmer, using a flyby spacecraft [5]. Architecture 2 uses a low-altitude probe that collects samples at low velocities [5]. Architecture 3 and 4 use a lander to collect surface samples, with a balloon that brings the VAV (in 3) or just the sample (in 4) to the VAV launch height. Once in orbit, it rendezvous with an orbiting tug [5]-[6]. Architecture 5 has a high-altitude spacecraft burn at the flyby periapsis while collecting samples [7].

ARCHIVAL DATA AND COMPUTATIONAL POWER IN PLANETARY ASTRONOMY: LESSONS LEARNED 1979–2016 AND A VISION FOR 2020–2050. Mark R. Showalter[1], Matthew S. Tiscareno[1], and Robert S. French[1], [1]SETI Institute (189 Bernardo Ave, Suite 200, Mountain View, CA 94043; mshowalter@seti.org; mtiscareno@seti.org; rfrench@seti.org).

Introduction. When the Voyager spacecraft flew past Jupiter in 1979, the most powerful computer available to most planetary scientists was a PDP-11. With 64K of addressable memory, analyzing even a single 800×800 Voyager image posed serious challenges. Disk storage might hold a few tens of images, but anything beyond that had to be stored off-line on tapes. Retrieving data entailed mailing (not emailing) a request to JPL and waiting for the cross-country shipment of tapes to arrive, perhaps weeks later.

Today, the entire Voyager image archive can be stored on a thumb drive. Scientists routinely analyze thousands of planetary data products on a laptop. Computational advances like these have been fueled by Moore's Law, which predicts that compute power doubles every two years. With our 37-year baseline of experience, we present some ideas about how planetary science can prepare to take advantage of the next decades of growth in compute power. However, we must also acknowledge the perils of making any such predictions, given that so many of today's capabilities were unimaginable in 1979. As a result, our primary focus is on the next 10–15 years. However, we also offer some suggestions for how to prepare for what might come thereafter.

Trends in Scientific Computing: Moore's Law has proceeded uninterrupted for many decades. However, as with any exponential trend, it cannot continue forever [1]. For example, CPU clock rates appear to be maxing out at the level of a few GHz, where heat dissipation becomes a limiting factor. Modern CPUs can execute more instructions per clock cycle, but even this trend cannot continue without limit. However, compensating for these limits is parallelism—the ability to harness very large numbers of CPUs to work on the same problem simultaneously. For example, the display of any laptop is driven by a Graphical Processing Unit (GPU), which is capable of performing many thousands of floating-point operations in parallel. With the proper re-formulation, many computational problems can already take advantage of GPU acceleration.

Data storage capacities and Internet access speeds continue to grow exponentially. However, at the same time, many NASA missions and Earth-based astronomers have demonstrated the capacity to generate exponentially increasing volumes of data. For example, NASA's Large Synoptic Survey Telescope (LSST) will generate 15 TB every night. Although the current Deep Space Network has distinct downlink limits, NASA and other agencies are already experimenting with laser-based optical transmission; this could dramatically increase the data volume from interplanetary spacecraft. Thus, we need to prepare for the possibility that data storage and access times will continue to be limiting factors in scientific research.

Cloud computing will provide a work-around to these limitations. Today, a scientist can construct a "virtual machine" (VM) that contains all of the software and data needed to perform a particular calculation. An arbitrary number of these VMs can execute simultaneously in the cloud. In one recent project, we developed a procedure that processes each image in the Cassini archive. Processing all 400,000 images required 30 days on an eight-core machine. We found that the problem was straightforward to re-formulate for Amazon's EC2 cloud computing platform, where it can now run much faster and for a total cost of $200 (using the lowest-priced computing tier). Depending on the application, other uses of cloud computing could easily run into the thousands of dollars at current prices, but these prices are certain to drop over time. Within the next decade, we can comfortably predict that most scientific computing will be performed in the cloud.

Steps Toward the Future of Cloud-Based Planetary Astronomy: Although cloud computing is our future, it has one marked disadvantage relative to the personal laptop—data analysis cannot be interactive. For this reason, we must explore key and fundamental changes to the way scientists analyze data.

Cloud-based data. Today, the Planetary Data System provides direct on-line access to NASA's planetary data. A typical user searches for data, downloads a small subset to their laptop, and proceeds with the analysis. In the future, it will be much more practical to move the "laptop" to the data. By this, we mean that the PDS should store complete, calibrated data sets in the cloud and make them available through pre-packaged VMs. When a scientist wishes to analyze a data set, s/he will download a VM, install into it the needed software, submit it to the cloud, and let it run there. In many cases, the data will never need to be downloaded.

Software preservation. Each NASA mission's data pipelines are written for its current era. As we all know, old source code is extremely difficult to maintain because hardware, operating systems and programming languages continue to evolve. The calibration pipelines of some NASA missions are already nearly impossible to run, because they were developed for architectures that no longer exists. For the sake of each mission's long-term legacy, it is critically important to begin preserving these pipelines. VMs provide a partial solution, because they also capture the OS and the environment needed to run software. Although a VM may not continue to run once the associated hardware is obsolete, hardware emulators can, in principle, preserve the functionality indefinitely. The broader computer science community has recognized the importance of this problem; NASA should endorse and support these efforts.

Calibration. Many mission data sets are still delivered to the PDS in raw form. In the future, it will be increasingly impractical to expect users to calibrate their own data products (except perhaps under specialized circumstances). Although preserving software pipelines via VMs, as discussed above, could be part of the solution, the ideal is for calibrated data always to be preserved as a part of the permanent PDS archive.

Precision navigation. One of the key steps in analyzing almost any planetary data product is navigation—aligning the data with a geometric description of the field of view. In the case of images, navigation can be based on the locations of fiducial features such as stars, moons, rings or specific craters. Instrument pointing is imperfect, so until the product is navigated, the predicted and observed locations of features in the field of view will disagree. In the past, navigation was almost always done by hand, product by product; such manual navigation is obviously impractical when TB of data are being generated each day. We have been developing procedures for the automated navigation of Cassini Saturn images, and are achieving a high rate of success [2,3]. Such procedures must be developed and perfected for all NASA data sets. Alternatively, spacecraft systems should be developed such that pointing and telemetry are sufficiently accurate that navigation becomes unnecessary.

Metadata and backplanes. A complete geometric description of each product's field of view serves two purposes. First, it potentially simplifies the analysis by automatically associating the geometry of each pixel with its geometric content. Second, it provides the robust information that might be needed for a user to determine, before checking, whether the geometric content of a particular product meets certain scientific requirements such as target body, resolution and lighting geometry. As one example, such information is critical to our ability to track new discoveries back through old data sets. Accurate metadata is contingent upon already having well-navigated products. VMs that generate specialized metadata and backplanes could also have a place in the archive.

Pattern recognition and neural networks. Many pocket cameras and phones now contain sophisticated algorithms for smile detection and blink detection. Additionally, popular photo software is capable of classifying images according to categories like "dog" and "birthday cake." One can only imagine the power of similar algorithms when applied to our planetary archives, where features like "cloud", "dust devil", "new crater" or "impact event" could potentially be identified automatically. The technology behind these algorithms must be harnessed for planetary data analysis and discovery.

Longer-term trends. The future of computing is driven by for-profit companies investing in tools to reach large markets. Beyond the next decade or so, it is impossible to predict where the big breakthroughs will occur. Planetary science will never be a large market, so we cannot necessarily expect profit-driven corporations to produce scientifically useful tools. However, we can and should piggy-back off the newest technologies as they emerge. We note that the greatest benefit from our tools can only emerge if we share them and agree to build upon them; this requires that NASA and the planetary science community reaffirm our commitment to open source.

Conclusions: Any survey of the literature from the 1980s and 1990s will confirm that it was a vibrant time in planetary astronomy, even though we were working with hardware that might today be compared to stone knives and bearskins. This illustrates the point that computers alone are insufficient to solve our scientific problems; the fundamental first steps will always originate with humans, via their ideas and innovations. Computers can, however, eliminate much of the hands-on drudgery that went into the pixel-by-pixel data analysis of earlier decades, streamlining the path from a germ of an idea to a refereed publication. With Moore's Law still in force, or nearly so, we will also be able to revisit old data and perform analyses that were once computationally impossible. Thus, computational advances will not just support future missions; they will, with the proper groundwork, make it possible to uncover fundamental new discoveries in NASA's existing archives.

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Science and Exploration in the Outer Solar System in 2050. A. A. Simon (NASA Goddard Space Flight Center)

Introduction: The best way to approach a vision 35 years into the future is to begin by looking back. A snapshot of the state of knowledge of the outer solar system in 1980 is quite different from what we know today. Voyager 1 and 2 had just flown by Jupiter in 1979 and were approaching Saturn for 1981 encounters, leaving the Uranus and Neptune systems still fully unexplored. Although the Jupiter encounters revealed Io as an active moon, and the planet's fast moving clouds were observed, our view of the solar system was still of bodies that were rather static and unchanging. Even our knowledge of solar system formation was one of planets that formed neatly in place.

We now know that the bodies in the outer system likely migrated vast distances during their formation, affecting the formation of the rest of the solar system. We have also witnessed multiple objects impacting Jupiter several times and observed geysers on Enceladus and Triton, weather and seasons on Titan, and many other dynamic phenomena. In other words, the paradigm has shifted to viewing planets as active and evolving. We now even search for possible signs of life under the surfaces of the moons outer solar system, a concept easily dismissible 35 years ago.

Current Goals: Based on current knowledge, the Planetary Science Decadal Survey (PSDS) identified overarching science themes and exploration goals for the 2013-2022 time frame, along with recommended missions to many bodies of the outer solar system, including Europa, Uranus, the Trojan asteroids, Enceladus and more. If we assume that these missions occur on schedule and meet their science goals, we further advance our knowledge in key cross-cutting areas.

The PSDS Giant Planets chapter focused on the exploration of the four giant planets and defined three overarching science themes: Giant Planets' Role in Promoting Habitable Environments, Giant Planets as Groundtruth for Exoplanets, and Giant Planets as Laboratories for Properties and Processes on Earth. These themes involve exploration of the planet atmospheres and magnetospheres, as well as the rings and satellite systems, with an eye toward understanding the solar system as a whole by studying the smaller, but pivotal, pieces.

Decadal Missions: The main Giant Planet mission recommendations were a New Frontiers Saturn Probe mission, as well as a strategic Uranus-system orbiter and probe mission. Other focused missions were also recommended for key outer planet satellites, such as Europa, Enceladus and Io. In particular, the probe missions both provide significant *in situ* characterization, completing our knowledge of the upper atmosphere of these two giant planets, as well as detailed remote sensing of the Uranus atmosphere, magnetosphere, rings, and satellite system.

These missions, when combined with results from Cassini for Saturn and Galileo and Juno for Jupiter, will further constrain our understanding of solar system formation and atmospheric processes, but undoubtedly will raise new questions. However, each of the Giant Planet systems is different, with varying size, solar distance, migration history, and seasonal influence. Thus, we need to understand each individually, as well as in a combined picture, to best address the crosscutting Decadal themes. Under the assumption that a Uranus mission will occur first, *a Neptune orbiter and probe mission is crucial for completing the characterization of the unique properties of the major bodies in the solar system and would be a high priority if it has not been initiated by 2050.*

Science Priorities in 2050: With existing data, and the proposed Decadal missions, many bulk properties will be constrained for 3 of the 4 giant planets. However, there are many areas that will still be unaddressed and are important for better understanding both exoplanets and atmospheric processes in comparison with Earth. For example:

1) *Seasonal effects*: the yearly variations of the outer planets are not well understood. Given the long orbital periods for Uranus (84 yrs.) and Neptune (165 yrs.), and even our limited coverage of the Jovian (12 yrs.) and Saturnian (30 yrs.) yearly cycles, there is much to be understood about the connections between solar insolation and convective activity, as well as other atmospheric wave-driven cycles. Even activity on the satellites may have seasonal components. Long-term remote sensing coverage is needed for each planet.
2) *Interior structure*: another key to understanding winds and weather, as well as observed atmospheric temperatures, is knowledge of the deep interior structure, equations of state, and the effects/likelihood of helium rain. New laboratory work, science instrumentation, and analysis techniques hold promise for beginning to remotely explore those regions.

And many more…

Summary: Given the expected state of knowledge for the Giant Planets at the end of the Decadal period, the highest science and exploration priorities can be projected for 2050. Our understanding of giant planet systems is critical to informing exoplanet, solar system formation, and atmospheric dynamic studies.

EVOLVING PLANETARY GEOLOGIC MAPPING EFFORTS IN FUTURE DECADES BY IMPLEMENTING A COMMON FRAMEWORK FOR SCIENTIFIC INVESTIGATION, EXPLORATION, AND POLICY.

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Introduction: In the most basic sense, geologic maps record the three-dimensional distribution of rock, sediment, and soil materials at and near the land surface including key geologic features or characteristics that occur on, within, or across these material units. Terrestrial geologic mapping is predominantly a field-based, applied research endeavor that leverages collaborations with and contributions from multiple disciplines. The goal is to establish a geologic framework for not only promoting comparability of basic research but also ensuring that decision-makers have the tools necessary to identify valuable natural resources, avoid risks from natural hazards, and make wise use of national assets. Planetary geologic mapping is predominantly a remote-based, basic research endeavor that contributes to the establishment of geologic frameworks in parallel with other geoscience disciplines using data acquired by orbiting and landed spacecraft. Technological advances have altered the process and product of geologic mapping over the past few decades, most specifically the availability of geospatial data that permit geologic map information to be electronically stored, displayed, queried, and analyzed in conjunction with a variety of other data types. However, contrary to terrestrial geologic mapping, planetary geologic mapping efforts have experienced no impetus to migrate into applied research products that specifically integrate co-located basic research results to enable decisions that impact national assets. By using advances in the preparation and dissemination of terrestrial geologic maps as a gauge and understanding likely off-planet exploration initiatives in the coming decades, it is apparent that planetary geologic mapping efforts are primed for a renaissance.

Standards: It is increasingly clear to data producers and users that certain widely-accepted standards are essential to creating, managing, and disseminating digital geoscience information [1-3]. Planetary geologic maps exist as either contextual standardized maps (*i.e.*, those published by USGS, in coordination with NASA, which strictly adhere to recognized standards) or topical non-standardized maps (*i.e.*, those published by peer-reviewed journals, which are not required to adhere to standards). There are many planetary geologic and topical thematic maps that are produced through NASA-funded investigation that do not – and are not intended to – strictly adhere to U.S. federal mapping standards. These maps are encouraged and should not be perceived as scientifically deficient. Likewise, standardized geologic maps should not be perceived as an approved geologic framework that does not require further refinement. These perceptions are unhelpful and should be thoroughly abolished. The community must recognize that these products work in tandem to establish context and will, in future years, need to more closely align and be integrated to ensure the full range of geologic map information is available for scientific investigation and policy decisions. Standardized and non-standardized geologic maps both satisfy critical needs with respect to our understanding and continual refinement of the geologic frameworks of solid surface bodies in the Solar System. Much of the knowledge of assessing resources beyond Earth will require extrapolation of not only direct measurement of analogous terrains on Earth but also very localized direct observation of multiple planetary bodies. This necessitates development and adherence to a common suite of cartographic representations – whether published by USGS or by peer-reviewed journals – that enable seamless cross-comparison. Standardization of geologic map information is an existing challenge. Both standardized and non-standardized geologic maps should not only adhere to a base level set of cartographic conventions but also be distributed through a common geologic map database for cross-reference. The absence of broadly-applied standards impedes development of a common database that enables co-location of planetary geologic map information and should be addressed in coming decades.

Core Competence: The development and implementation of standards related to planetary geologic mapping and applying these standards to the construction of planetary geologic maps requires maintenance of core competence. Digital data formats and geographic information system (GIS) technology allow modern planetary geoscientists to leverage a complex array of data across a range of spatial scales to complete investigations, often culminating in the production of a map product. The requisite skillset of modern planetary geologists has expanded to include not only scientific expertise in the discovery and refinement of geologic frameworks but also technical expertise in the collation, management, representation, and delivery of data. The community should make significant efforts to ensure that there is sufficient expertise available in the short- and long-term to conduct and distribute results from systematic planetary geologic mapping campaigns in response to evolving off-planet developmental needs, including training geologic mappers, discipline scientists, cartographers, and technical experts. In addition, the planetary geologic mapping community must improve its ability to communicate with not only the broad geoscience and engineering community but also those federal, state, and institutional entities and steering committees that facilitate the creation and distribution of terrestrial geologic maps.

Strategic Planning: The NASA-USGS relationship in production of standardized planetary geologic maps as well as resources for the creation and distribution of geologic map information is a critical investment that should be fully leveraged for not only current basic research but also future applied research. However, the planetary geologic mapping community, in coordination with the broader scientific community, has not formulated a modern road map that outlines the strategic needs of the community or devises a plan to address those needs in the short and long term. To fully make use of the NASA-USGS relationship, the planetary mapping community needs to develop and implement a plan for selecting the most applicable, strategic geologic maps for production and promote the distribution of both standard and non-standard maps as geospatial layers via a queriable planetary geologic map database. Likewise, standardized geologic maps require considerable investment and the planetary community must strategically expend resources on the production of standardized geologic maps that are likely to fundamentally alter our basic understanding of geologic frameworks. The geologic mapping community should immediately begin preparing a strategic road-map using input from the broader geoscience and programmatic community in order to realize and plan for the role of geologic maps in achieving NASA's current and future scientific and exploration goals. We must ensure that we are capturing geologic mapping results from various geoscience disciplines and not only making these available to the public but also specifically targeting areas of high value to complete standardized production of USGS series geologic maps.

Paths Forward: Geologic maps constitute a fundamental and objective scientific foundation upon which the results of basic and applied geoscience investigations are communicated and placed into a broader context on behalf of decision makers and the public. In order to maximize the scientific interrogation of existing and future data sets and ensure the success and safety of future exploratory missions beyond low-Earth orbit, the community needs to understand the characteristics and distributions of geologic materials across all bodies within the Solar System in general and targeted regions across particular bodies that will likely be sites of *in situ* exploration within the coming decades. The long-term vision of the planetary geologic mapping community should be guided by the following efforts: (1) determine the geologic framework of all Solar System bodies through the systematic development of geologic maps at scales appropriate to the geologic setting, available data sets, and perceived future land-use assessments, (2) develop cost-effective mapping techniques, conventions, and standards that assist with assembling, producing, translating, and disseminating geologic map information to increase their application to the scientific community and public, (3) develop public awareness of the role and application of geologic map-information to the resolution of national issues relevant to planetary science and eventual off-planet resource assessments, (4) use topical science to drive mapping in areas determined or likely to be determined vital to the welfare of endeavors related to planetary science and exploration, and (5) cultivate and sustain core competence in geologic mapping. Moving forward, planetary geologic mapping efforts need to be far more aware of the applied research applications of these maps, creating suites of correlative product through strategic mapping campaigns using standardized (broadly recognizable) formats that are simultaneously beneficial at establishing common context for multiple disciplines as well as for informing programmatic decisions. To realize this long-term vision, planetary geologic mapping efforts should take cues from the USGS National Cooperative Geologic Mapping Program (NCGMP), the National Geologic Map Database (ngmdb.usgs.gov), and guidance issued from the Office of Science Technology and Policy [4], which should serve as models for the planning, management, and dissemination of both topical and standardized planetary geologic maps. As the NCGMP is congressionally mandated by the National Geologic Mapping Act of 1992, it would behoove the planetary science community to start considering issues related to collating and disseminating planetary geologic map information, which will require encoding spatial content for use in multi-map databases. This will ensure that relevant planetary science investigations build upon and make available geologic frameworks for all non-terrestrial solid bodies in the Solar System and provide stakeholders with a landscape-level understanding of these bodies as well as their potential for resources, hazards, and siting assessments.

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Observing Earth as an Exoplanet. S. M. Som[1,2] and T. D. Robinson[3], [1]Blue Marble Space Institute of Science (1001 4th ave, Suite 3201, Seattle WA 98145, USA, sanjoy@bmsis.org), [2]Exobiology Branch, NASA Ames Research Center (MS 239-4, Moffett Field, CA 94035, USA), [3]Department of Astronomy and Astrophysics, University of California, Santa Cruz (1156 High St., Santa Cruz, CA 95064, USA)

Introduction: Earth is the only inhabited planet that we know of. How it is perceived from an external observer is interesting because such knowledge will guide how astronomers will detect life on other worlds. We propose an Earth observer mission on a hyperbolic trajectory, with cameras, spectrometers (UV, visible, NIR, & mid-IR), and multiwavelengths photometers continuously pointing at Earth (except during opposition), to validate models regarding how the Earth's biological spectral signatures change with observer distance and with seasons. The effect of an orbiting moon could be examined as well. High throughput antenna's transmitting the Earth's image would provide impactful Education and Public Outreach material, building on the success of the DISCOVR mission's broadcast of Earth from space.

Characterizing terrestrial exoplanets present many significant observational challenges. Existing models, such as the Virtual Planetary Laboratory 3-D spectral Earth model have been validated using a combination of data from the EPOXI mission and the Atmospheric Infrared Sounder (part of the instrument suite of the Aqua satellite), but these data exist only for a fixed distance from Earth [1]. Wide wavelength coverage, and complete temporal coverage do not currently exist. As exoplanet characterizations will improve with upcoming space telescopes, experience with interpreting known inhabited planetary spectra would prove invaluable, particularly in anticipation of the proposed LOUVOIR observatory.

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Radio Technologies for Planetary Explorations

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The concept development of a Planetary Advanced Radio Sounder (PARS) for planetary missions had been funded by NASA, however instrument development has been stalled. Over the years, the concept has been refined by adding key elements that have been developed in conjunction with the development of a radio wave transmitter and receiver system for the Air Force DSX mission. The augmented PARS instrument will be able to conduct (1) subsurface sounding of solid planetary bodies covered either with soil or ice, to survey stratigraphy underlying visible planetologic features, and to detect the presence and location of regional ice below soil or lakes and global oceans below the ice, (2) remote magnetospheric sounding, to obtain electron density distributions from the spacecraft toward the planetary body along the magnetic field line, (3) remote sounding of the ionosphere of a planetary body, to measure altitude profiles of electron density below the spacecraft at points along its orbit, (4) local sounding, to determine the magnetic field strength and the electron density at the spacecraft, and (5) passive electric field observations, to measure natural electromagnetic and electrostatic emissions. The presentation will summarize the concepts and the developed technologies.

SCIENCE AND EXPLORATION OR SHOP: A FORUM TO ARTICULATE SCIENCE ENABLED BY SPACE EXPLORATION. J. Spann[1], P. Niles[2], R. Webber[1], and D. Needham[1], [1]NASA Marshall Space Flight Center, (jim.spann@nasa.gov) [2]NASA Johnson Space Center.

Introduction: The themes of "Living and Working in Space" and "Understanding Our Place in the Universe" are crucial components of NASA's 2014 Strategic Plan to "expand the frontiers of knowledge, capability, and opportunity in space" [1]. This abstract outlines a plan to coordinate existing efforts that leverage human exploration and robotic investigations in a crucial step towards improving crew safety and enhancing science returns during upcoming space exploration operations. NASA's Marshall Space Flight Center and Johnson Space Center plan to jointly host a "Science and Exploration Workshop" to produce and publically disseminate a document that articulates Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) investigations made possible by enhanced exploration capabilities and new opportunities in space.

Purpose: This workshop will serve multiple purposes, including: (1) input to upcoming SMD Decadal Surveys, (2) guidance for HEOMD exploration mission architectures, (3) valued propositions for space opportunities and platforms, (4) augmented content for applied research programs from space, and (5) identification of new enabling opportunities for international partnerships and collaborations. This workshop is not intended to duplicate current efforts and scope of established supporting groups such as the Mars Exploration Program Analysis Group (MEPAG), Lunar Exploration Analysis Group (LEAG), Small Bodies Analysis Group (SBAG), or International Space Exploration Coordination Group (ISECG). The intent is to augment existing discussions of science enabled by exploration to disciplines beyond the scope of these groups, to engage a broader science community, and to update content based on current programmatic realities.

Vision: The vision for this workshop is that it will be (1) jointly sponsored by SMD and HEOMD, (2) produced under the auspices of the NASA Science Advisory Committee and their respective discipline subcommittees, and (3) co-convened by NASA MSFC and JSC using (4) collaborative leadership and expertise from NASA field centers and JPL. After this workshop, we will (5) produce a report that summarizes scientific investigations enabled by space exploration, and (6) submit this product for review to the National Academy of Sciences. MSFC will lead the focus on SMD under the theme of "Understanding Our Place in the Universe", and JSC will lead the focus on HEOMD under the theme of "Living and Working in Space."

hy now As NASA prepares to establish a human presence beyond the near-Earth space environment, it is timely and prudent to assess and articulate the value, benefit, and opportunity these efforts provide to the broad science and research areas NASA pursues. Associated with this is the need for a coordinated overview and assessment of the science relevant to and/or benefiting from the evolving and emerging NASA exploration capabilities. Therefore, this workshop will provide a timely opportunity to conduct an overall assessment, with diverse community input, of the science that is enabled by new agency exploration capabilities and by international efforts.

This workshop is timely for several additional reasons. Its proposed product will provide valuable input to current NASA exploration activities that can also benefit science (e.g. Space Launch System, Orion, Solar System Exploration Research Virtual Institute, and Deep-Space Habitat), and to upcoming decadal survey efforts that help establish future science and exploration priorities, missions, and research investments. Furthermore, relevant international space exploration and investigations are being developed, and this workshop provides input to those efforts by identifying potential partnering opportunities for NASA.

The timeliness of this proposal is further enhanced by recent efforts that have laid a valuable foundation. For example, HEOMD chartered a Human Exploration Proving Ground special action team to provide science objectives consistent with the set of planned cis-lunar missions. Additionally, the ISECG recently published a summary of their Global Exploration Roadmap designed for policy makers and stakeholders [2]. That document focuses on scientific investigations enabled by exploration with an emphasis "on the beginning of the journey, which will one day lead to human exploration on the surface of Mars."

The Science & Exploration Workshop builds on the results of these and other efforts and broadens the diversity of discipline input by inviting the broader science community to participate directly, in order to focus on possible SMD and HEOMD investigations that are made possible by upcoming opportunities in space.

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PLANETARY PROTECTION AS AN ENABLER IN THE EXPLORATION OF THE SOLAR SYSTEM.

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Introduction: Planetary protection is the discipline of discipline of preventing "harmful contamination" of extraterrestrial solar system bodies by terrestrial biology, and of similarly preventing uncontrolled release of returned extraterrestrial material into the Earth's biosphere. Since the earliest days of the "Space Race", scientists have considered that, for certain targets in the solar system, particularly those held as being; "of significant interest relative to the process of chemical evolution and/or the origin of life in the solar system", or for which "scientific opinion provides a significant chance of contamination which could jeopardize a future biological experiment", precautions need to be taken to avoid confusing a terrestrial biosignature for an extra-terrestrial one. An international consensus policy of how this should be achieved has been managed by the Committee on Space Research (COSPAR) since the early 1960s.

To date, only three solar system bodies have been identified as warranting such a high level of planetary protection concern; Mars, Europa and Enceladus. Planetary protection implementation for robotic explorers at Mars has focused on limiting the introduction and release of viable organisms into the martian environment to avoid such harmful contamination at the 99.99% probability level (per mission). For the other targets, landers have not been yet launched to them, and it has been sufficient to manage the contamination problem by avoiding impact of fly-by spacecraft.

Initially, when little is known about the habitability of a target body to support viable terrestrial biology (or its own extraterrestrial biology), the protection levels need to be the most conservative. But as knowledge of the target is increased, the potential exists to modify requirements without threatening the overall goal of avoiding harmful contamination of the target before the "period of biological exploration" is completed.

This paper will address what planetary protection will look like in the middle of the 21st century. By this time, it is anticipated that the first human crews will have visited (and returned samples from) the surface of Mars, but to only limited locations on the surface. Similarly, robotic explorers may have visited the surfaces of Europa and Enceladus in search for evidence of life there. So maybe planetary protection in this era is about lateral and vertical constraints on terrestrial biological contamination as the "period of biological exploration" (when the desire is for exploration of the target body to be able to proceed unencumbered by terrestrial biological contamination) continues.

To maintain such a level of contamination avoidance during crewed exploration will however need a revision to the current planetary protection paradigm for Mars; the implementation will need to not only take account of the number of organisms introduced into the martian environment, but also what happens to them on their release. The technology increments and knowledge gaps that need to be addressed in the intervening period will be discussed. Additionally, topics relevant in this time frame to the return of extraterrestrial samples (and the spacecraft and crews that collected them) to the home planet will be addressed.

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FUTURE SCIENTIFIC EXPLORATION OF THE MOON: SAMPLE RETURN FROM THE LOWELL CRATER, ORIENTALE BASIN N. Srivastava, Planetary Sciences Division, Physical Research Laboratory, India, email: sneeraj@prl.res.in

Lunar Science & Exploration - Current State: The Moon witnessed a string of remote sensing missions during the past decade due to its immense scientific and strategic importance, revealed mostly from laboratory analysis of Apollo and Luna samples and remote sensing orbiters such as Clementine (NASA; 1994) & Lunar Prospector (NASA; 1998). The missions include SMART-1 (ESA; 2003), Kaguya /SELENE (JAXA; 2007), Chandrayaan-1 (ISRO; 2008), Chang´e 1 & 2 (CNSA; 2007 & 2010), Lunar Reconnaissance Orbiter (LRO, NASA; 2009 – still continuing), and Gravity Recovery and Interior Laboratory (GRAIL, NASA; 2011). In addition to these missions, Moon Impact Probe (MIP) onboard Chandrayaan-1 and Lunar Crater Observation and Sensing Satellite (LCROSS) associated with LRO mission crash landed on the Moon in the year 2008 & 2009 respectively. Further, Chang´e 3 the 3rd mission of the Chinese Lunar Exploration Program successfully landed Yutu rover on the near side of the Moon on 14th Dec. 2013, becoming the first spacecraft to soft-land on the Moon since Luna 24 of Soviet Union in 1976.

Voluminous high resolution remote sensing data of various sorts have been generated from these missions which are being currently analyzed for deciphering surface and subsurface geology of the Moon and composition and generation of its exosphere. Untill now, some of the major discoveries and substantial enhancements made from earlier understanding of the Moon include evidences for recent volcanism [1-4] and tectonism [5], presence solar wind produced [6] and endogenous H_2O/OH^- [7], observation of mini-magnetosphere over magnetic anamoly [8], exposures of mantle rocks [9], new rock types such as pink spinel anorthosite [10] and a new type of basalt [11], massive globally distributed blocks of pure crystalline anorthosite [12], un-expectedly numerous exposures of silicic lithologies [13], and a substantially thinner global lunar crust than thought earlier [14].

Need for sample returns from Moon in future: The Moon is the only planetary body that has been sampled through manned (Apollo missions) and robotic missions (Luna missions) and from which we have meteorites. Studies of these samples have displayed that they can be used to understand planetary - to solar system scale problems [15]. Popular hypothesis and major advancements concerning the fundamental processes related to the origin and evolution of the Moon (and also other planetary bodies) such as Giant Impact hypothesis [16], Global Magma Ocean hypothesis [17], Impact Cratering - Late Heavy Bombardment (LHB) [18], and space weathering [19] are outcome of mostly laboratory studies of the lunar samples. Since, these insights are based on samples that were collected within a limited lunar terrain, our comprehensive understand about these is somewhat biased [15]. The same is also evident from the above mentioned surprising outcomes from the exhaustive reconnaissance phase of lunar exploration during the past decade and studies of lunar meteorites derived from unknown provenances.

Several earlier questions still remain unanswered and many new questions have erupted regarding origin and evolution of the Moon, its current thermal state, nature of its crust and interior, impact cratering process, relationship between impact cratering and volcanism, and soil maturation process [1-14, 15, 20, 21]. Unanimously, the Moon is now much more diverse than thought earlier from the study of Apollo and Luna samples. In order to answer these questions and to put forward another giant leap in lunar and planetary exploration, it is imperative to obtain rover based and/or manned sample returns from well characterized sites of scientific importance, during the next few decades. The samples thus obtained will enable us to validate the findings from remote sensing, refine the existing hypothesis and build new hypothesis, which would potentially improve our understanding of the Moon as well as that of the solar system as a whole.

Potential sample return sites: Several studies have addressed to the scientific rationale for lunar sample return in future and potential sampling targets [e.g. 15, 20, 21]. Most of these studies have identified the largest South Pole Aitken Basin (SPAB) on the farside and the proto-type multi-ring Orientale basin on the western limb of the Moon as the sites of prime geological importance. Since SPAB is the oldest and the Orientale basin is the youngest multi-ring basin on the Moon, radiometric age of both these basins is imperative to constrain the basin forming epoch and refining of the existing Crater Chronology function widely used for deriving surface ages of planetary bodies [22]. Further, it is now widely accepted from observations and modeling that these colossal impact structures could have exhumed and ejected precious deep-seated rocks along the basin margins [9, 23], which can be sampled and brought back for detailed lab investigations.

Sample return from the Lowell crater, Orientale Basin: The Lowell crater (centre lat lon: 13.0°S; 103.4°W, Diameter: 69 km), located in the NW far-side quadrant of the Orientale Basin has emerged as a site of prime geological importance from detailed studies carried out using recently available remote sensing datasets from Kaguya, LRO, and Chandrayaan-1 missions [1-3, 24-27]. The Lowell crater is younger Copernican in age (though devoid of rays) and is a host to the ~ 2-10 Ma youngest volcanic flows on the Moon (Figure 1) [1-3] or uniquely developed fresh impact melts [24]. The Lowell crater exhibits conspicuous W-E asymmetries in the morphological make-up of the central peak, crater wall and floor constituents, ejecta distribution, and have potentially sampled undifferentiated mantle rocks, rocks from lower crust and anorthosites (PSA & PAN) [1, 3]. Most of these observed peculiarities in the case of the Lowell crater are related its broad geological context. The location of the Lowell crater along the mantle extending normal faults constituting the Outer Rook Ring of the Orientale basin [23, 28] favors recent volcanic activity inside it [1-3] and its location at the edge of the Orientale transient cavity provides an opportunity to sample exhumed and ejected deep seated rocks by the Orientale impact event [23]. Potentially, a manned / rover based sample return mission from the Lowell crater would be able to address the following important science goals related to the geology of the Moon:

1. Recent volcanism with implications to the thermal state of the Moon and relationship between basin evolution and volcanism.
2. Nature of the lower crust and the mantle with implications to Global Magma Ocean hypothesis.
3. Impact cratering process: Role of pre-existing structural features on complex crater formation and validation of the multi-ring basin forming models.
4. Radiometric age of the Lowell crater and the Orientale basin with implications to the basin forming epoch on the Moon and the cratering rate in the Copernican period. These inputs are important for refining the existing crater chronology function.
5. Regolith evolution: The astonishingly fresh volcanic formation offers a unique opportunity to investigate the advent of the surface maturation process on the airless Moon devoid of magnetic shielding.

The Lowell crater region is still un-sampled and is far from the sites from where samples were obtained during the Apollo and the Luna missions. The crater floor exhibits sufficiently large flat areas (slope ≤ 5°) that can be used for landing and rover operations.

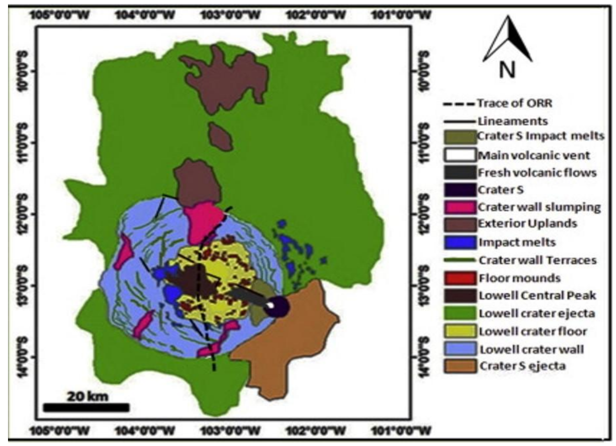

Figure 1. Geological Map of the Lowell Crater [3].

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EXPLORATION MISSIONS TO THE KUIPER BELT AND OORT CLOUD. S. A. Stern[1], W. B. McKinnon[2], J. M. Moore[3], M.W. Buie[1], A. Zangari[1] , J.R. Spencer[1], A.H. Parker[1], and R. L. McNutt, Jr.[4], [1]Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO 80302, [2]Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130, USA, [3]NASA [3]National Aeronautics and Space Administration Ames Research Center, Space Science Division, Moffett Field, CA 94035, [4]Johns Hopkins University Applied Physics Laboratory, 11101 Johns Hopkins Road, M/S 200-E254, Laurel, MD 20723.

Introduction and Background: The Kuiper Belt (KB) and Oort Cloud (OC) are a scientific wonderland containing a treasure trove of information about the origin of our solar system, the accretion of the planets, the workings of small planets, the nature of planetesimals, and more. The Kuiper Belt is known to contain numerous dwarf planets, only one of which has been explored to any degree [1]—Pluto. The Oort Cloud is likely to contain many more dwarf planets and quite plausibly many larger ones. Further exploration of these worlds, as well as small Kuiper Belt Objects (KBOs) that are relics of the dwarf planet formation era is crucial to understanding both the origin of our solar system and the workings of small planets.

The KBO population, viewed broadly, stretches from the Jupiter-family comets, through the Centaurs, across the 'classical' Kuiper Belt objects outside Neptune's orbit, to scattering and detached deep space objects well beyond [2, and refs. therein]. As of December 2016, nearly 2500 such bodies are known, but the actual population is much larger, perhaps 200,000 bodies of 100-km diameter or more and with a combined mass of at least 0.03–0.10 Earth masses. The Kuiper belt is dynamically complex, and composed of numerous resonant and non-resonant subpopulations [e.g., 3]; understanding its details has opened a window to understanding the origin and evolution of the early Solar System that never existed before.

Next Step Missions: With the 2015 flyby of Pluto and the planned 2019 flyby of KBO 2014 MU_{69}, the New Horizons mission has only undertaken the very earliest reconnaissance phase of the exploration of the Kuiper Belt.

The overall science strategy for incrementing knowledge of solar system objects was articulated by the Committee on Planetary and Lunar Exploration (COMPLEX) in the 1970's; it begins with flyby reconnaissance and progresses exploration with orbiters and then landers [4].

The Kuiper Belt and Oort Cloud will next require a series of flyby missions to explore the diversity of phenomenology and origins of the objects found in these vast, primordial reservoirs. Additionally, Pluto system orbiters or landers are also needed to understand its unexpectedly complex surface geology, atmospheric dynamics and volatile transport, its satellite system, and the possibility and characteristics of its suspected interior ocean.

Technology Needs: Both flyby and orbiter missions to the Kuiper Belt and Oort Cloud benefit from fast transport, as well as power at heliocentric distances too large for conventional solar arrays. Additionally, orbiters require breaking propulsion from high speed transits. Yet to date, robotic flyby exploration of the solar system has never combined high flyout speeds with braking near the target to enabld orbiters and landers. The employment of high launch energies coupled with efficient radioisotope propulsion [5] is a natural solution to this problem [6]. Orbiters additionally require high bandwidth communications in order to be effective. Laser communications may be a solution but will also impose significant pointing stability requirements on the spacecraft during downlinks.

Finally, we note that flyby missions to these locales involving surface impactors and landers also desire technology requirements with such survivable penetrator systems and payloads for impactor landers, and very light mass/surface area loading for landers on fragile surfaces.

Presentation: We will review the nature of the Kuiper Belt and Oort Cloud, the scientific promise of further exploration in these locales, various strawman exploration mission concepts and science objectives for these destinations, the technology developments that such missions would benefit from.

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AFFORDABLE PRECURSOR MISSIONS TO SEARCH FOR LIFE AND PAVE THE WAY FOR HUMAN EXPLORATION OF MARS

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Introduction: Humans on Mars in 2033. So reads is the headline of USA today (Nov. 5 2016) accompanying a National Geographic Special that dramatizes NASA's current plans for landing humans on Mars in that timeframe. To achieve this goal, a critical precursor program must occur in the 2020's to identify landing sites that are safe and have the necessary resources to sustain a human presence. A key precursor requirement prior to human landing is to understand whether there is extant life on Mars that could pose a risk not only to Mars crews but to Earth when the crew returns. This risk must be evaluated even if no life is currently metabolically active on Mars, because extant martian life may be presently dormant but grow when exposed to humid conditions within crew habitats or once returned to Earth. Recent discoveries related to periodic habitable conditions occurring in near surface ground ice associated with changes in orbital forcing [1], Recurring Slope Linnea [2] features that flow seasonally in association with warm temperatures, and salt deposits that can host life by concentrating atmospheric water vapor [3] suggest that Mars may host environments with habitable conditions in modern times. The possibility that life persists on Mars in near surface environments can't be ignored. Furthermore, once humans land on Mars, it will be contaminated with Earth life and a search for indigenous Martian life will be confounded. So it is important to characterize whether life exists on modern Mars prior to human landing. This paper describes mission concepts studied by the author and colleagues that provide crucial precursor information about the possibility of extant life on Mars, as well as characterizing near surface ground ice as a resource for human exploration.

Icebreaker Life Mission: The Icebreaker Life mission [4] (Figure 1) proposed to Discovery in 2015, places a small stationary lander near the high N. latitude site characterized by the Phoenix mission. Ground ice there hosts habitable conditions for life periodically, most recently during high obliquity, 0.5 to 10 M yr ago. Habitable conditions include 1) pressure above the triple point of liquid water; 2) ice near the surface as a source of liquid water; 3) high summer insolation at orbital tilts >35^o which recur periodically and are equivalent to levels of summer sunlight in Earth's polar regions at the present time. Terrestrial permafrost communities are examples of possible life in the ground ice. Studies in permafrost have shown that microorganisms can function in ice-soil mixtures at temperatures as low as -20°C, living in thin films of interfacial water. In addition, it is well established that ground ice preserves living cells, biological material, and organic compounds for long periods of time, and living microorganisms have been preserved under frozen conditions for thousands and sometimes millions of years. During high obliquity, which has occurred in the last 10 MY, the ground ice experiences habitable conditions down to depths of 75 cm. If inhabited and metabolically active at high obliquity, biomolecular evidence of life could have accumulated in the ice-rich regolith on Mars. The Icebreaker payload includes a 1-m drill that brings cuttings samples to the surface where they are analyzed by instruments to search for definitive biosignatures (proof) of life, as well as broad spectrum organic analysis and habitability assessment. By drilling to 1m, the history of habitable conditions in the modern epoch can be studied, and the search for life advanced.

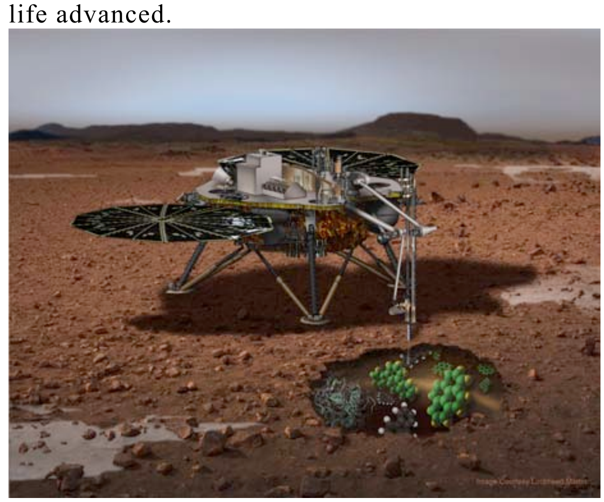

Figure 1. Icebreaker lander to search for life on Mars.

IceDragon: A human precursor mission to characterize midlatitude ground ice. Geomorphological evidence suggests ground ice is widespread on Mars north of 40^o latitude. Recent impacts have exposed near surface ground ice at less than 1 m depth [5] which can provide an important and easily accessible resource for human exploration. The IceDragon mission [6] has a 2m drill and payload instruments within a Red Dragon Mars lander (Fig. 2), in development by SpaceX Corp. The large interior volume of Red Dragon allows delivery of a variety of engineering and analytical payload to the surface of Mars, and payload masses in excess of a metric ton can be delivered. Mission objectives for a midlatitude ice lander include: 1) *Search for Life and assess subsurface habitability using methods proposed for Icebreaker Life, 2) Establish the origin, vertical distribution and composition of ground ice, and 3) Demonstrate ISRU for propellant production on Mars.* Furthermore, Red Dragon enters and lands on Mars using an EDL system that is relevant to spacecraft that may land humans on Mars in future missions, but have not previously been demonstrated in flight.

Figure 2. Red Dragon mars lander can host a variety of payloads including a deep drill to search for life and a return rocket to bring samples from Mars to Earth.

Mars Sample Return from potential human landing site: Previous studies have concluded that sample return from the site of future human landings would provide the best information on site characteristics and materials, including resources, and the most unambiguous way to evaluate risks to human crews. A study of Mars Sample Return using the SpaceX Dragon to land the sample return hardware [7] showed that a single landed Dragon capsule could collect samples from a potential human landing site and launch them all the way back to Earth Orbit. A rendezvous with the sample capsule in Earth orbit brings the samples to Earth while completely breaking the chain of contact with Mars, thereby addressing Planetary Protection requirements for return samples. By using the large payload capacity of Red Dragon to host both the sample collection and return rocket capabilities, Mars sample return can be achieved affordably, providing essential precursor information to prepare for human landing on Mars.

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A GROUND TRUTH-BASED APPROACH TO FUTURE SOLAR SYSTEM ORIGINS RESEARCH. Rhonda. M. Stroud[1], [1]Code 6360, U.S. Naval Research Laboratory, 4555 Overlook Ave. SW, Washington, DC, 20375. (rhonda.stroud@nrl.navy.mil)

Introduction: One of the most fundamental questions human researchers can strive to answer is, “How did we get here?” Part of the answer lies in understanding the conditions that lead to the formation of the Solar System. While remote sensing and lander-based measurements for exploration of the primitive Solar System bodies are essential, full knowledge of the Early Solar System (ESS) also requires detailed laboratory-based analyses. For example, our knowledge of the first solid particles in the Solar System comes primarily from laboratory measurements of refractory inclusions in meteorites [1]. Our knowledge of the gaseous components of the ESS come primarily from laboratory-based noble gas studies of dust grains, and carbonaceous extracts from meteorites [2]. We have even identified organic matter from the ESS [3] and individual dust grains that pre-date the SS formation [4]. These discoveries could not have been made through any means other than direct laboratory measurements. Furthermore, such laboratory analyses of planetary materials provide the motivating context for, and ground truth for interpretation of, spacecraft-based missions, be these science, hazard mitigation, or commercial interest -driven.

Three essential resources are needed to carry out the laboratory analyses: samples of planetary materials from diverse primitive Solar System bodies, state-of-the-art laboratory instrumentation, and trained researchers. Over the next three decades, we can expect to dramatically expand the inventory of planetary materials. Two missions already underway, NASA’s OSIRIS-Rex [5] and JAXA’s Hayabusa2 [6], will return samples from the primitive carbonaceous asteroids Bennu in 2023, and Ryugu in 2020, respectively. Sample return from Mars is plausible in the mid ‘20’s to early ‘30’s. Comet surface and lunar South Pole Aiken sample return are among targets of the current New Frontiers competition. Cryogenic sample return missions, preserving water and organic ices from a comet, or moons of outer planets, are in the conceptual stage and could be implemented by the mid’30’s to early ‘40s. Earth-based sample collection of asteroidal and cometary materials is on-going, and continues to benefit from improvements in collection methods, e.g., Australian Fireball Network, for rapid meteorite fall recovery, and South Pole-based interplanetary dust particle (IDP) collection, both of which have the potential provide among the most pristine asteroid samples and cometary dust yet available. Private sector sampling of asteroids is also now in the planning stages.

Expanding the Planetary Materials Analysis Toolkit: To continue to push forward our understanding of how the Solar System, and thus humanity itself, came into being, we must also push forward the state-of-the-art in planetary materials analysis capabilities over the next three decades. The instrumentation currently available for planetary materials research is truly impressive. Isotope composition signatures that identify the ESS, interstellar, or even presolar provenance of individual particles can be imaged at scales down to 10’s of nm’s. The isotope compositions of the Solar Wind can be measured from a few implanted ions in the Genesis sample collection [7]. Imaging and spectroscopy of individual atoms with electron microscopes provide clues to the formation and processing of organics in the ESS. Focused ion beam instruments can enable site-selective coordinated analysis at the sub-micrometer scale, so that the when, where, and how are precisely determined for an individual EES sample. Measurements of the infra-red spectra of individual sub-micrometer grains can help link the extraterrestrial materials with established origins and processing histories to remote sensing of primitive solar system bodies. Molecule-specific isotope measurements allow the identification of labile organics, including amino acids, in meteorite and comet samples.

Decades of laboratory work on meteorites, IDPs and samples returned by Apollo, Genesis, and Stardust, have well prepared us to handle the soon-to-be returned Bennu and Ryugu asteroid samples. And yet, new advances in analytical instrumentation occur yearly, if not daily, driven by a wide range of basic and applied science and technology needs, from quantum computing, to genomic medicine to renewable energy. The planetary materials community will be only of one many research communities pushing the frontiers of analytical methods development over the next three decades and it behooves us to identify emerging instrumentation championed in our own, and related fields, that can address key questions in SS origins research.

Several key instrumentation improvements are already under development or commercially available, but not yet widely adopted. These include improved ion sources for SIMS machines; resonant ion mass spectrometers with sub-10 nm spatial resolution; a time-of-flight sputtered neutral mass spectrometer with non-resonant laser post-ionization system for in-situ mapping of all elements in solid materials down to 10's of nm; atomic-force microscope-based infra-red microscopes for sub- 100 nm-scale IR characterization of polished thick samples; monochromation for electron microscopes that enable characterization of IR properties at spatial scales to ~ 1 nm for thin samples; higher sensitivity detectors for imaging and spectroscopy in electron microscopes that enable high-resolution characterization of highly beam sensitivity samples, e.g., organic molecules; and a single-stage accelerator mass spectrometer with multiple ion sources, for high sensitivity, molecular-interference-free elemental and isotopic analysis. Each of these new tools will enable planetary scientists to reveal previously hidden signatures of Early Solar System processes in extraterrestrial samples, such as interfacial reactions between sulfide nanoparticles are fluids on asteroids affected the inventory of prebiotic chemistry.

Two key additional expected needs for future sample analysis are: (1) sample storage, handling, preparation and coordinated multi-instrument analyses, all under vacuum or inert gas to prevent air, water and/or ambient organic exposure; (2) cryogenic sample handling and analysis capability for liquid and other volatile sample analyses. Although storage of valuable planetary materials are under inert gas is standard practice, the sample handling, processing, and transfer between instruments typically requires air exposure. This can lead to alteration of space weathered surfaces on returned asteroid samples, and molecular cross-contamination of Martian samples with terrestrial matter. The longer term goal of sampling volatiles from the outer solar system, which have key roles in ESS processes from providing “glue” to aid in the planetesimal formation to serving as key ingredients for the emergence of life, will require to ability preserve, process, and analyze volatile samples under cryogenic conditions. Some such capabilities exist, e.g., cryo-SIMS has been performed on individual liquid-bearing halite crystals, cryo-TEM is widely used in the biological microscopy community, and cryo-FIB lift-out has been demonstrated. However, in most cases, the samples are handled first at ambient temperature, and cooled to cryogenic temperatures either during sample preparation, or only after loading in the vacuum instrumentation. Further research into cryogenic sample storage, sample handling, instrumentation, and transfer between instruments for coordinated analysis will be required in advance of cryogenic sample return, but also in the near term, to advance our understanding of the preserved ESS volatiles in our existing suite of meteorite samples.

Developing the Planetary Materials Analysis Community: Visionary planetary science necessarily includes experts in planetary materials. The real driving force behind the new discoveries in SS Origins will be not the samples or instrumentation, but the next generation of expert researchers. Planetary science is an inherently interdisciplinary endeavor, which benefits from a great deal of international cooperation. Developing a ground-truth based approach to visionary planetary science means ensuring that the next generation of researchers draws broadly across disciplinary and demographic boundaries. More specifically, it means ensuring that researchers have training opportunities in state-of-the-art analytical laboratory methods on real planetary materials samples, and that the skills and knowledge gained from these studies continue to provide a basis for the sound conceptualization, implementation, and interpretation of the full suite of planetary science goals.

Summary: An essential goal of planetary science research is to connect the dots spanning the roughly billion years from the proto-solar molecular cloud to the emergence of terrestrial life. Equally compelling goals are the need to protect Earth from potential devastating asteroid or cometary impacts; and the desire to explore beyond the boundaries of Earth. In addressing these goals over the next three decades, we should not forget that the microscope is as an important tool as the telescope. Laboratory analysis of recovered, e.g., meteorites and interplanetary dust, and returned, e.g., Stardust, and Hayabusa samples have, and will continue, to provide some of the strongest scientific evidence for the pathways of the evolution of gaseous, rocky, and organic materials in the SS. In the next decade, SS origins researchers, using a full complement of advanced analytical laboratory instruments, will connect the dots from remote sensing C-class of asteroids to amino acid, water, and even rare earth and refractory metal contents. In two decades, we could have analyses of actual samples of Martian water, and perhaps even direct evidence of prior life on Mars. In three, we could be distinguishing the interstellar organic components from the SS components in cometary ices to identify whether there is evidence for extra-solar life.

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Venus E ploration Power Technologies Rao Surampudi, Kumar Bugga, Jonathan Grandidier, James Cutts, Patricia Beauchamp Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, Subbaro.Surampudi@jpl.nasa.gov

Venus should be an Earth-like planet due to its similar size and adjacent position in the solar system, but its dense atmosphere, high surface temperature, lack of water, and unique geology indicate it developed very differently. Understanding why will require in situ exploration of the planet including scientific investigation of the near surface environment where temperature extend up to 465C. Limited Venus exploration missions were carried out in the past and they are mostly orbital and short duration surface missions. Venus orbital missions were implemented with State-of-the-Practice (SOP) power systems (employing SOP solar cells & arrays) as the Venus orbital environmental conditions are benign and are similar to that of the Earth orbital missions. Short duration Venus surface missions of few hours were implemented using SOP primary batteries enclosed in a environmental chamber equipped with complex thermal management subsystem. The Russian Venera landers lasted less than 2 hours on the surface of Venus and the American Pioneer probe survived about an hour. Future emphasis for Venus *in situ* exploration is likely to focus on mid to low altitude aerial missions and long duration surface missions [1] [2]. To understand the evolutionary paths of Venus in relation to Earth, the recent decadal survey, 'Vision and Voyages for Planetary Science in the Decade (2013-2022) and the more recent VEXAG study (2014)2", emphasized the need to gather basic information on the crust, mantle, core, atmosphere/exosphere and bulk composition of Venus. More specifically, the VEXAG study recommended future explorations through in-situ investigations using low altitude aerial platforms, landers and probes.

Power Re uirements: The low/altitude aerial missions and long duration surface exploration missions require new power sources capable of surviving and operating in the extreme Venus environments. The power systems that are under consideration can be classified into four categories: 1) Radioisotope Power Systems (RPS), 2) Solar Power Systems, 3) Electrochemical Power Systems, and 4) Chemical Power Systems. Wind power systems have also been considered. This paper gives an overview of the status of these SOP power technologies and examines the technical challenges associated in adopting these technologies to the future Venus aerial and surface missions.

Radioisotope Power Systems: Radioisotope power systems have been used in missions when it is not possible to use solar power systems. They have been used in several outer planetary missions and some surface missions. All the missions flown to-date have used Radioisotope Thermoelectric Generators to power the spacecraft. Four types of RTG's have used in these missions and they are: a) SNAP-19, b) MHWRTG, c) GPHS RTG, and d) MMRTG. The first three types of RTG's are not currently available for use as their production has been discontinued. MMRTG is the only RTG that is currently available for use in future missions. SOP MMRTG needs further development before it can be considered for future Venus surface missions. NASA is developing two types of advanced Radioisotope power systems: a) eMMRTG and b) ASRG. They are currently at TRL 3-4 and may be available for missions beyond 2025. They may also need further enhancements for use in Venus missions.

Solar Power Systems: High altitude aerial missions can be implemented with SOP solar power systems as the environmental conditions are not that severe. However, variable altitude (middle to low) aerial and surface missions that are currently under consideration for the next decade are very challenging because they require solar power systems that can: a) operate at high temperatures aerial environments (200-350°C) for long duration, b) survive high temperatures surface environments (450-500°C) for short duration, c) generate power at various low solar intensities (300-50 W/m2/) and Venus solar spectrum conditions encountered at various altitudes and d) survive in Venus corrosive atmospheric environments. The SOP solar cells do not function effectively in Venus aerial and surface environments and are not suitable for long duration Venus aerial missions. ARPA_E is sponsoring programs to develop high temperature solar cells required for Concentrated Photovoltaic Power system applications. These cells could further be developed to meet future Venus aerial and surface missions.

Electrochemical Power Systems: Electrochemical Power Systems have been used in a number of space missions either as a primary source of electrical power or for storing electrical energy. The energy storage technologies that have been used in space science missions are primary batteries, rechargeable batteries, capacitors and fuel cells. SOP electrochemical power systems cannot survive and operate in extreme environments of Venus. Primary Li-SO2 batteries have been used in short duration Venus surface missions. These batteries were protected from the Venus surface environment by a thermally-insulating pressure vessel in an environmental chamber along with the payload and other spacecraft subsystems. These batteries have lasted for <2 h, i.e., before the batteries were heated to their maximum survivable temperature of ~80^{o}C. Future Venus surface missions require primary batteries or fuel cells that: a) can operate at high temperatures (> 450C), b) have high specific energy (> 300 Wh/kg to provide long duration operation capability several hundreds of hours, c) survive corrosive Venus environments and d) with stand high Venus pressures. SOP thermal batteries could be modified to meet the near term mission needs. Some fuel cell systems (solid oxide and molten carbonate) are capable operating at high temperatures. They could be adopted with further development. Future mid/low aerial missions require rechargeable batteries that operate over a wide range of high temperatures (200- 450C), b) have high specific energy (> 150 Wh/kg) to reduce power system mass, c) survive corrosive Venus environments and d) with stand high Venus pressures. The rechargeable battery systems of interest include: a) sodium-sulfur, b) sodium-metal chloride, and lithium-iron disulfide. These battery systems need to be further developed to meet the needs of future Venus missions.

Chemical Power Systems: A power systems that converts heat generated from chemical reactions (lithium combustion with sulfur-hexafluoride oxidizer or atmospheric CO2) using a Stirling engine is also currently being studied [3]. This concept looks appealing in terms of specific energy, but is currently at a low TRL with quantitative verification studies yet to be done.

ind Power Systems: While the possibility of extracting energy from the Venus environment exists, no credible concepts have yet been proposed.

Summary: A range of power choices exist for Venus in situ missions. NASA's Planetary science Division is currently completing an assessment of future needs for both solar power generation and energy storage technologies [3] that will provide more specific guidance on future needs and opportunities.

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SMALL BODIES EXPLORATION IN THE NEXT 35 YEARS. T. D. Swindle[1] and The SBAG Steering Committee (N. Chabot (APL), B. Barbee (NASA GSFC), J. Bauer (JPL), B. Bierhaus (Lockheed Martin), D. Britt (UCF), J. Castillo-Rogez (JPL), P. Chodas (JPL), L. Feaga (U. Maryland), C. Hartzell (U. Maryland), C. Mercer (NASA Glenn), A. Stickle (APL)), [1]LPL, University of Arizona, tswindle@lpl.arizona.edu.

In the last 35 years, our knowledge of small bodies has increased by orders of magnitude, from roughly 2000 numbered asteroids to nearly 500,000, from one known trans-Neptunian object (Pluto) to 2300, from ~2000 meteorites to more than 55,000, from no samples from any specific small body to samples returned from a comet's coma (Stardust) and an asteroid's regolith (Hayabusa) with two more spacecraft on their way to return asteroidal samples, from no spacecraft images of small bodies other than Martian moons to flyby, rendezvous, and/or landing missions to a dozen comets and asteroids plus Pluto. What will we achieve in the next 35 years? A good place to start is to look at the goals that the Small Bodies Assessment Group (SBAG) has defined for the exploration of small bodies, and consider where we are poised to make progress.

The SBAG Goals Document [1] identifies three overarching, high-level goals pertaining to the Solar System's small bodies, 1) utilizing the Solar System's small bodies as the scientific probes of the Solar System's formation and evolution, 2) defending planet Earth against the potential hazard that the impact of comets or asteroids represents, and 3) taking advantage of the unique properties of the small bodies in the inner Solar System to enable human exploration.

Science: Small bodies provide unique scientific opportunities to investigate the formation of the Solar System. They represent remnants of the building blocks of the planets and provide insight into the conditions of the earliest history of the Solar System and the factors that gave rise to the origin of life. Small bodies also experience a myriad of processes, providing numerous natural science laboratories to gain knowledge into the evolution of the Solar System. The high priority scientific objectives identified by SBAG are to understand the census and architecture of small bodies in the Solar System, to study small bodies to understand the origin of the Solar System and the dynamical evolution of the Solar System, to understand the evolution of small bodies' surfaces and interiors, and the relationship to other events and processes in the Solar System, and to determine the source, amount, and evolution of volatiles within small bodies in the Solar System. There are numerous ways in which the science related to small bodies is likely to advance.

We are likely to achieve much greater knowledge of the population of TNOs and the Oort Cloud (which should become accessible at least to telescopic observations), enabling us to address questions not just of the origin of the known planets, but also of whether other large, perhaps even planet-sized, objects exist in the cold outer reaches of the Solar System. The New Horizons spacecraft has demonstrated that Pluto is a much more active body than had been expected, and it will be flying by another TNO in its extended mission. Centaurs are an as of yet unexplored category of small bodies that exhibit evidence of cometary activity, ring systems, and binaries, and may serve as a mid-stage sample of the effects of solar exposure on TNOs. Whether we send spacecraft to explore the outer reaches of the Solar System may depend on development of effective communications and propulsion systems.

Already, we have two spacecraft, Hayabusa-2 and OSIRIS-REx, en route to return samples from (primitive?) carbonaceous asteroids. The study of that material, plus refractory and sub-surface cryogenic material returned from a cometary nucleus, will give us a much greater knowledge of what kinds of materials were available to provide volatiles to the terrestrial planets, and how closely the origin of water and/or organic material on Earth may be tied to different types of small bodies that we can study today. In addition, Ceres may be the most accessible ocean world.

Increased scrutiny of, and, in particular, sample return from, from Mars' moons can address the longstanding puzzle of their origin. That question has fundamental implications for the dynamical environment in the vicinity of Mars, which, in turn, is wrapped up in the origin and evolution of the entire inner Solar System.

We are only beginning to study Jupiter's Trojan asteroids. They are highlighted as a New Frontiers mission target in the most recent Decadal Survey, with a history waiting to be deciphered.

Meteorite investigations have led to dramatic increases in our understanding of the nature and timing of accretion and differentiation of small bodies within the early Solar System. Future analytical advances and the continued discovery of rare meteorite types will lead to new insights during the next 35 years. The study of more asteroids (both in situ and via sample return) will lead to more specific constraints for Earth-based laboratory studies of meteorites.

Planetary defense: Some small bodies have orbits that approach and intersect Earth's orbit, and thus have the potential to impact Earth, possibly with damaging consequences to humankind. Planetary defense refers to the combined activities undertaken to understand the hazards posed by near-Earth objects impacting our planet and develop strategies for avoiding impacts or managing their aftermath. In 2005, Congress directed NASA to detect 90% of all near-Earth objects (NEOs) larger than 140 m in diameter by 2020 [2]. Current surveys are inadequate for achieving this goal, even by 2050. But, a combination of space-based and next-generation ground-based systems could complete the survey well before 2030, as well as increase the number of detected NEOs of all sizes by more than an order of magnitude. Several multi-meter objects are likely to be found days before impacting Earth. Although probably too small to be hazardous, observing these objects as they impact, and possibly collecting resulting meteorites, will provide unique opportunities to study asteroid strengths and link asteroid classes with meteorite physical properties.

In order to develop robust mitigation approaches to address potential impactor threats, it will be important to validate these techniques through demonstration missions. It is likely that we will launch a Kinetic Impactor demonstration mission in order to assess the importance of ejecta in the momentum transfer of the mission. Deflection demonstrations of other techniques, such as gravity tractor, ion beam deflection, and laser ablation would be appropriate to ensure robust operations during an actual emergency scenario.

Enabling human exploration: The accessibility of NEOs, and in particular, near-Earth asteroids (NEAs), presents opportunities to enable human exploration of our Solar System, and the Martian moons represent natural outposts in the Mars system. NEAs may contain resources, such as water, that human explorers could utilize, thereby enabling exploration missions that would otherwise require the launch of significantly more material from Earth. In this context, NEAs are inner Solar System destinations in their own right, as well as a proving ground at which we can learn vital lessons pertinent to the extension of human exploration capabilities to more distant destinations. Moreover, the crucial resources offered by small bodies may enable novel exploration strategies in the future. The main objectives for human exploration of small bodies are based on key strategic knowledge gaps, including identification and characterization of potential human mission targets; understanding how to work on or interact with the surfaces of small bodies; understanding the small body environment and its potential risks and benefits to crew, systems, and operational assets; and evaluation and utilization of the resources provided by small bodies.

The techniques that will make it possible to identify hazardous NEOs for planetary defense purposes will also vastly increase the number of known NEOs that are potential exploration targets for humans. This is because many of the most hazardous NEOs occupy rather Earth-like orbits, which also makes them the most accessible objects outside the Earth-Moon system. NASA monitors the accessibility of the NEAs via the automated Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) system. At the time of this writing, 1,894 of the known NEAs have been identified by the NHATS system as being more round-trip accessible than Mars, and 70 are more round-trip accessible than low lunar orbit.

Missions like Hayabusa, Hayabusa-2, OSIRIS-REx, and Rosetta are spending more and more time working and taking measurements in the vicinity of asteroids and comets. As a result, we are learning, and will continue to learn, about the physics of operations in the vicinity of small bodies. Large increases in knowledge are likely to occur when humans are actually present. Although SBAG's human exploration objectives are tied to closing the existing Strategic Knowledge Gaps, there is much intrinsic science about small body environments that astronauts will uncover.

Phobos and Deimos are easier to access with a crewed spacecraft than the surface of Mars, and lack the planetary protection issues posed by Mars, so they are likely to play key roles in the human exploration of Mars, either for precursor missions or as outposts for teleoperated activities on the Martian surface.

At present, exploration missions rely on bringing all needed supplies, from fuel to shielding to building materials (for space stations) to food (for crewed missions). There are NEOs that can probably satisfy many of these needs, and there are now private companies with the stated goal of mining asteroids. If any of these companies are successful, it will not only revolutionize travel beyond Earth orbit (for both crewed and robotic spacecraft), but there are also a host of scientifically interesting properties about the structure and interiors of asteroids that will be learned through these activities. Furthermore, the amount of material that would be moved around the inner Solar System by a commercial mining operation will mean that far greater quantities of material will be available for scientific study than would ever be acquired based solely on a science justification.

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ON NEUROMORPHIC ARCHITECTURES FOR EFFICIENT, ROBUST, AND ADAPTABLE AUTONOMY IN LIFE DETECTION AND OTHER DEEP SPACE MISSIONS. J. Tani[1], G. Ruvkun[2], M. T. Zuber[1] and C. E. Carr[1-2]. [1]MIT Department of Earth, Atmospheric and Planetary Sciences, Cambridge, MA, [2]Massachusetts General Hospital, Department of Molecular Biology, Boston, MA.

Introduction: Recent discoveries on Mars, at icy moons (Europa, Enceladus), and at dwarf planets have reshaped our notions of the solar system to encompass a wider array of active processes, and in some cases, perhaps life itself. Despite intense interest in these worlds and those yet unexplored, deep space missions are currently limited in scope and cadence due to their significant cost. All deep space missions share stringent limits on mass, power, volume, and many require tolerance to extreme temperatures or radiation, long lifespans, and, perhaps most critically, autonomy to carry out mission activities despite time delays or limited or absent communications opportunities. How can costs be lowered while improving science value?

Background: On Earth, autonomy is poised to create and dramatically reshape entire industries, from drones to autonomous cars. Future planetary science missions should leverage these massive investments in autonomy (perception, planning and control) and develop implementations offering the efficiency and robustness required for deep space missions.

The 2011 Planetary Science Decadal Survey [1] specifically describes these technology needs, including “increased spacecraft autonomy,” “new and improved sensors,” and highlights prospects for life beyond Earth. Here we focus on this search, recognizing that neuromorphic architectures are a cross-cutting technology with applicability to all deep space missions.

Neuromorphic Architectures (NAs): NAs use a distributed representation, in which independent units cooperate to perform a computation, and communications are encoded via *events* (inspired by spikes) transmitted among units [2]. In neuromorphic architectures computation and memory are co-localized and distributed through massive parallelism, while these functions are separated through dedicated hardware in typical (von Neumann) computational architectures. Moreover, neuromorphic systems are asynchronous and event-driven, as opposed to the periodically sampled/updated traditional architectures, which allow for treatment of salient data exclusively, easing the extraction of useful information from the measured data.

While neuromorphic computing has been pursued since the ‘70s, concrete implementations of neuromorphic sensors (e.g., Dynamic Vision Sensor, DVS) or processors (e.g., IBM’s *TrueNorth*) are recent [3]. For example, *TrueNorth* has 1 million digital neurons, each with 256 connections to other neurons, and achieves 4 billion calculations/s. IBM reports an energy cost of 30 pJ per operation, up to 10^5-fold more efficient than traditional computers [4, 5], and DVSs achieves an equivalent of thousands of frames/s at 23 mW.

Neuromorphic algorithms, such as the neural networks that power so-called deep learning, can be implemented using traditional computers but perform best when paired with distributed computation and memory hardware, hence the current trends, by Google, Intel, NVIDIA, IBM, and others, towards distributed systems.

Challenges for Life Detection: Major mission challenges include access to habitable zones, sample acquisition, *in situ* data processing, and, when the data are too extensive to transmit back to Earth, selection of data or analyses to return to Earth.

On *Mars*, access to so-called *special regions* is inhibited by both inaccessibility and the expense of rating vehicles for Planetary Protection (PP) IVc operations; we envision breaking the current paradigm through a division of labor between multiple vehicles with different PP classifications, e.g. IVc-rated drone or climbing/burrowing bots surveying and sampling, then caching samples to be retrieved and processed by a rover or astronaut. Interesting sampling sites include cave systems and other subsurface environments, or recurring slope lineae [6], locations sheltered from space radiation and where liquid water brines may exist, respectively, that are typically unreachable with a rover.

A plume sampling mission to *Enceladus* [7] would require fine orbit and attitude control to compensate for the instability of the polar orbit, if low relative velocities are required in order to preserve biomarkers of interest. Of note, plumes may host high molecular weight organic materials [8].

The extreme radiation environment of *Europa*, in addition to limited bandwidth to Earth, pose non trivial challenges. Payload operations will have to push the balance between performance, power efficiency, and robustness, e.g., to radiation induced memory errors [9]. Future missions may extend into Europa’s icy shell or explore its ocean, requiring extreme autonomy to permit operation without Earth contact for extended periods.

Life Detection: Adaptation to the unexpected is critical for navigating these worlds as well as for life detection. For example, biomarkers such as informational polymers (IPs) could include deoxyribonucleic acid (DNA) or involve non-standard bases or polymers, requiring *adaptability* of the processing algorithms.

Approaches for *in situ* detection and sequencing of IPs include our Search for Extra-Terrestrial Genomes (SETG) instrument, which currently utilizes strand sequencing using protein nanopores [10] coupled to recurrent neural network (RNN) basecalling [11] deployed on a traditional (von Neumann) architecture. Strand sequencing detects translocations of bases through an array of nanopores. The assignment of sequence data (e.g., A,C,G,T bases for DNA) is achieved by monitoring the ionic current blockage produced by bases within a critical pore region. The simplicity and versatility of pore sequencing is not limited to DNA and can be used to detect RNA, modified or non-standard bases, and, potentially, other IPs.

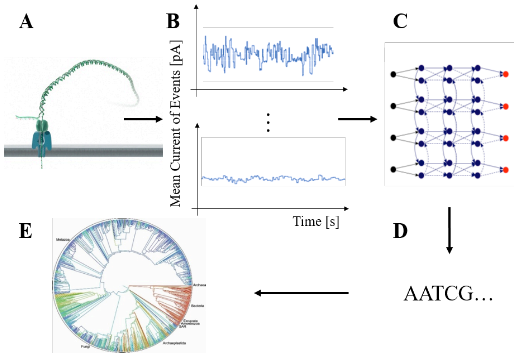

Figure 1: Typical pipeline for single molecule nanopore-based sequencing. Translocation of IPs through a nanopore array (A) generates a large quantity of ionic current measurements (B), that are processed through a RNN to detect the polymer type and (C) to generate an estimated base sequence (D), which, for DNA or RNA, is mapped to the known tree of life (E) to detect ancestral relationships or identify contaminants.

A future NA approach would integrate *event-based sensing*, to reduce the rate of uninformative ionic current measurements, and a distributed hardware *implementation* of the RNN, to improve data processing efficiency, fault tolerance, robustness, and adaptability.

Event-based sensing allows for efficient data processing. DVSs convert the luminance of a signal to a series of events. No events are generated if the signal does not change, therefore no computation is wasted on redundant data, achieving efficient data processing. Similarly, ionic-current signatures of specific bases are detected through impulsive variations of the measured current. *Event-based neuromorphic sequencing and analysis:* detected events would then be processed through a neuromorphic implementation of an ionic-current to taxonomic classification RNN, allowing the sequencing technology to adapt to interpret *in situ* findings. In addition, just as a brain can heal, a neuromorphic architecture can likely be made resilient to radiation noise. In a conventional processor, a bit flip can provoke catastrophic failure while in distributed neural coding, an error or permanent fault of one unit does not propagate catastrophically. Instead, it is expected that a bounded interference will produce bounded degeneration of the output, i.e., a *graceful degradation* of performances. Moreover, *redundancy* in the neural architecture (number of neurons and layers) adds *regenerative* capabilities, where spare units replace damaged ones.

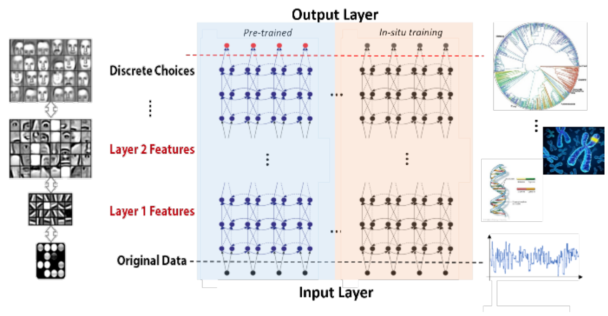

Figure 2: Neuromorphic algorithms in computer vision and speech recognition learn hierarchies of relevant features within noisy data for pattern recognition applications. A similar process applies to *in situ* detection of IPs. Augmenting pre-trained networks with *in situ* training supports adaptation.

Conclusions: NAs, paired with new radiation resistant forms of memory, offer solutions for extreme autonomy. To leverage the inherent advantages of neuromorphic computation over traditional computing and enable a host of deep space missions, in particular for life detection, it is desirable to have a (a) neuromorphic hardware implementation qualified for space flight, in addition to (b) specifically designed neuromorphic algorithms. Event based sensors for strand sequencing and end-to-end learning networks represent examples of promising avenues of research. NASA's interest in considering secondary payloads on essentially all future planetary science missions offers opportunities to demonstrate neuromorphic solutions for deep space, with the vision of developing brain-like systems that can go where no human brain has gone before.

Acknowledgements: NASA award NNX15AF85G.

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GROUND-BASED RADAR OBSERVATIONS: ENABLING THE FUTURE OF SMALL-BODY SCIENCE, PLANETARY DEFENSE, AND SOLAR SYSTEM EXPLORATION. P. A. Taylor[1], L. A. M. Benner[2], E. G. Rivera-Valentín[1], A. Virkki[1], M. W. Busch[3], and M. C. Nolan[4], [1]Arecibo Observatory, Universities Space Research Association, Arecibo, PR 00612; [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; [3]SETI Institute, Mountain View, CA 94043; [4]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

State of the Art: The S-band (2.38 GHz, 12.6 cm; 1 MW output power) planetary radar system on the 305-m William E. Gordon telescope at Arecibo Observatory is the most sensitive planetary radar system in the world, a factor of ~15 more sensitive than the X-band Goldstone Solar System Radar (8.56 GHz, 3.5 cm; 450 kW) on the 70-m DSS-14 antenna. The unmatched sensitivity and 7.5-m minimum range resolution of Arecibo make it the premiere instrument for ultra-precise astrometric measurements and detailed physical characterization of near-Earth objects (NEOs), though its field of view is limited to declinations between +0 and +38 degrees. While less sensitive, the flexibility of the fully steerable Goldstone system, along with its finer frequency resolution and 3.75-m minimum range resolution, complements Arecibo by detecting NEOs at southern (above -35 degrees) and high northern declinations and over longer windows of visibility. Together, Arecibo and Goldstone typically detect more than 100 NEOs each year and play a vital role in the tracking and characterization of potentially hazardous objects (PHOs) for planetary defense purposes and NHATS (Near-Earth Object Human Space-flight Accessible Targets Study) compliant objects for future spacecraft mission planning. Overall, ~660 NEOs have been detected with radar, about 4.3% of the population. Additionally, in the last two years, the C-band (7.16 GHz, 4.2 cm; 80 kW) system on the 34-m DSS-13 antenna at Goldstone and the S-band (2.11 GHz, 13 cm; 100 kW) system on the 70-m DSS-43 antenna in Canberra, Australia have detected several asteroids, though their relative sensitivities compared to Arecibo and DSS-14 have limited their utility. The 100-m Green Bank Telescope and elements of the Very Long Baseline Array are regularly utilized as radar receivers for Arecibo and Goldstone, while the 64-m Parkes telescope receives for DSS-43.

Radar Capabilities: Range-Doppler radar measurements provide line-of-sight positional astrometry, orthogonal and complementary to optical plane-of-sky astrometry, with precision as fine as ~10 m in range and ~1 mm/s in velocity with a fractional precision of one part in 10^7, which is 100 to 1000 times finer than that of typical optical measurements. Radar astrometry routinely extends the ability to accurately predict the trajectories of asteroids for decades or centuries into the future, often preventing newly discovered objects from being lost and requiring optical re-discovery. Two-dimensional range-Doppler images that resolve the target spatially along the line of sight and in frequency (velocity) space reveal its basic shape and surface features that may be inverted to provide a three-dimensional shape model and complete spin-state description. Further, range-Doppler images unambiguously reveal binary and triple asteroid systems, which provide estimates of the mass, density, and internal structure of the bodies. The demonstrated correlation between radar polarization ratio and asteroid spectral type, in addition to the unique radar-reflection properties of metals, allows for the interpretation of asteroid composition.

Planetary Defense: Ground-based radar observations enable accurate projection of trajectories into the future, including measurement of the subtle Yarkovsky drift, while constraining the physical properties of potential impactors. This combination of knowledge will allow for well-informed planning of impact mitigation strategies. Potential impact hazards are best managed with a long lead time as the utility of different deflection techniques improves with the amount of warning time given. Although to date, impact mitigation technologies have not been tested, potential technology demonstrations require ground-based radar observations to confirm mission success, including the proposed ESA/NASA Asteroid Impact Mission/Double Asteroid Redirect Test kinetic impactor demonstration and the enhanced gravity tractor demonstration by the NASA Asteroid Robotic Redirect Mission.

Solar System Exploration: Ground-based radar observations inform mission planning by constraining the target's trajectory, size, shape, mass, spin state, composition, potential satellites, and gravitational and surface environments. Such detailed characterizations of a large number of objects cannot be obtained by other ground-based techniques. In fact, nearly all missions to asteroids have had their targets first characterized by radar. Arecibo and Goldstone have contributed to the mission planning for a number of successful (and proposed) spacecraft from NASA, ESA, JAXA, and CNSA (China) over the last 30 years.

Vision: *Observing cadence:* All current radar-enabled telescopes share observing time with other sciences and/or deep-space communication; there is no dedicated radar installation for the study of NEOs. Currently, less than 30% of radar-detectable asteroids are actually detected with Arecibo and Goldstone, partly due to scheduling constraints. The number of discoveries and, hence, the number of radar-detectable NEOs, will only increase with the advent of Large Synoptic Survey Telescope. Keeping up with the rate of discovery will require more observing time on existing radar telescopes, improved automation of observing, and streamlining of data-reduction and data-analysis pipelines. Truly keeping up with the rate of discovery will require dedicated radar facilities unconstrained by time sharing with other disciplines. With more radar observations come more physical characterizations that will benefit planetary defense, mission planning, and resource identification.

Additional radar stations: An 80-kW, C-band transmitter on the 34-m antenna in Canberra would be more sensitive than the current S-band system on DSS-43. A radar system on the 100-m Green Bank Telescope, especially at Ka band (30 GHz, 1 cm), would be more sensitive than the DSS-14 system at Goldstone and complement the existing S-, C-, and X-band systems. However, a more arid location for such high frequencies is preferred, *e.g.*, 100-m telescope(s) at Goldstone or the Atacama desert. By 2050, Arecibo and Goldstone will be ~85 years old and the Green Bank Telescope will be 50 years old; new facilities must be considered in the coming decades.

Hardware upgrades: Upgrading the Arecibo system to a higher frequency would allow for finer resolution down a few meters in range (matching DSS-14), which combined with its unmatched sensitivity would improve the ability to characterize small NEOs and the surfaces of larger NEOs. Observing more NEOs would benefit from increased sensitivity or being able to “see” further into space with radar. This can be accomplished at existing sites by increasing the transmitted power: doubling the output power results in “seeing” 20% further and increasing the number of radar-detectable NEOs by a similar amount.

New technologies: Preliminary work on the use of solid-state amplifiers as radar transmitters is promising and could replace expensive, highly specialized klystrons with “off-the-shelf” technology. The long-term future of ground-based planetary radar may lie in phased arrays at higher frequencies, *e.g.*, Ka band (30 GHz, 1.0 cm) and higher, that could provide dedicated high-power, high-resolution stations for tracking and characterizing NEOs.

Summary: As noted in the Vision and Voyages planetary science decadal survey, ground-based radar observations play a unique and vital role in planetary science and will continue to be instrumental in understanding the nature of the Solar System, supporting planetary defense capabilities, and informing spacecraft mission planning. Therefore, a healthy ground-based radar infrastructure is required to enable the goals and objectives of planetary science, as prioritized by the decadal survey, for the foreseeable future.

Acknowledgements: The Arecibo Observatory is operated by SRI International under a cooperative agreement with the National Science Foundation (AST-1100968) and in alliance with Ana G. Méndez-Universidad Metropolitana and the Universities Space Research Association. The Arecibo Planetary Radar Program is supported by NASA under grants NNX12AF24G and NNX13AQ46G issued through the Near Earth Object Observations program to USRA. Part of this work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

ON-ORBIT PLANETARY SCIENCE LABORATORIES FOR SIMULATING SURFACE CONDITIONS OF PLANETS AND SMALL BODIES. J. Thangavelautham[1], E. Asphaug[1], S.R. Schwartz[1] [1]Space and Terresterial Robotic Exploration (SpaceTREx) Laboratory, School of Earth and Space Exploration, Arizona State University, 781 E Terrace Rd, Tempe, Arizona, 85283, {jekan, easphaug, srs}@asu.edu

Introduction: In the next 35 years, we aspire to be on our way to sending human and robotic explorers to every corner of our solar system to perform orbital, surface and even subsurface exploration. These explorers will pave the way towards cataloging the diverse surface environments, physical processes and structure of the planets and small bodies answering fundamental questions about the origins of the solar system, conditions to sustain life and prospects for resource utilization and off-world human settlement. Achieving this major exploration milestone remains technologically daunting but not *impossible*. Conditions on some of these planets and small bodies are not well understood. Robert Scott's ill-fated expeditions to the South Pole in contrast to Amundsen's shows that pre-conceived notions, assumptions and planning without room for in-situ adaptation can have disastrous consequences.

Challenges: One of the major challenges in recreating or even understanding these off-world conditions is the low surface gravity. We lack fundamental knowledge of surface material properties, especially the dangers that may prematurely end a mission. Our lack of understanding poses a major risk due to inherent uncertainties in the design and development of robotic and human vehicles to explore the far reaches of the solar-system. This leads to significant cost increases, schedule delays and lack of technical or political confidence in these missions. This is a major concern for small-body exploration, where the low gravity makes surface landing and mobility extremely challenging, as evidenced by JAXA's first Hayabusa mission and ESA's Philae lander aboard Rosetta [1–2].

Physical processes in these alien environments may be simulated using ever-realistic computer models, but these models are dependent on our current domain knowledge. Ultimately, these computer simulations, as well as analytical scaling relations (e.g., [3]), need to be validated against the real thing. The logistics and resources required to reach these far corners of the solar system make the process of simulation validation and trial-and-error learning a very slow and cumbersome process as a mission, from concept to launch, may take 5–10 years or longer.

On-Orbit Centrifuge Laboratory: Our work has identified the use of on-orbit centrifuge science laboratories (**Fig. 1**) as a key enabler towards low-cost, fast-track understanding and simulation of off-world environments for the dual purpose of planetary science and exploration engineering. We have developed AOSAT I (Asteroid Origins Satellite I) [4–7], a 3U CubeSat (**Fig. 2**) that is intended as a low-cost proof-of-concept on-orbit demonstrator to show the feasibility of a centrifuge science laboratory for planetary science and to simulate asteroid surface conditions. The concept of an on-orbit centrifuge is not new [8–10]. Our work identifies new use for these as laboratories and proving grounds to simulate off-world environments. We envision follow-on missions that include enlarged centrifuges with much larger internal volume to test instruments and major parts of a spacecraft under alien surface conditions.

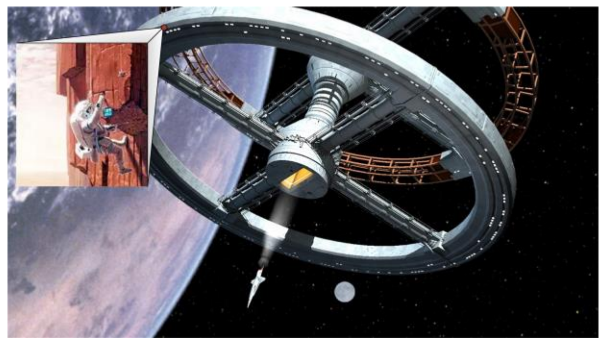

Fig. 1. An on-orbit centrifuge can be used as a laboratory and proving ground to simulate the range in gravitational conditions we expect to find on different worlds. Planetary science instruments, scaled or full size spacecraft, and even astronauts can be trained or tested in these laboratories ahead of upcoming missions. Space Station V from the movie *2001: A Space Odyssey* based on artwork by Robert McCall.

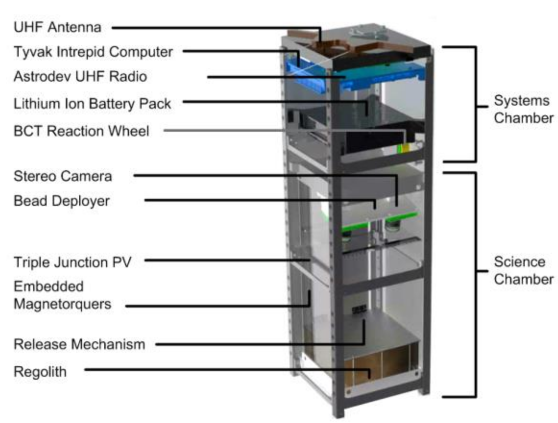

Fig. 2. Asteroid Origins Satellite 1 is proof-of-concept CubeSat demonstrator to be launched in the 2017–2018 timeframe. The mission will demonstrate an on-orbit centrifuge laboratory to simulate asteroid gravity conditions

Persistent Link to Off-World Environments: Using such laboratories it is possible to simulate alien environments (different gravity, atmospheric pressure, electrical conditions and so on) and test hypotheses for unknown or poorly understood planetary surface processes; this, in turn, may be used to validate computer models in order to develop advanced simulation proxies for science, exploration, mining, habitation, and hazardous asteroid deflection. By recreating alien surface environments we can test and validate robotic landing technology and human adaptation to these environments, and broaden our understanding and prove the feasibility of risky off-world surface exploration techniques before going to these locations [6].

These laboratories can be enlarged and transformed into miniature proving grounds for testing and demonstration of entire spacecraft and landing systems. They may be used to train and condition astronauts for efficient mobility and to perform both basic and complex tasks in the low-gravity environments of Moon and Mars to sustain long-life expeditions. This may include evaluating self-sustaining farms and an artificial ecosystem to sustain the health and the well-being of human explorers. As a specific example, directly determining the effect of Martian gravity on plant-life will be critical in long term exploration and settlement of Mars and can be done in LEO (see **Fig. 3**).

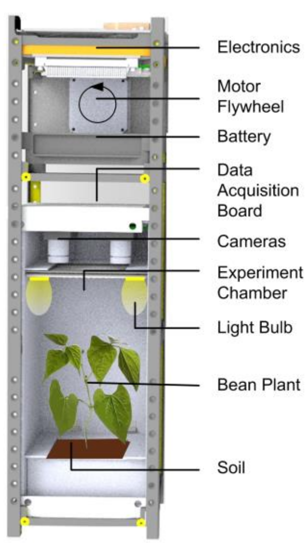

Fig. 3. A modified centrifuge for use on the ISS to demonstrate plant growth under artificial gravity.

Further, these facilities will require significantly less resources and budget to maintain, operating in LEO, compared to the voyages to deep space, and will hence serve an important tactical goal of preparing and maintainning readiness, even when missions are delayed or individual programs cancelled. Imagine being able to recreate Mars or lunar surface conditions to sand grain detail without having to go there. Imagine recreating a patch of the Moon and having astronauts train and adapt to lunar conditions from the end of the Apollo mission in 1972 till now. The technologies we propose facilitates our abilitiy to effectively accumulate and maintain knowledge to explore the diverse environments in our solar system.

By letting us have persistent access to simulated versions of these off-world environments, these laboratories will allow us to forecast and avoid surprises in-situ, and to increase confidence and support for such ambitious exploration endeavours. We also believe these facilities will be critical for resource prospecting and mining as they can be used to rapidly perform trial-and-error experiments, followed by refinement of the technology towards efficient surveying, extraction and processing of resources in-situ both for fuel, parts repair and settlement/infrastructure construction.

Conclusions: Centrifuge science laboratories, from CubeSat and larger scales, can be used to recreate the low-gravity off-world conditions of the Moon, Mars, asteroids and other small bodies in the solar system. The laboratories can provide a persistent link to better understand and perform hypothesis-testing of planetary surface processes. The power of hypothesis-testing of planetary science processes, being able to fully recreate them in controlled laboratory conditions in low-Earth orbit, and to prove or disprove hypotheses directly, will have major consequences for the field. Detailed numerical simulation environments can be developed and validated for end-to-end process testing. Furthermore, this technology can be applied to de-risk next generation spacecraft technology especially for landing, surface mobility and even for subsurface exploration with increased confidence and long term planning.

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THE FUTURE OF ASTEROID CHARACTERIZATION C. A. Thomas[1] and L. A. McFadden[2], [1]Planetary Science Institute (1700 East Fort Lowell, Suite 106, Tucson, AZ, 85719, USA, cthomas@psi.edu), [2]NASA Goddard Space Flight Center.

Introduction: The characterization of asteroids is an important methodology for understanding the past and current evolution of our Solar System. As we look to the future, we will discover a large number of objects and our ability to study these objects in detail will be greatly improved. We will have to determine a balance between the in depth analyses (e.g., mineralogy, rotation rate, spin pole) and the broad survey work (e.g., taxonomic type). Both of these types of studies are extremely useful, but as the field grows we will be limited by the assets available to us (including telescope time and researchers).

Main Belt and Trojan Asteroids: The Main Belt and Trojan asteroid populations are large reservoirs of material from the early Solar System. The diversity of composition in the Main Belt can tell us a lot about the starting conditions and early evolution of the primordial disk. Determining the composition of the Trojan asteroids of Jupiter can enable scientists to distinguish between dynamical models of Solar System evolution.

Near-Earth Asteroids: The majority of near-Earth objects originated in collisions between bodies in the Main Belt and subsequently found their way into near-Earth space through a series of dynamical interactions. Large scale spectral analyses of the near-Earth asteroid population can shed light on a variety of topics including source regions for the various populations and the distribution of taxonomic types and mineralogies. Additionally, near-Earth asteroid physical studies are important for understanding the hazard level associated with any potential impactors.

Future work:

Near-Earth Asteroids. For years the community has been working to characterize ~10% of the NEA population. Through various efforts such as MANOS [1], the MIT-UH-IRTF Joint Campaign for Spectral Reconaissance [2], and other published surveys [3,4] we have been able to keep that pace. However, the planned addition of the Large Synoptic Survey Telescope to discovery efforts will add at least 40,000 known objects (H<22.4) [6] to the population. The community and the various organizations that support near-Earth object studies (such as the NASA Planetary Defense Coordination Office) should assess the future needs and goals. If we want to continue characterization at a pace in line with the future discovery pace, then we need to support survey programs and the necessary telescopic assets. To execute a characterization program of such a large scale, the community needs programmatic organization in excess of what is currently available today. There will be a much larger number of observations to coordinate and we would need to work to prevent excessive duplication of efforts. Additionally, we should have a series of priorities to guide the overall effort. Such a large program would also require a significant outlay of telescopic resources. We need to invest in instrumentation suited to the specific studies (e.g., wide field cameras, low resolution spectrometers) and obtain significant amounts of time on various telescopes with a wide variety of apertures.

Main Belt and Trojan Asteroids. The Main Belt and Trojan asteroid populations have the potential to teach us about the past and present of our Solar System. We understand the structure of the Main Belt, so we should turn our focus towards in depth characterization. As we learn more about the current dynamical evolution of the Main Belt, we can start to understand the structure and compositions of the past. By examining the range of compositions of the old families and the meteorites with the oldest cosmic ray exposure ages, we can start to understand how dynamic the compositions of the Main Belt have been. Understanding the compositions of the Trojan asteroids can be potentially change our understanding of early Solar System evolution so further studies of these objects are imperative. Any extensive mineralogical studies will need to leverage the full wavelength range of spectroscopic studies. These studies will require a comprehensive set of complementary laboratory studies. Otherwise, we will not be able to fully leverage the new observations.

Conclusion. We will explore the necessary coordination and analytical tools to optimize our scientific investigations. As a community, asteroid researchers should work together to define our future priorities.

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OBSERVING OUTER PLANET SYSTEMS IN THE MID-21ST CENTURY.

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Executive Summary: We offer several ideas on studying the outer solar system during the coming decades. Our particular interest is in ring systems and satellite systems, though surfaces and interiors and atmospheres are briefly touched upon.

The technology of tomorrow will likely make basic hardware increasingly inexpensive, both for computing and for rocketry. Data transmission and storage will also become much more inexpensive, such that human attention rather than data will be the limiting factors in scientific endeavor. Automation and other data strategies will help us to grapple with this new reality [1].

These trends will enable better traditional spacecraft missions as well as entirely new kinds of spacecraft missions. We discuss some modest ideas for spacecraft missions in the second part of this abstract.

On a parallel track, there is enormous potential in taking existing technology and multiplying it as it becomes more inexpensive, especially in the realm of space telescopes. We discuss some of the science return that could accrue in response to a major increase in time-domain observations.

Finally, we close by discussing the scientific community of tomorrow, with hopes that it will be more diverse and welcoming.

Space Telescopes: Studying the outer planets with space-based and ground-based telescopes will be essential in the near-term future, as no spacecraft will be operating in any outer planet system between the impending close of the Cassini and Juno missions and the arrival of the Europa and Juice missions around 2030.

The Hubble Space Telescope continues to generate critically important science, and the James Webb Space Telescope will improve upon its capabilities in several ways. Particularly in regard to rings and small moons, JWST will discover new rings and moons that are beyond the sensitivity of Hubble, will conduct unprecedented spectroscopy of rings and moons, and will continue Hubble's important work of time-domain science [2].

Time-domain science: Many aspects of the solar system are in constant flux, including planetary rings, satellite systems, and atmospheres. Examples include

- Impacts and storms and cloud movements in giant planet atmospheres, all of which are transient events that are best studied frequently [3,4,5]
- Jupiter's Great Red Spot, which may be in the process of disappearing [6]
- Volcanic activity at Io, with correlated changes in the Io Plasma Torus and in Jupiter's aurorae [7]
- The plumes of Enceladus [8]
- "Propeller" moons embedded in Saturn's rings [9]
- The ring arcs of Neptune, post-Voyager movements of which have invalidated the prevailing model from the Voyager era [10]
- The F ring of Saturn [11]
- The spokes in Saturn's rings; a seasonal pattern has been discerned [12], but we do not know how they vary on a climate-like scale from one Saturn year to another [2].
- The ring-moon system of Uranus, which shows signs of recent and frequent change [13]

Heretofore, the study of such systems has involved periodically taking detailed snapshots and then using theory to figure out how the snapshots fit together. While that method has met with much success, the enormous increase in understanding that has come from Cassini's extended time baseline in the Saturn system demonstrates how often nature surprises us when we fill in the gaps with more data, rather than with our own surmises.

By the mid-21st century, it will have become vastly more inexpensive to launch a space telescope incurporating Hubble-class optics and electronics. Data transmission and storage will also become more and more affordable, to the point that they no longer exert limitations on our work. This will open an entirely new horizon with regard to time-domain science. It is not difficult to imagine a number of space telescopes, each focused on extended observations of one or a few targets. This will enable us to move beyond understanding basic structure and to focus our attention on weather and climate (and their analogues in other types of systems).

Spacecraft Mission Concepts:

Visiting Ocean Worlds. The currently planned missions to Europa (NASA) and Ganymede (ESA) will have concluded by 2050. As we continue to search for evidence of habitability on the "ocean worlds" of the solar system, perhaps the most compelling target is Enceladus, whose subsurface water reservoirs were recently shown by analysis of its rotation state to extend globally [14]. A more multifaceted target would be one or both of the Ice Giant planets, which feature complex ring systems wholly unlike those of Saturn, nearly unexplored icy moons that may well harbor oceans, and planets of a size class that is poorly understood yet known to be plentiful among exoplanets. Ice Giant orbiter missions have been proposed to ESA [15] and are under study by NASA [16]; a joint effort between the two agencies is likely the best solution.

Returning to Saturn's rings. Ring systems furnish the only accessible natural laboratory in which we can study disk processes, which are of high importance for understanding the origins of planetary systems [5,17]. The Cassini mission has returned a wealth of discoveries regarding Saturn's rings and moons [18,19], opening a window onto a new set of more detailed science questions. Are the rings much younger than the planet and its moons, or indeed are many of the moons also younger than 100 Myr? How do disk processes such as self-gravity wakes and propeller moons shed light on the workings of proto-planetary systems? Spacecraft that specifically study Saturn's rings in more detail, whether as dedicated missions or opportunistically, have the potential for high science return.

Advances in propulsion technology may enable the Saturn Ring Observer mission concept [20] to be realized. By exerting a low but constant vertical thrust, such a spacecraft would "hover" over the rings and take detailed movies of individual particle interactions within the rings.

Also, Keplerian trajectories that repeatedly skim above Saturn's rings in a geometry similar to that of Cassini's Saturn Orbit Insertion are in development and could be used for a variety of mission concepts, including low-cost ones.

Cubesat/Chipsat concepts. As Moore's Law runs aground due to physical limitations associated with heat flow and other factors [21], computer innovation will increasingly shift towards parallelization and towards making small components that are more capable and more affordable. Planetary scientists would do well to consider the new vistas opened up by large numbers of small components. Seeding Saturn's rings with a swarm of "chipsats" may be more affordable than a hovering spacecraft as a way of studying the inter-particle interactions within disk systems [22]. Other problems amenable to swarms of chipsats might include mapping the magnetospheres, gravity fields, and/or atmospheres of the giant planets [23]. When they become sufficiently plentiful, "cubesats" may also be deployed inexpensively for focused studies of targets such as Iapetus or Chariklo that raise compelling science questions that are perhaps not broad enough to justify missions of even Discovery-class expense [23].

Workforce Makeup and Climate: No less important than the goals we will pursue in the coming decades and the means we will use to get there is the scientific community that will undertake the work. Currently, several communities within the general population are severely underrepresented among planetary scientists, as are women [24], and members of those minoritized groups have reported various forms of harassment and other difficulties that hamper the advancement and flourishing of their careers [25]. To give one example, a recent study showed that spacecraft science teams and other paths to career advancement commonly lack women, even compared only to the pool of qualified applicants at the time the team was formed [26]. Far more research is needed to illuminate the magnitude of the problem, and the community must forge a courageous consensus to implement solutions.

We particularly endorse the abstract submitted to this workshop by Rathbun et al. [24], which is dedicated to discussing this important topic.

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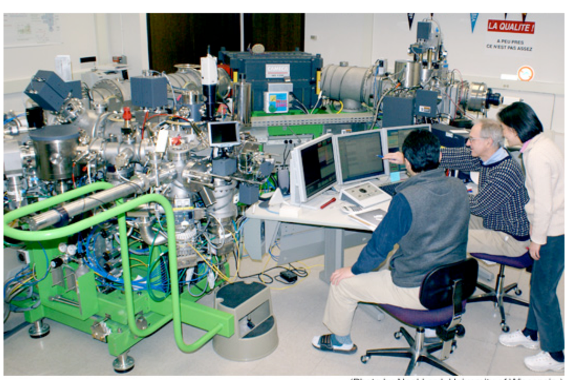
SAMPLING THE SOLAR SYSTEM: THE NEXT LEVEL OF UNDERSTANDING. A.H. Treiman, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058. treiman@lpi.usra.edu.

Introduction: With the success of the Dawn and New Horizons missions, NASA has completed its first-cut inventory of the major bodies in the solar system. The next level of understanding of the solar system will come from detailed analyses of its materials. For most materials, sample return to Earth will be essential, permitting use of massive, power-hungry, and delicate instrumentation. Some sample return missions have succeeded, others are in flight, and NASA should formally encourage many sample returns in its long-term plans [1,2]. NASA should also encourage collection of larger (kilogram-size) and temperature-sensitive (e.g., ice) samples, and develop curation and analysis capabilities for them here on Earth.

Importance of Sample Science: Study of the solar system through samples, its physical materials, is crucial for understanding its origins, the origins of life, and the extension of human presence beyond Earth. Knowledge from samples has completely reshaped our understanding of the solar system, its history, and events before and beyond it (e.g., [3-5]). Sample science is complementary to remote sensing and in-situ studies (e.g., orbiters and rovers). Remote sensing allows the Apollo lunar samples to be placed in a geologic context and relative chronology, and the samples provide calibration for remote spectral observations.

Rationale for Sample Return: The value of extraterrestrial samples on Earth is well documented (e.g., [3,6]). Returned samples can be prepared for analysis in various ways (e.g., FIB sections, mineral separates) and be analyzed in instruments that could not conceivably be sent off Earth (constrained by power, mass, and delicacy), Fig. 1. Samples, properly curated, are "gifts that keeps on giving" [6], in that they can be studied into the future with increasingly precise instruments and in response to new discoveries and new hypotheses. As proof, consider how re-analyses of Apollo lunar samples has completely overturned of our thinking about lunar volatiles (e.g., [7,8]).



(Photo by Neal Lord, University of Wisconsin.)

Figure 1. A modern laboratory instrument: Cameca 1280 SIMS (secondary ion mass spectrometer). University of Wisconsin SIMS lab, Drs. J. Valley and N. Kita at right (for scale, ~ 1.5 m tall)

Rationale for Large Samples: Recent sample returns have been of tiny particles, ranging from individual solar wind atoms (Genesis mission) to ~200 µm grains (Stardust, Hayabusa). Small samples permit important science (e.g., [3-5]) but cannot address other crucial objectives. (1) Such small samples may not be representative of planetologically significant masses (Fig. 2); e.g., a volcanic glass bead could represent a magma composition, but a single mineral grain would not. (2) Small samples may not show multiple mineral grains and their intergranular relationships (i.e., textures) that permit one to unravel the formation conditions and histories of the grains. (3) Small samples may not be massive enough for specific analysis, e.g., a radiometric W-Hf isochron age.

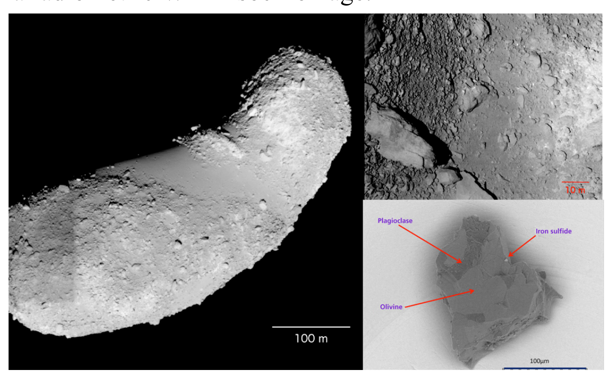


Figure 2. Asteroid Itokawa. Left is whole object, ~ 525 m long; note variety of boulders and fines on surface. Right above, closeup showing range of textures and fragments at meter scales. Right below, backscattered electron image of a large particle of Itokawa regolith, returned by Hayabusa spacecraft. All images from JAXA.

Long-Term Strategy: In the long term, NASA should encourage returns of material samples from all classes of objects across the solar system. This program should begin with the simplest missions, building from current successful architectures outward to larger samples and to more difficult logistics and curation needs. Hayabusa, Hayabusa II, and Osiris REX have (will) sample several sorts of asteroids without ice, but many more spectral/compositional types are known (including the martian moons Phobos and Deimos). Stardust sampled one comet, but many different types are known. Lunar sample returns should also be early, and build on known architectures. Later sample returns would include volatile-rich targets (asteroids, comets), distant high Δv objects (moons of outer planets, KBOs), and those with special logistical issues.

Moon, Involatile Asteroids, Comet Material, Phobos, Deimos. Samples have been returned from volatile-poor (not icy) small bodies (by Apollo, Luna, Hayabusa, Stardust) and others returns are in progress (Hayabusa 2, Osiris REX). Most such bodies are in the inner solar system, allowing relatively rapid and low Δv access. Lunar sample return has been discussed at length (e.g., [3]), and many important lunar targets remain unsampled [9]. The asteroids include a huge diversity of spectral types [10,11], and each may represent a different sort of solid (e.g., like a meteorite type [12]). Comets come in a wide range of types also, at least from their volatile constituents [13,14]. Phobos and Deimos are strong targets for sample returns (e.g., [15-17]), and could possibly preserve Martian ejecta [18]

Icy Asteroids & Comets. Returns of icy materials should be enabled next. Their samples will provide crucial evidence about the sources, processing and distribution of volatiles in the solar system, and the foundation for the emergence of life. Ices are characteristic of comets 'dead comets' in the asteroid-belt, and also of larger indigenous asteroids [19].

Sample returns of solar system ices will require mechanisms of cryogenic transfer to Earth, and cold curation procedures and facilities on Earth. Cryogenic curation is under study [20], but perhaps not ready yet.

Outer Solar System. Proposals have been floated for sample returns from the outer solar system, like from Enceladus, Europa and KBOs (e.g., [21-24]). These are technically challenging, and must follow establishment of cryogenic curation practices (see above). Such missions also require large Δv's, especially to bodies orbiting close to giant planets (e.g., Europa). Planetary protection could be a major issue for many such bodies [21,25,26].

Mars, Venus and Mercury: Technical Challenges. The terrestrial planets (except Earth) present unique challenges for sample return. Mars sample return has been studied unto death for ~40 years [27], and planning for the Mars 2020 Rover includes caching of samples for eventual return. Planetary protection is a major issue, and will require development of spacecraft and earth-based infrastructure [25], some of which in planning [28,29]. Venus sample return, though proposed [30,31], would need to penetrate its thick atmosphere, and possibly conduct surface operations at its ambient conditions. Mercury sample return [32] could be similar in concept to lunar return, but the Δv needed to traverse to Mercury, land there [33], and return to Earth is huge.

Summary: Returned samples of solar system objects will provide crucial data on the constitution, variety, and history of the solar system. Returned samples will provide data that cannot be obtained by conceivable robotic instrumentation, increase the value of remote observations by providing ground truths, and (properly curated) allow for testing of new hypotheses by ever-more-capable instruments. Sample returns from across the solar system should be among NASA's long-term goals, and can be achieved in a logical sequence of activities, building on its current successes.

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Seismic Exploration of the Solar System's Icy Moons. S. D. Vance*, S. Kedar, B. G. Bills, D. Wenkert; Jet Propulsion Laboratory, California Institute of Technology, CA (*svance@jpl.nasa.gov).

Introduction: Seismic investigations offer the most comprehensive view into the deep interiors of planetary bodies and thus hold the potential for enabling detailed exploration and resource utilization on icy satellites in the coming decades. Missions under way (InSight) and in development (*e.g.*, a Europa lander concept [1]) have identified seismology as a critical measurement to constrain interior structure and thermal state of astrobiological targets. By pinpointing the radial depth of compositional interfaces, seismic investigations can complement otherwise non-unique composition and density structures inferred from gravity and magnetometry studies, such as those planned for NASA's Europa mission and ESA's JUICE mission. Seismic investigations also offer information about fluid motions within or beneath ice, which complements magnetic studies, and they can record the dynamics of the shell, providing new information on how cracks form and propagate. Seismology fits well with other geophysical investigation of oceanic icy moons, as demonstrated here using physically consistent interior models. Planning for the coming decades will require more detailed modeling and laboratory studies of geophysical data related to habitability, comparative planetology making use of past and pending mission data, and development of innovative technology.

The View to 2050: Currently known ocean worlds pose an intriguing challenge for human and robotic exploration: to access vast reserves of liquid water and to look for extant life. With strong evidence for oceans in Jupiter's moons Europa, Ganymede, Callisto, and Saturn's moons Enceladus and Titan, the coming decades of further data analyses reconnaissance will set the stage for detailed in situ measurements.

Any landed mission should carry with it a seismic experiment to constrain present-day activity, deep subsurface chemistry, and accessibility of liquids. This information will be critical for any drilling activities, and for constraining the nature of any subsurface ocean and its suitability for extant life. An ancillary outcome of such an investigation would be to provide reconnaissance for robotic or crewed outposts for ongoing scientific exploration and in situ resource utilization. Callisto in particular is a relatively accessible target that has been considered for such activities [2].

Relation to Other Geophysical Measurements: Planned missions to the Galilean satellites would provide powerful prior constraints for seismic investigations that could enable characterization of the deeper interior: ice shell and ocean thickness, radial density structure, and ocean electrical conductivity.

Interior and Habitability of Europa: We are constructing interior models for icy moons that can be used to evaluate geophysical measurements. The calculation [3] uses available geophysical constraints to propagate profiles in density, sound speed, temperature, and electrical conductivity, for specified heat flux configurations and ocean compositions. A sample output for Europa (Fig. 1) illustrates the unique signatures of these key measures that might be used to distinguish between an ocean dominated by $MgSO_4$ and one with a seawater composition identical to Earth's.

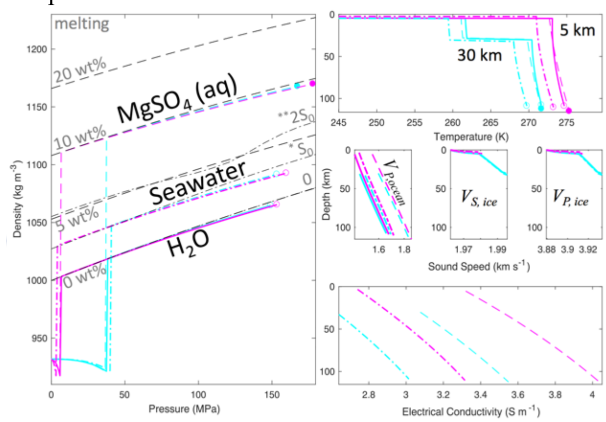

Fig. 1. Modeled density structure of Europa vs pressure (left) for pure water (solid lines), 10 wt% $MgSO_4$ (dashes), and seawater (dot-dash; 35 g/kg solution) for 5 km and 30 km thick ice. Grey lines indicating density along the melting curves illustrate that the Gibbs Seawater package is unstable above 100 MPa for high salinities. Depth-dependent curves (right) of temperature (top), sound speed (middle), and electrical conductivity (bottom) illustrate the distinct signatures that may be observed by future investigations.

Interior of Callisto: Models for Callisto point to an ocean intermediate to that of Europa and larger Ganymede [4] (Fig. 2). The warmer pure water models do not have high-pressure ice because the high inferred gravitational moment of inertia (assuming a hydrostatic body) requires a low-pressure ocean. Ice V is present in the cooler cases, but not ice VI. The lowest temperature case produces buoyant high-pressure ice III in the lower part of the ocean. Sound speeds for different phases are distinct. Recent progress in understanding the heat transport and convection in such high-pressure layers points to the key role of fluids within the ice [5]. The presence of fluids would strongly influence the sound speed profile and associated seismic attenuation.

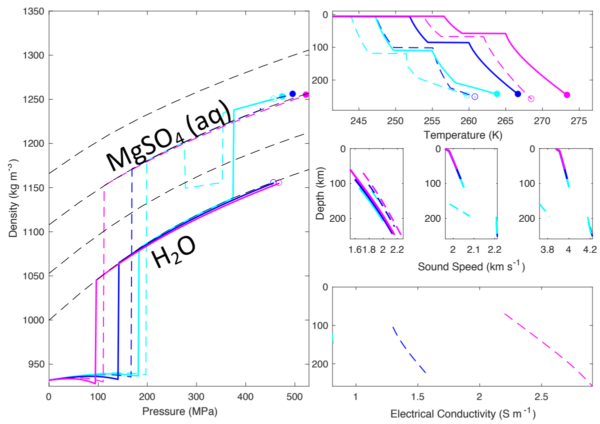

Fig. 2. Model for Callisto's interior, displayed as in Fig. 1, for pure water (solid) and 10 wt% $MgSO_4$ (dashes) for ice thicknesses ranging from 60 km to 130 km.

Planning: Implementing seismic investigations will be dictated by technical constraints on needed measurement sensitivity imposed by the physical environment. Precedents for planetary seismology approaches exist in the Apollo seismic network [6] and detailed studies for a Lunar Geophysical Network [7] and documentation for the planned Mars InSight mission [8]. Icy moons of the outer planets differ from Earth, the Moon and Mars, and from one another, so that their possible seismic characteristics much be evaluated carefully and on an individual basis.

Long Term Vision for Icy-Moon Seismic Networks: Sensitive seismometers are critical for detecting faint motions deep within the planetary bodies that can be used to reconstruct their interior workings while shedding light on fundamental processes such as tectonics, and where relevant, volcanism, ocean noise, ice flow, and geysering. To detect the minimum number of events required for constructing a model of the interior, a geophysical investigation has two options: (1) Increased sensitivity enabling the detection of low magnitude quakes; (2) Deploying a network of seismometers whose sensitivity requirements may be relaxed somewhat. The challenge of the first option (chosen by the InSight mission) is the consequent instrument and lander size and complexities. Option 2 is prohibitively expensive using current lander technology. There is a dire need for a solution that circumvents both complexities by enabling simple deployments of future seismic networks to icy moons.

The obvious solution calls for the capability to land multiple broad-band, high-dynamic-range, sensitive MEMS seismometers. MEMS technology is on the verge of meeting the sensitivity requirements for studying the interior of most of the Solar Systems Icy Moons. In parallel, 3D printing technologies are emerging that are capable of seamless integration of power, communication, data-processing and shock absorption systems. Combining the two capabilities may offer a cost effective and relatively simple deployment approach that will bypass the challenges of traditional seismic networks.

A distributed network of seismometers will diverge from traditional networks in one more key aspect. It will require autonomous smart on-board data processing capabilities, and tolerance to node failures. Even with increased power and communication capabilities, the return from multiple triaxial seismometers recording 24-bit data at standard 100Hz implies an exhorbitant data volume. Future planetary seismologists will have to forgo the natural desire to process every bit of data on Earth, and rather, design and implement seismic data processing software that can adapt to the seismic signals it records,and that enables interaction between seismic nodes, which may be invisible to network operators. This will be particularly challenging if the network is to be deployed onto the surface of a never before explored planetary body, highlighting the importance of comparative planetology and detailed physically consistent models encompassing the full range of possible activity [9].

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Sample Return from Water Worlds: Requirements, Risks and Enabling Technologies.

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Introduction: Recent discoveries of the presence of water on planetary bodies within our solar system and on exo-planets in the known Universe hass excited the imagination of the scientific community and the general public. "Follow the water" is a defining scenario for scientific exploration in the coming decades. The future presents opportunities for us to answer the very existential question that has been asked by humanity, "Can life be present elsewhere or are we alone?" Planetary Science Division's Vision 2050 is a perfect venue to discuss the challenges and how to overcome them.

We have observed, orbited, landed and are roving at Mars today and will be collecting samples and caching them in the near future. It is expected that in situ discoveries from these samples will drive demand from the astro-biology community for samples to be brought back. The possibility, although low likelihood, that biologically sensitive Martian samples, if released, may cause catastrophic harm to Earth, has caused both NASA and ESA Planetary Protection Offices to place very stringent requirements on sample containment through transit from Mars all the way to the secure labs on earth. These planetary protection requirements are also applicable for Sample Return for "Water Worlds", which is another mission class of primary importance for exploration within the next 3 decades.

Background and Lessons Learned: Mission planning undertaken jointly by NASA and CNES for Mars Sample Return mission in the late 1990's provided insight in to the challenges associated with meeting the reliability. The highest risks along the sample transfer chain of events occur during entry, descent and landing. Two different approaches have been proposed, and both require highly reliable EDL system. The first option is direct entry, where the Earth entry vehicle (EEV) is released by the spacecraft from the interplanetary trajectory as it approaches Earth, and enters, descends and lands passively (i.e. without active control). In the second architecture, an in-orbit transfer of the sample container to Space Station and/or Orion takes place and then Orion carries the sample container to earth. Analysis of both these architectures places different levels of burden on the EDL system, but both architectures will require EDL to be far more reliable than any prior entrymission, including those that carry astronauts.

Entry, Descent and Landing and Thermal Protection Systems: The thermal protection system around an entry aeroshell is a single string system. The probability of failure leading to accidental release of the sample has to be proven to be extremely small. For example, MMOD damage to the heat-shield and backshell can lead to precursor damage to the heat-shield and this upon entry may allow a hot gas breach. Another possible risk during EDL is that needs to be avoided is failure during descent and landing. Though every sample return mission to-date has used a parachute to slow down during descent, the parachute failure of Genesis makes it necessary to consider direct impact as a landing alternative.

Are there other architectures where the EDL risk can be managed and the very high reliability requirement can be reduced? We will present some thoughts on alternate approaches that have strong potential to radically reduce the cost and test demonstration burden for developmental systems

Focus of the Presentation/Poster: Our presentation or poster will address enabling technologies for critical sub-systems and alternate mission architecture considerations that could lead to meeting the planetary protection requirements. This proposed presentation/poster will present:

- State of the art in TPS design and the reliability challenges,
- The emerging technologies that drive our ability to design a single string system to meet the very stringent reliability requirements
- Potential pathways to mature these emerging technologies, together with time line and plans to establish reliability of the proposed system
- Approaches to managing the risk of MMOD damage
- Recommendations for cost effective testing (including flight tests) to obtain data that will be needed to establish credible reliability estimates.

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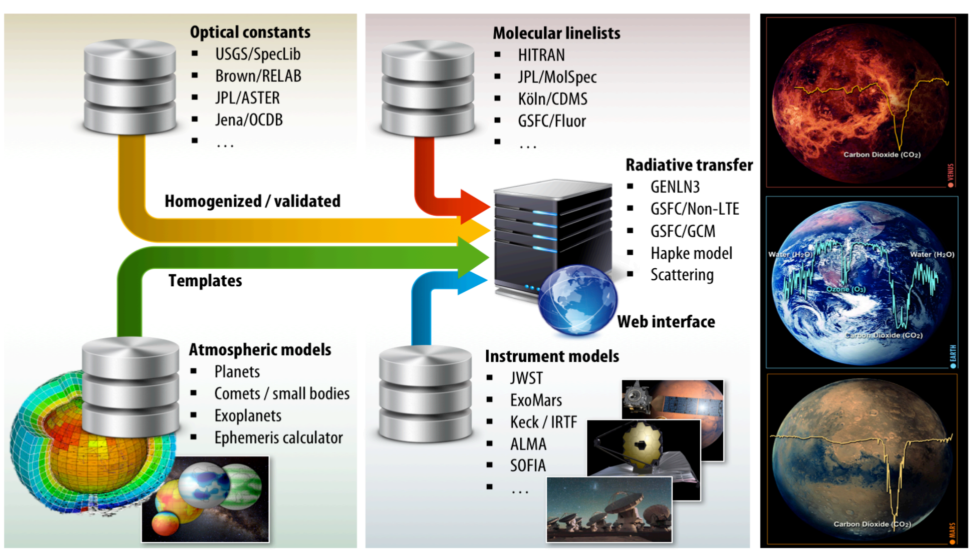
PLANETARY SPECTRUM GENERATOR (PSG): AN ONLINE TOOL TO SYNTHESIZE SPECTRA OF COMETS, SMALL BODIES AND (EXO)PLANETS. G. L. Villanueva[1], A. Mandell[1], S. Protopapa[2], S. Faggi[1,3], M. D. Smith[1], M. Wolff[4], T. Hewagama[1,2], M. J. Mumma[1], 1NASA Goddard Space Flight Center (geronimo.villanueva@nasa.gov), [2]University of Maryland, [3]Arcetri Observatory, [4]Space Science Institute.

Introduction: NASA's exploration of our Solar System and beyond is heavily reliant on our advances in remote sensing via spectroscopy. The definition of which missions to fly and which instruments to develop are established in order to maximize the science return, requiring accurate and precise modeling of the different components for such investigation, from the properties of the object of study (composition, orbit, temperature) to accurate modeling of the mission performance in space. For that purpose, we have developed the Planetary Spectrum Generator (PSG), which is an online tool for synthesizing planetary spectra (atmospheres and surfaces) in a broad range of wavelengths (0.1 μm to 100 mm, UV/Vis/near-IR/IR/far-IR/THz/sub-mm/radio) for observatories (e.g., JWST, ALMA, Keck, SOFIA, HST), orbiters (e.g., MRO, ExoMars, Cassini, New Horizons), or landers (e.g., MSL). This is achieved by combining state-of-the-art radiative-transfer/planetary models, and spectroscopic databases.

Planetary generator: there are numerous radiative transfer packages, each tailored to a specific object-type, spectral range, geometry, or instrument. More problematic, these packages typically require complex installations, compilations, and libraries; and require maintenance, and are restrictive in operational scope. PSG overcomes these limitations by implementing several efficient radiative-transfer modules on high-performance NASA servers, which are accessed via a user-friendly web interface. The operational principle is similar to that of the JPL/Horizons ephemeris calculator, in which calculations are performed on the server side, with the user simply defining the parameters.

PSG capabilities - ssed.gsfc.nasa.gov/psg
A 3D (three-dimensional) **orbital calculator** for all solar system bodies and confirmed exoplanets, for Nadir, limb and occultation geometries.
The tool ingests **billions** of spectral **lines** and spectral **constants** from almost 1,000 chemical species from several spectroscopic repositories (e.g., HITRAN, CDMS, USGS, GSFC-Fluor).
Accurate **atmospheric profiles and surface** templates are available for the main bodies (e.g., Venus, Earth, Mars, Titan, Uranus, Pluto).
Radiative transfer performed with several modules: **GENLN3**, **correlated-K**, **non-LTE** fluorescence, and **surface models.**
The code synthesizes **fluxes** in any desired unit.
The tool allows applying **terrestrial transmittances** for a broad range of conditions (altitude and water, also from SOFIA and balloons).
For exoplanets, it includes the possibility to integrate **realistic stellar templates** (0.15-300 μm), and the high-resolution ACE Solar spectrum (2-14 μm) for G-type stars.
It includes a **noise and signal-to-noise calculator** for quantum and thermal detectors, at any observatory (e.g., Keck, ALMA, JWST).



The tool can synthesize a broad range of planetary spectra by combining a modern and versatile online radiative transfer suite that uses state-of-the-art spectroscopic databases. The modules are computationally optimized, with a typical runtime of one second.

ANALOGIES AMONG CURRENT AND FUTURE LIFE DETECTION MISSIONS AND THE PHARMACEUTICAL / BIOMEDICAL INDUSTRIES. N. R. Wainwright[1], A. Steele[2], L. Monaco[3], and M. Fries[4] [1]Charles River Laboratories, 1023 Wappoo Rd, Charleston SC 29407, [2]Carnegie Institution, Washington, DC, 20015, [3]Jacobs ESSSA, Marshall Space Flight Center, Huntsville, AL, 35812, [4]NASA Johnson Space Center, ARES, Houston TX 77059.

Introduction: From the earliest days of modern pharmaceutical manufacturing, the producers have been on a life detection mission. While governmental regulation has been primarily focused on ensuring the safety and efficacy of the products for the public, establishing the Food and Drug Administration in the early twentieth century in the U.S., manufacturers were equally driven by the financial impact of product contaminated by microbes. In 2004, the FDA has pressed for modernization of analytical approaches to quality control in its PAT (Process Analytical Technology) initiative. [1] While simple, traditional culture methods became adopted by the industry to quantify contamination, linking the results to some criterion of safety, the methods were far from perfect. Which species should be grown on defined media, under what conditions? Is it acceptable to hold a product in limbo for several days to achieve release? The food industry similarly focused concern on potential pathogens that spoiled product could transmit to the public. However, the pharmaceutical industry further became responsible for toxicity that could result from fractions of microbial cells that confer toxicity upon injection. As the value of sophisticated new drugs has gone up, more sensitivity and specificity of testing is demanded, likewise the pressure to get results faster to minimize costs of halting the production lines. Whether the milieu is a highly purified drug, or the barren, surface of an asteroid or planet, the quest for life is on similar paths.

Viking and Planetary Protection: The seminal life detection mission of the 1970's forced a new approach to life detection. [2] Not only did the technology of onboard experiments become increasingly sophisticated, but issues of potential transfer of Earth life to the surface of Mars become an issue, not only for interference with detection experiments, but for planetary protection as well. Elimination of Earth microbes involved creatively sterilizing the spacecraft after assembly by dry heat in a custom built oven, essentially analogous to "Pasteurizing" the product before use.

Non-Culture Methods:

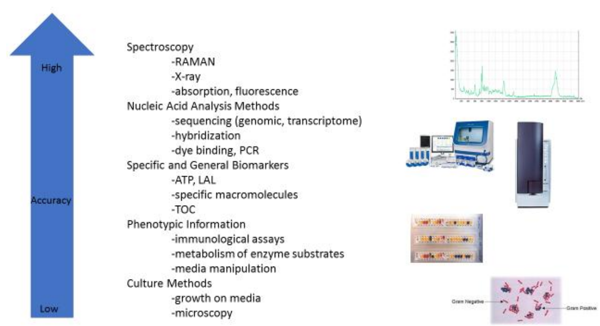
Limitations. More recently, the realization that microbial species cultivable on defined media are a minority of the biodiversity in the environment causes concern for both Astrobiology and commercial needs. It relinquishes culture results from the definitive to the indicative. It also exposes that there is much more bioburden potentially present than can be accounted for by culture.

Methods such as specific biomarker or ATP detection came into focus. PCR and DNA sequencing became eagerly adapted to the issue. [3] These methods did find very useful application where specific species and DNA sequences were known, but unknown organisms, potential false positive and negative results due to sample acquisition and preparation add some uncertainty; further improvements and refinements will certainly follow.

LAL and LOCAD. An example of non-culture dependent methods, the *Limulus* Amebocyte Assay (LAL) test found eager acceptance in the pharmaceutical industry for quantifying bacterial endotoxin, a potent pyrogen when contaminating human injectable drugs. The FDA approved its use in the 1970's and it has become widely accepted in the industry. Its use was adopted for Technology Evaluation flights to ISS Expeditions 14 and 15 as part of NASA's LOCAD (Lab-on-a-Chip Application Development) Mission. Small, portable equipment developed for the Pharmaceutical industry was adapted for spaceflight and the LAL test for endotoxin became a rapid, non-culture assessment of microbial contamination of spacecraft surfaces in flight. [4]

Future Progression:

Increased specificity and sensitivity. For both space-based science missions as well as the biomedical industry, technology must develop further.



Multipurpose development. The need for timely information during a manufacturing process to keep products safe and affordable are employing many of the same tools used to probe for the presence of extraterrestrial life. Rather than to develop custom tools for each mission or job at hand, a better use of resources would be to develop tools general enough, yet powerful enough to be tailored to specific mission requirements. One way to visualize this concept is to realize that in many cases the hardware for sample preparation, sample inoculation, sample analyses and data read out and interpretation are very similar across the range of applications such as; life detection planetary protection, environment monitoring and astronaut health. That being said it becomes a simple proposal to tailor the assays for each purpose but have the hardware be standardized. With every increasing laboratory instrument sensitivities being translated into field or person portable instrumentation and with the realization of micromachining and microfluidic technologies in the medical and environmental monitoring fields it becomes a simple extrapolation to a miniaturized platform that could be deployed on human and robotic missions where the assays are tailored to specific life / organic chemistry or health and environmental priorities. We advance the proposition that the best place for this platform development is within the commercial sector where issues such as FDA approval, quality control and fabrication are already rigidly controlled and that assay development alone is the bailiwick of space technology development. Just as in the commercial space flight world, there is a move away from government organizations to fulfill space flight goals, there should be an impetus to involve the medical and environmental technology industry in the cost effective controlled production of the next generation techniques to fulfill science and monitoring goals for missions in the 2050 time frame.

Wish list.

Projecting twenty or more years into the future is necessarily uncertain, however the direction that would be worthy of considering should include:

1- Production of small low cost probes to detect life or organics in a drone-like format that can be employed en-mass to survey the surface of an icy moon or planet for signs of life, organics, radiation environment etc.
2- Personalized medical diagnosis and treatment of Astronauts based on small analyte, genomic and proteomic monitoring.
3- Air, water and materials quality monitoring on human missions for both organisms and chemometric tests for anion and cation concentrations.
4- Planetary protection monitoring to verify procedures for “breaking the chain” of possible forward and backward contamination during sample return missions from Mars and icy moons.
5- Laboratory based rapid analysis of returned samples for the presence of specific organic species, terrestrial contamination and possible presence of life.
6- Instruments and algorithms capable of assessing complexity, i.e., able to discriminate unknowns of high complexity from uniform or known material background.

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HOW PLANETARY MAGNETOSPHERES HAVE AND CAN CONTINUE TO DRIVE SOLAR SYSTEM EXPLORATION. J. H. Westlake[1] and P. C. Brandt[1], R. L. McNutt[1], D. G. Mitchell[1], A. M. Rymer[1], [1]Johns Hopkins University Applied Physics Laboratory, 11000 Johns Hopkins Rd., Laurel, MD 20723, joseph.westlake@jhuapl.edu, [2]Affiliation for second author (full mailing address and e-mail address).

Introduction: The study of planetary magnetospheres has driven solar system exploration from the earliest Explorer 1 mission that discovered the Van Allen radiation belts around our Earth, to the Voyager spacecraft that presented the first comprehensive view of the multitude of novel magnetospheres in our solar system, to the flagship Cassini and Galileo spacecraft that have discovered and studied the magnetospheres of our closest giant planet neighbors Saturn and Jupiter. Understanding these planetary magnetospheres is fundamental to our determination of the origins and workings of solar systems and could also be crucial to understanding how life is protected from the harsh space environment. In this presentation we will discuss the evolution of planetary magnetospheric research and our vision for the future including a discussion of targets within the solar system and also how magnetospheric research can advance our knowledge of exoplanetary systems, as well as inform the interpretation of those emissions.

History: The study of planetary magnetospheres has evolved from the detailed studies of the Earth's magnetosphere to the long-term deep dive into Saturn's magnetosphere provided by the Cassini mission. Single flyby missions such as the Voyagers provided the initial insight into the outer planetary magnetospheres that was followed by orbital missions such as the Galileo mission at Jupiter and Cassini at Saturn.

As the field has evolved, capabilities have as well. We have come from single point measurements of plasmas to global imaging of magnetospheres through Energetic Neutral Atom (ENA) imaging. Further study of the workings of the giant planets has also added to our toolkit with induction measurements and their value to assessing the habitability of icy moons in the outer solar system, and also radio emissions from the giant planet auroral zones as proxies for the true planetary rotation rate and interior structure.

Future Exploration: The structure of planetary magnetic fields provide a crucial insights to the inner workings of giant planets. The magnetic field structure can also be used to discern fundamental properties of ocean worlds such as whether or not there are salty subsurface oceans. In addition radio emissions from aurora can be used to determine the planetary spin rate and other features of the magnetosphere. Exploiting these space physics phenomena to discover the fundamental physics of planetary systems is crucial to our future exploration of the solar system and our understanding of solar systems beyond our own.

In the next decade NASA and ESA have planned detailed exploration of the Jovian magnetosphere, specifically its moons Europa and Ganymede. Currently the Juno mission is undergoing detailed mapping of Jupiter's deep interior by making unprecedented magnetospheric observations via a sequence of highly-inclined orbits. The Europa Clipper mission will exploit Europa's moon-magnetosphere interaction to study the magnetic induction signal from the subsurface ocean. This magnetic induction signal is key to understanding the global characteristics of Europa's subsurface ocean, including the ocean depth and salinity. The Jupiter Icy Moons Explorer (JUICE) mission from ESA will study both the Jovian magnetosphere and the mini-magnetosphere of Ganymede. These missions will unlock the mysteries of Jupiter's magnetosphere providing detailed understanding that will be needed to assess radio emissions from the multitude of giant planets found in exoplanetary systems.

Following these missions the key next step for planetary magnetospheres is the detailed exploration of the ice giants. Ice giants are one of the most commonly found type of exoplanets, and so understanding our two closest ice giants Uranus and Neptune is key to understanding the constituents of other planetary systems. Uranus and Neptune are known to have magnetospheres unlike any yet studied in detail, with 59° and 47° tilts of their magnetic axis from the spin axis respectively. Uranus, with its spin axis nearly pointing to the sun for some portions of its year such that it rolls about its orbit, consequently has a unique solar wind-magnetosphere interaction. Neptune's magnetosphere is known to produce aurora, and the tilt of the magnetic pole could result in time-dependent induction effects on its large moon Triton, which is theorized but not yet known to contain a liquid ocean. Both ice giants emit powerful radio emission from their auroral zones.

Exoplanetary Magnetospheres: The planets of our solar system display a range of different space environments and solar interaction regimes, from non/weakly magnetized, to magnetized with solar wind-driven convection, to rotation-dominated magnetospheres. All magnetized planets with an appreciable magnetosphere are immersed in a dynamic energetic particle (hot plasma), as well as cold plasma environment. Within our solar system these planetary magnetospheres (Earth, Jupiter, Saturn, Uranus, and Neptune) are also significant emitters of low-frequency radio waves that are consistent with a cyclotron-maser instability set up in a field-aligned current region.

Terrestrial Auroral Kilometric Radiation (AKR) emissions in the ~30-800 kHz range have long been known to be associated with auroral intensifications and magnetospheric substorms. In a similar fashion, recent remote imaging using Energetic Neutral Atoms (ENAs) obtained by the Cassini mission have revealed that the periodic Saturn Kilometric Radiation (SKR) emission from Saturn's high-latitude magnetosphere is highly correlated with simultaneous large-scale injections of energetic particles in the night side magnetosphere. These observations imply that the engine behind the AKR and SKR is a current system associated with the planetward fast plasma flows during an injection and/or the resulting plasma pressure gradients of the heated plasma.

Radio observations in the <200 MHz range is so far the only technique that shows promise to provide constraints on the magnetospheric processes of exoplanets and their stellar-wind interaction. In this presentation we will show the relation between radio emissions and magnetospheric acceleration processes in our own solar system as a laboratory to determine what remote radio observations of exoplanets may tell us about magnetospheric processes. These observations could provide valuable insight into which exoplanets have magnetospheres and hence have some protection from their stellar-wind.

PLANETARY PITS AND CAVES: TARGETS FOR SCIENCE EXPLORATION W. L. Whittaker[1], P. J. Boston[2], G. Cushing[3], T. N. Titus[3], R.V. Wagner[7], A. Colaprete[2], J. Haruyama[4], H. L. Jones[1], J. G. Blank[2], R. P. Mueller[5], J. D. Stopar[6], W. Tabib[1], and U. Wong[2]. [1]Carnegie Mellon University, Pittsburgh, PA 15213, [2]NASA Ames Research Center, Moffet Field, CA 94035, [3]USGS, Flagstaff, AZ 86001, [4]JAXA, Sagamihara City, Kanagawa, Japan, [5]NASA Kennedy Space Center, Orlando, FL 32899, [6]Lunar and Planetary Institute, Houston, TX 77058, [7]Arizona State University, Tempe, AZ 85287.

Introduction: Planetary pits, caves, and voids differ fundamentally from their well-studied counterparts of features and phenomena on surfaces. Since caves and voids can't be visually observed from orbit, and no landed mission has yet targeted a void, many great discoveries are yet to come. Questions of origins, geology, mineralogy, stratigraphy, gravimetry and aging abound. Caves are enticing destinations for seeking evidence of life on Mars. Pits and caves are advantaged destinations for exploration and future human presence. Voids are compelling in their own right as pristine time capsules and as stepping stones for exploration beyond. The need is to discover and characterize pits by developing search methodologies that combine visual, topographic, gravimetric and radar sounding techniques. Landed missions will characterize spatio-physical, mineralogic, geologic, and volatiles studies with access, resolution and quality not possible from orbit. Robotic exploration techniques will ultimately explore caves, seek evidence of life, determine suitability for habitation, and pave the way for human presence [1].

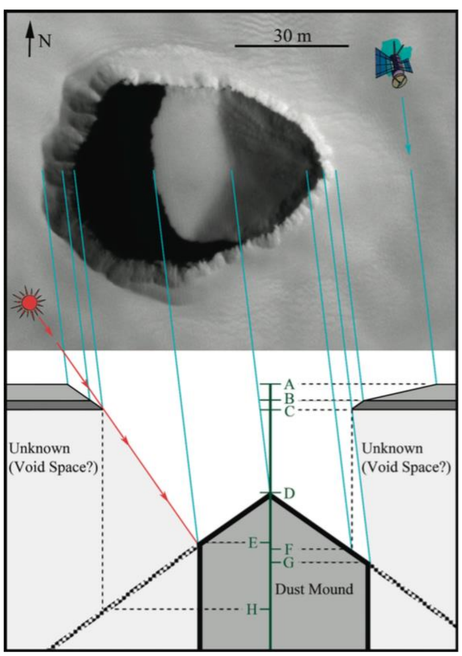

Fig 1. Pit on Mars in HiRISE: ESP_014380_1775 showing overhang that could indicate a larger void space [16].

Pits, Caves and Voids: Hundreds of astounding, diverse pits and candidate cave-entrances are being revealed by Mars Reconnsaince Orbiter (MRO) [2,3], Mars Express, Lunar Reconnaisance Orbiter (LRO) [4,5], MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) and SELenological and ENgineering Explorer (SELENE) data. Other missions, e.g. Cassini and Dawn, have identified terrains on Titan, Vesta, and Ceres that intimate evidence of pits and voids. Some imagery reveals cavernous portals that extend from pits, perhaps into extensive caves. Although existence of lava tube networks and voids were postulated many years before the orbital imaging of pits, no means of cave access was previously known (SELENE). Discoveries of skylights shattered that view. LRO and MRO now both observe caverns that depart from pits. Newest evidence identifies the first polar lunar pit that may contain pristine volatiles. Gravity Recovery and Interior Laboratory (GRAIL) data have revealed an immense submerged void that is half the size of Manhattan [6]. Relevance for exploration and new discoveries from Mars, Mercury and the Moon are springboards that compel subterranean science and exploration campaigns in pits, caves and voids.

Science: More is unknown than known about the origins, morphologies, volatiles, mineralogy, gravimetry, stratigraphy, thermal transients, and aging of planetary pits and caves. Little is known about questions of water, life and suitability for habitation, since caves hold their secrets unseeable from orbit and no landed robot mission has ventured even to (let alone into) a first pit.

There is great need and opportunity to investigate, model, and correlate mechanisms of formation and post-formation events of pits and voids. These include substantial features of collapse, scree, granular flow, and meteorite weathering that age skylights over billion-year timeframes. Analysis must innovate modeling means for billion-year cycles from void solidification through collapse formation and subsequent events and bombardment over deep time.

There is great opportunity to investigate volatiles and unique secondary mineralogies expressed on cave surfaces [7]. Volatiles studies for pits and caves will have to innovate models and lab recreations of accretion on relatively pristine surfaces versus volatile distribution in the deep regolith so common on planets and moons. Ultimately, robotic methods will be needed to study these phenomena in situ.

The greatest opportunities might relate to subterranean access. To date subsurface robotics has meant meter-scale drilling. Pits and caves will reveal billions of years of geologic column and history by merely accessing and descending. Water and volatiles not viable at the surface might be expressed at the depth of some caves. The ultimate scientific agenda might be lifeseeking that is favored by the protections from radiation, thermal extremes and impacts that pits and caves provide.

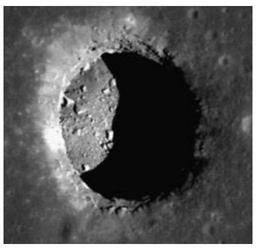

Fig 2. Mare Tranquillitatis pit, seen in LRO: M126710873R, was shown to have a subsurface void that extends 20m under an overhang [5].

Exploration: There is great opportunity and need for methods and campaigns of discovery and characterization that are possible from orbit, and moreso from surface missions that will land, view, enter and explore. New search and characterization methods will fuse visual, gravity, radar and topography phenomena to discover voids and features beyond what is possible by any single mode.

The need is to develop and deploy subsurface robotic exploration methodologies to access, observe, and measure scientific and geologic phenomena in pits and caves. Subplanetarian explorers will enter pits/caves, model features with orders-of-magnitude better coverage and precision than possible from orbit, and conduct otherwise infeasible science, sampling and in-situ analysis. This requires a technological leap beyond surface roving. New technologies will achieve flyover, apron viewing, and extensive robotic caving. Cave robots will rappel [8,9], climb [10], hop [11], and fly [12].

Missions: Missions specific to cave exploration include orbital, surface, spelunking, science and habitation precursors [13]. Visual, gravity, radar sounding and topography data from orbit (coupled with characterization and search methods) are already our eyes for pit and cave discoveries. Missions are needed with multimodal sensing and investigations specific to void discoveries and characterization. Since pits are point features, not regions, precision landing is a pivotal technology for surface and subsurface exploration. Early robotic missions can make great discoveries and perform significant science by traversing around rims and crossing tubes. The great leaps are achieved when descent, autonomy and energetics for robotic caving are brought to bear in missions. Once robotic caving is an exploration capability, campaigns of missions will perform subplanetarian science, lifeseeking and precursor agenda for habitation.

Utilization: Pits and caves may offer natural, unparalleled protection from hazards of radiation, thermal swings, and meteorites [14]. These are significant advantages to any human exploration that aspires beyond flags and footprints. Sci-fi, Hollywood and pit discoveries commonly and superficially cite advantages of caves for habitation. However, no rigorous evaluations are yet possible to determine habitability. This will doubtless include amenability for deployment and protection from launch/landing ejecta in addition to the more obvious issues of access, thermal, radiation, morphology, structural integrity and proximity to landing site [15]. All of this will require precursor robotic reconnaissance.

A mammoth void has recently been identified [6]. It is submerged at several hundred meters on the moon adjacent to a nearby pit. If access is somehow discovered or created, such a void could host a settlement half the size of Manhattan. Analogous wonders from pit chains to skylights appear at other destinations. Mere existence transforms the futuristic view of subsurface science and escalation of the habitation vision from accommodating a few astronauts to sustaining metropolis-scale populations.

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Routine and Recurring Economical Delivery of Missions RAREDOM to Beyond Earth Orbit Destinations.

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Introduction: Forty seven years after the Apollo 11 lunar landing - There exists today an inability for NASA to routinely deliver payloads (either experiments, R&T payloads, or scientific payloads) to space (other than to the ISS destination) on a recurring cost-effective manner., Therefore, a national need exists today for an acceptable approach to satisfy this functional deficit (delivery of payloads to LEO, GEO, or Beyond Earth Orbit (BEO)) at an economic cost point that will provide a positive net savings of ~$125 mil/year to the agency, while enabling 800% more scientific and R&T payloads to be injected BEO. Today's NASA establishment may state that the above outcome is improbable; but, our team will provide actual analysis and data to justify that such a system could be fielded in five to ten years. This cost effective space architecture will be an excellent return on investment to our nation, the US taxpayers, scientists, NASA Science and Research & Technology (R&T) investigators and STEM students throughout the USA and will enable/provide much greater scientific returns then we currently achieve.

Note, the crux of the problem that this RAREDOM architecture will be addressing is not in the contracting of the commercial ETO launch vehicle families, nor does it reside with the launch vehicles themselves, but actually utilizes the commercial launch services industry to the maximum extent possible to reduce cost for BEO payloads. The current Mission Operational culture at NASA is grounded in an established manner of doing business in the same manner as was done in the 1960's and 1970's (NASA Announcement of Opportunity (AO) calls generally have the primary payload being launched on a dedicated launch vehicle provided by NASA's Launch Service Providers Office at KSC. Figure 1 shows the past ten years of NASA's BEO launches. The average scientific payload for 10 of the 11 missions was 72 kg. For this problem to be solved effectively a paradigm shift on how NASA effectively does mission operations will be required and this proposed RAREDOM architecture will establish the factual basis to begin this process shift.

Todays BEO Problem: Currently, when NASA releases an AO call, this is in response to specific national science communities needs and there usually is a particular scientific destination (i.e., Mars, Phobos, Venus, lunar, etc.) that is sought.

List of NASA Orbiting and Flyby Spacecraft Launched 2006-2016

Mission Name	Launch Date	Target	Flyby/Orbiter	Spacecraft Wet Mass [kg]	Spacecraft Dry Mass [kg]	Payload Mass [kg]
LUNAR						
LRO	6/18/2009	Moon	Orbiter	1916	1018	**93**
LCROSS	6/18/2009	Moon	Impactor	891	858	**27**
GRAIL	9/10/2011	Moon	Orbiter	306	200	**20**
LADEE	9/6/2013	Moon	Orbiter	383	248.2	**50**
HELIOCENTRIC						
DSCOVR	2/11/2015	ESL-1	Orbiter	573	428	**86**
STEREO A/B	10/26/2006	Heliocentric	--	654.5	547	**149**
Kepler	3/7/2009	Heliocentric	--	1052.4	1040.7	~~**478**~~
OTHER						
New Horizons	1/19/2006	Pluto	Flyby	478.3	401	**30**
Dawn	9/27/2007	Vesta/Ceres	Orbiter	1240	815	**35**
Juno	8/5/2011	Jupiter	Orbiter	3625	976	**174**
MAVEN	11/18/2013	Mars	Orbiter	2454	809	**65**
			Average Payload Mass w/o Kepler (kg)			**72.8**

Figure 1: NASA's Beyond Earth Orbit Missions over past 10 years

Then the various scientific proposal teams develop proposals to this AO and when selected they build the set of instrumentation that becomes the payload for a spacecraft that must be acquired and then is launched via the Launch Service Providers Office at KSC. The total mission costs are not well established as the costs of the launch is underwritten by another NASA Directorate.

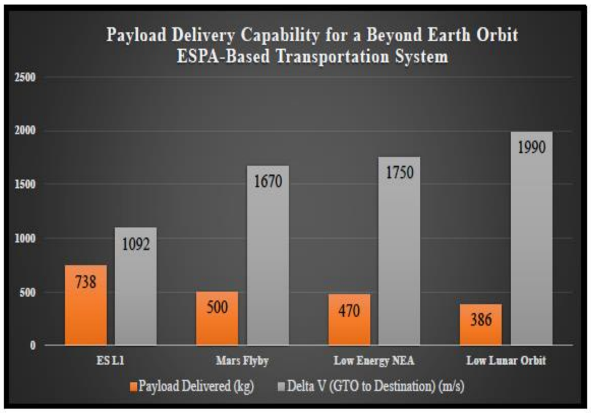

Figure 2: Payload delivery capability to various BEO destinations

The Solution: The RAREDOM architecture would utilize commercially available components from avionics, valves, propulsion systems, and ELVs, combined with the Expendable Secondary Payload Adaptor (ESPA) to develop an in-space transportation system based upon the ESPA ring structure that could deliver over 700 kg of scientific payloads (see Figure 2 above) on a single mission of discovery. In addition to the agency coming out with selected AO calls, the agency would also field one of these BEO spacecraft's per year to various destinations as needed. By having routine missions of payload delivery to various deep space destinations orders of magnitude of science returns can be achieved for the same or much less cost of doing business now. The estimated total mission cost to fabricate an ESPA spacecraft and launch it to a BEO would be in the $50 to $80 million dollar range or $70k to $115k per kg of payload. And that includes the launch costs. These costs do not include the payload costs or payload integration costs. But the payload integration costs would be a fraction of today's costs as the payloads would be designed to fit within various standard interfaces.

System Operations: One example of how this system would operate is as follows. In year #1 NASA would procure an ESPA in-space transportation system and its destination would be the Earth Sun L1 Lagrange point, NASA would have the capability to send 738 kg of payloads to this location. Note, this payload mass is ~10 times greater than a payload that was flown before on a single dedicated mission architecture (Figure 1). Imagine the scientific returns, instead of selecting only a small handful of the scientific proposals submitted, by offering a ride of up to 738 kg. The agency could enable many more researchers and technologists to actually fly their payloads to BEO destinations. Then in year #2 the destination may shift to a Mars Flyby type of mission, in Year #3 it could be a low lunar orbit mission or a near Earth asteroid mission and then the cycle would repeat.

Conclusions: By having the agency procure in-space transportation options based upon the ESPA structural hardware for 10 years forward, the US scientific, educational, and government researchers would be enabled to do up to ~ 900% more science (738 kg/72 kg) per opportunity for a savings of ~$100 million per GTO launched ESPA versus todays standard methods of business via a dedicated spacecraft on a dedicated launcher.

MSFC and Moog Space have been working on this particular architecture for several years and both parties believe this architecture investigation as a NIAC Phase I awarded grant would shine the light on what is possible and deliver major return on investments. By performing this architectural analysis under the NIAC umbrella, the agency could then direct future missions of discovery to take this approach as an alternative to today's current methods of payload delivery BEO.

Today's inability is solved by interjecting cost effective methodologies to leverage the future planned NASA and US government launches as well as selected commercial launches to the fullest potential possible via the addition of a propulsive rideshare spacecraft (RAREDOM) whose heritage began with the USAF's Expendable Secondary Payload Adaptor (ESPA) and now marketed by Moog Inc.. This RAREDOM payload delivery architecture would enable recurring delivery of ~600 kg of payloads per launch opportunity to destinations BEO when co-manifested with a satellite on a Geostationary Transfer Orbit (GTO) trajectory.

NOVEL PLANETARY SCIENCE ENABLED BY NETWORKED CONSTELLATIONS. E. J. Wyatt[1], J. C. Castillo-Rogez[1], S. A. Chien[1], L. P. Clare[1], A. A. Fraeman[1], S. J. Herzig[1], I. A. Nesnas, J. Lazio[1]. [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA (e.jay.wyatt@jpl.nasa.gov).

Introduction: To date, planetary science investigations have largely been conducted with point measurements. Notable exceptions include lunar laser ranging to the Moon, for both studies of the lunar interior and testing theories of gravity, the rovers on Mars, which are able to collect measurements at a distributed set of locations, and GRAIL's measurements of the lunar gravity field. With the emergence of small platforms (CubeSat and other form factors) enabled by advances in electronics and miniaturized instruments, distributed sets of sensors will enable the realization of novel science that requires distributed measurements and push the boundaries of exploration. Ambitious concepts for "fleets" or "constellations" of spacecraft are beginning to be deployed, with additional concepts in development for terrestrial applications. Multi-satellite missions have also been embraced in various solar and space physics applications. The science potential offered by these architectures has not really permeated either Astrophysics or Planetary Science—except for the special case of the GRAIL mission, but is poised to become a prime form of exploration over the next three decades.

The recent NRC report "*Achieving Science with CubeSats: Thinking Inside the Box*" [1] has highlighted constellations as science enablers, which is the thrust explored by this abstract. Constellation architectures may also aid Human exploration for reconnaissance and then local telecommunication infrastructure. An essential element of many of these concepts is that the "whole is greater than the sum of the parts"—the science return is enhanced only if the measurements from the individual sensors can be combined, but intra-constellation communication and coordination is often identified as a key challenge for these concepts and even more so for deep space missions that are frequently resource-constrained. This abstract summarizes the state of thinking in constellation architectures as a means to address the 2050 Vision themes and pave the way for Human exploration of the Moon, Mars, and asteroids.

Key Science Applications: The main application areas include: (a) Distributed measurements (homogeneous and heterogeneous) for increased spatial and temporal sampling, (b) multi-satellite architectures, (c) communication network for relay, (d) task distribution.

Distributed Measurements would especially benefit science based on fields and particles, for example when tracking the response of a magnetic field induced in the salty oceans of the Galilean satellites as a function of latitude and true anomaly. As another example, knowledge of the interior structure of near-Earth asteroids addresses the Origins theme and Threats & Resources theme by informing approaches for planetary defense and for *in situ* resource utilization as well as providing potential targets for human exploration. These bodies are generally too small for casual gravity science via radio-tracking. A GRAIL-like observation strategy involving many sensors could be used to capture that information. Communication between assets is used to increase position knowledge accuracy.

In the same vein, radio-occultations among multiple spacecraft can address the Workings theme by monitoring atmospheric conditions (e.g., temperature, dust content). This approach is analogous to radio occultation constellations using the Global Positioning System (GPS) signals on Earth, and could be used at any body with an atmosphere. Targets that have been considered include Mars, Venus, and an ice giant (or giants). Such investigations may also prove important in preparation for crewed exploration of Mars.

Multi-Satellite Architecture for in-depth study of a planetary body may involve surface and above-surface assets as well as one or several orbiters. The relay network established by the set of Mars orbiters is already critical to returning data from Martian landers and rovers and provides first glimpse of what a future multi-asset network at a planetary body might be. Such networks could address the Workings theme, potentially the Origins theme, and, at Mars, potentially the Life theme. The real-time sharing of information among assets would facilitate autonomous *in situ* decision-making, enabling new science and more effective and productive operations. This is particular critical for systems that operate in dynamic environments, where Earth-bound communication cannot meet the need response time. Examples include the exploration of bodies such as Titan, Venus and Mars using above-surface assets. Rotorcrafts, balloons, or aerobots would critically benefit from weather information gathered by the accompanying orbiters and landers. The Titan and Saturn System Mission concept included a combination of Montgolfier, lander, and orbiter. In the same vein, fractionated payload, i.e., the distribution of instrumentation among assets exploring different regions of a given body, can increase science return by optimizing science capture in a short timeframe. Networking between assets may be used for autonomous positioning as well as for enabling synchronized science acquisition. An example of application is the data (particle density, vapor production, etc.) that can be obtained from multiple vantage points of dynamical processes to support the quest for habitable environments and biomolecules in the case of icy satellites (Life Theme) and more generally understand the physics of these processes and they information they bring on the interiors of comets and asteroids (Origins and Workings Themes).

Communication Network for Relay is critical to the exploration of sites with limited or no line-of-sight to a mothership. Much like multi-satellite architectures, relay communications may be an essential aspect of future missions to address the Origins, Workings, and Life themes. Relay communication is already routinely used at Mars. The discovery of caves both on Mars and the Moon and suspected at Titan opens new directions in the search of habitats for human exploration and past or extant life forms. The reconnaissance of these areas should become of primary importance in the future and requires special strategies for exploration in highly resource-constrained conditions and challenging communication configurations. An asset wandering in a cave would have to rely on intermediate relay nodes to eventually channel the information back to Earth. This network would also help in the localization of the exploring assets.

Task Distribution between assets for increased science return and decreased operational complexity. This includes scouting by small assets traveling with a larger platform such as the Mars Science Laboratory. The Mars Helicopter currently under study is an example of asset that could provide a general overview of the environment and science targets of a future rover to Mars to help pave the journey forward. A follow-on architecture could involve several small scouting rovers with minimum reconnaissance payload who explore in advance of the larger platform and may relay their information based on the autonomous, on-board prioritization of their findings.

Technological Roadmap: A key game changer for deep space constellations is the introduction of advanced deep space CubeSats. JPL introduced deep space CubeSat with the INSPIRE and Mars Cubesat One (MarCO) pathfinders; notably INSPIRE will demonstrate inter-CubeSat relay in deep space. Low-cost nano-satellite, even more so with the CubeSat form factor, have easier access to space and may replace decaying assets in constellations in order to enable long-lived missions. On the other hand, limited communication capability in turn requires agile strategies for increased science return. Autonomous operations that include self and situational awareness and onboard decision-making and control are key to maximizing operations in challenging and resource-constrained environments. While autonomy for deep-space missions can leverage in part the advances developed in the private sector, it also requires in-depth thinking to address challenges specific to planetary exploration, for example with regards to fault protection and resilience against the many unknowns that may occur throughout the lifetime of the mission. Automating relays by implementing networking functionality is another important technology for lowering operational cost, improving data return, and enabling autonomous coordination among assets.

Acknowledgements: This work is being carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA.

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CHARACTERIZING ASTEROID INTERNAL STRUCTURE THROUGH TECTONIC ANALYSES. D. Y. Wyrick[1] , D. L. Buczkowski[2], and D. D. Durda[1], [1]Southwest Research Institute (6220 Culebra Rd, San Antonio, TX 78238; dwyrick@swri.org; durda@boulder.swri.edu), [2]Johns Hopkins University Applied Physics Lab (Laurel, MD 20723; debra.buczkowski@jhuapl.edu).

Introduction: Asteroids are thought to be the source bodies of the majority of meteorites on Earth [1,2] and are likely leftovers from the formation of the solar system [e.g., 3,4]. It is this direct relationship between meteorites and asteroids that reminds us all that understanding small bodies in our solar system is critical toward understanding the threat they may pose for Earth. In particular, characterizing the mechanical strength and internal structure of asteroids is needed in order to effectively mitigate, divert or destroy them as a potential impactors. Recent analyses of the tectonic deformation and geomorphology of small bodies provides important insights into the subsurface processes and geologic histories of these small bodies, which in turn provides constraints on their internal porosity, composition, and coherency. Critical data gaps remain in observations, however, namely high resolution imagery, topography (shape), gravity, and momentum transfer data that provide critical information on internal structure. Top priority should be considered for high quality data products from these smalls bodies in the coming decades through a combination of single and multi-spacecraft missions, as well as flyby opportunities on other missions.

There are three types of meteorites: irons, stony-irons, and stones, which are further subdivided into ordinary chondrites, carbonaceous chondrites and achondrites [e.g., 5,6]. Ordinary chondrites are the most common type of meteorite [e.g., 6,7]. However, reflectance spectroscopy of asteroids indicates that ~75% of all known asteroids are the carbon-rich C-type asteroids [8], which most closely resemble carbonaceous chondrites spectroscopically. S-type, or silica-rich, asteroids comprise less than 17% of known asteroids [8] but may be the source of the ordinary chondrites. Theoretically, the density of an asteroid can be used to determine its composition. An asteroid density close to 5 g/cm3 should be indicative of a stony-iron composition [9], while a density close to 3.3 g/cm3 should be more consistent with an ordinary chondrite [9,10]. However, the densities of S-type asteroids are less than 3.3 g/cm3 [e.g., 11,12], which may be due to the internal structure of the asteroids.

There are four states of asteroid internal structural modification [13]: 1) completely coherent; 2) coherent but fractured; 3) heavily fractured (e.g. [14,15]); and 4) rubble pile (e.g. [16,17,18]). If the bulk density of an S-type asteroid is lower than the measured density of comparable ordinary chondrite meteorites (~3.3 g/cm3), the asteroid likely has a high porosity inconsistent with a completely coherent asteroid [12]. The presence of long structural features on the surface of an asteroid is indicative of significant internal strength despite low density values, as the body must be coherent enough to preserve tectonic deformation [20]. Since small solar system bodies (<200 km radius) don't have sufficient internal heat energy to drive terrestrial-style tectonics [19], determining how these features formed yields important information about their nature and the geological history of such lineated asteroids.

Motivation: A recently published paper [20] provides the most current review of the nine asteroids that have been visited by spacecraft to date. These asteroids — 951 Gaspra, 243 Ida, 253 Mathilde, 433 Eros, 25143 Itokawa, 2867 Steins, 5535 Annefrank, 21 Lutetia and 4 Vesta — span the range of internal coherency, from rubble piles to solid and potentially mechanically strong bodies. Their analyses focus on the tectonics of the asteroids, models of linear structure formation, and implications for the internal structure of the asteroids. This provides a framework to consider the data needed to characterize the internal structure of potential impactors in the coming decades.

Asteroid lineaments observed by spacecraft on small bodies appear to have several different origins, and are indicative of variable interior structures. Lineaments on Itokawa (an S-type asteroid; [21]) have been associated with boulders and are consistent with the excavation of regolith by boulder movement on a "rubble pile" asteroid [22]. Many of the linear structures, such as those on Ida (S-type; [23]), Eros (S-type; [24]), Lutetia (possible E-type; [25]) and Vesta (V-type, [24]), appear to be due to impact [26,27,28,29, 30, 31], but some lineaments have no obvious relationship to impact craters. For example, pitted grooves on identified on Gaspra [32] as well as some of the linear structures on mapped on Eros [29] are indicative of a coherent asteroid with inherited structural fabric from a parent body [33]. Pervasive subsurface fracturing can also be distinguished by the polygonal shapes of some craters on Mathilde, Eros and Lutetia [29,34,35].

Vesta represents the other end member of asteroids as a fully differentiated body [31], with a mantle and core [36]. Vesta presents an intermediate style of tectonic deformation, with fractures and grooves similar to those observed on other asteroids, as well as large-scale graben and trough structures more characteristic of tectonics on terrestrial planets. Vesta, being a differentiated proto-planet, is a unique body with which to study the roles played by internal rheologies and structures on the surface expressions of tectonism. Unlike many terrestrial planets, Vesta's main stressors have been primarily exogenic (i.e. impacts) rather than internally driven. The asteroid Lutetia is thought to be partially differentiated [37], but it lacks the tectonic signatures of Vesta, likely due to Lutetia's lower density contrasts and undifferentiated core [20]. It is therefore clear that determining how linear features formed on these asteroids yields important information about their internal structure and strength, as well as on the nature and history of the asteroid itself. Note that the largest asteroid in the solar system, 1 Ceres, has not been considered here, as its status as a likely differentiated ice-rich dwarf planet places it beyond the size range we consider for impact threats. However, Ceres shares several tectonic features with the other smaller bodies considered here including pit chains and polygonal craters which provide insight into the near subsurface structure [38,39].

Conclusions: As a group, asteroids represent some of the earliest remnants of the early solar system. Deciphering the tectonic histories of these bodies provides insight into the complex dynamical and geological history of the inner solar system. Our understanding of asteroid composition and structure has grown exponentially in the last few decades, leading to improved recognition and classification of asteroid characteristics based on strength and cohesion (i.e. solid bodies versus rubble piles). These initial observations and analyses all suggest structurally complex asteroid interiors. Understanding the heterogeneous nature of an asteroid's coherency and internal structure is needed in order to develop effective mitigation strategies for potential meteorite impact threats in the future.

Future Needs, Vision 2050: Priority should be placed in the next 10-20 years toward increasing the number of up close observations beyond the current nine asteroids to better characterize the range of potential impactors, including flyby opportunities on other missions. Within 20-30 years, asteroid divert/destroy demonstrations will be required to gain confidence in mitigation strategies. Future mission designs should retrieve high resolution image and shape data, in addition to spectral and gravity measurements, to characterize asteroid coherency. The recent decision by the European Space Agency to forego development on the Asteroid Impact Mission (AIM) severely curtails the data that can be collected from NASA's planned Double Asteroid Redirection Test (DART), and represents a loss of critical impactor information such as momentum transfer and internal strength. Future exploration should also consider joint multi-spacecraft collaboration built around understanding the physics of impacting an asteroid *in situ*.

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MARS TERRAFORMING - THE WRONG WAY

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The forecasting of the scientific research progress is possible for the applied aspects in case of understanding the general plan of specific activities development. The space research prospects should follow the human doctrine in space, which is quite simple: a man's leaving Earth and reclamation of new space home. This "new home" also is the key question. It is usually associated with the creation of colonies on the surface of Mars and planetary satellites. However, a radical obstacle to this is the unavailability of human beings to live in conditions of the reduced gravity of the Moon and Mars, being in their earthly bodies, at least in the next decades. The hope for the medicine development will not cancel the physical degradation of the muscles, bones and the whole organism. The rehabilitation in centrifuges is less expedient solution compared with the ship-biosphere where it is possible to provide a substantially constant imitation of the normal gravity and the protection complex from any harmful influences of the space environment. If the path of space exploration is to create a colony on Mars and furthermore the subsequent attempts to terraform the planet, it will lead to the unjustified loss of time and money and increase the known risks of human civilization.

The nearest challenge on our way to the Outer space besides the more perfect carrier creation and resources investigation is maintenance of the high-grade environment for life in space houses – the search of an optimum size, design and bacterial stability of the separate biosphere biocenosis, the development of the interact families of these biospheres. Simply speaking it is necessary to provide a certain comfort for the people's life in the space. It will allow to replace military pilots with experts of necessary professions and to form viable space colonies. It will allow not only to operate effectively the robotized investigation of space objects from a board of space biospheres but also to develop scientific researches by space colonies themselves.

It is obvious that the main barrier which is necessary for overcoming in space is not disembarkation to planets and satellites but a birth of viable full-grown generation of space children.

Already now we see the role of the basic catalyst of a wide human exit in the Space will be carried out by commercial activity of the arising space consortia especially in sphere of the space resources extraction. Owing to it the influence of political and other factors on the outer space exploration development is minor.

Considering the aforesaid the nearest prospects of the applied scientific workings out in the field of studying and the outer space exploration till 2030 can be connected with following directions:

- The designing of the first space biospheres with artificial gravitation will demand scientific implementations in the spheres of material technology, life-support systems, the protection, the robotized complexes for installation and service of the infrastructure elements in the outer space.
- At the first biospheres constructed in the low terrestrial orbits it is urgent to begin the reproductivity research in the space conditions on mammals.
- The prospect of disembarkation on Mars insistently demand the concept of planetary protection. It is connected and with the life searches on Mars and Europe. At the same time the actual problem is the water investigation on the Moon poles, the low latitudes of Mars and asteroids. At a sight of the author the most perspective places for the life search and water extraction in the low latitudes of Mars are big hydrolaccoliths [1,2]. And the Martian slope streaks studying [3,4], probably, will lead to the technology of fresh water receipt without power expenses.

- The preparation for the big biosphere building for the first colonies demands working out of the new effective vehicles first of all for the raw materials and constructions delivery from the Moon surface.
- The resources investigation of the asteroids and the most accessible objects of Solar system demand the universal robots-scouts creation.

In 2030-2050 following the logic of the biosphere idea development it is possible to expect:

- the building and testing of the inhabited biospheres in the low orbit of Earth, their transfer and modular integration in the orbit of the Moon with the resource maintenance with the lunar and asteroid material.
- it will be the most actual the medical and biologic researches onboard biospheres directed on the maintenance of valid development of children born in space.
- it will be required the reliable space shuttles for the communication of the orbital colonists with the Moon and Mars surfaces where stations for short-term stay of experts will be under construction. There also will be developed the extraction, raw materials processing and biosphere constructions manufacturing and space transport.
- during this period the same robotized complexes are reasonable to create on Phobos and on one of the asteroids with the extended orbit which will play also a role of the main space bases and the cosmodromes.
- the prospect to find a planet with the conditions similar to Earth which surfaces can be used as inhabited spaces can appear under condition of the tool perfection for the studying of planetary systems of the nearest stars.

The settling in Solar system and the development of its resources will continue some centuries but already in second half of this century prior to the beginning of the development of a belt of gas planets and objects of Kuiper belt the humanity will be technologically ready to go to other star systems on the big independent biosphere which design will be prepared by the previous experience of the space houses building.

Thus, the prospects of the applied space science on the nearest future will be inseparably connected with the arrangement of the new house for people – the space biospheres.

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DEVELOPING SCIENCE OPERATIONS CONCEPTS FOR THE FUTURE OF PLANETARY SURFACE EXPLORATION.

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Introduction: Through fly-by, orbiter, rover, and even crewed missions, National Aeronautics and Space Administration (NASA) has been extremely successful in exploring planetary bodies throughout our Solar System. The focus on increasingly complex Mars orbiter and rover missions has helped us understand how Mars has evolved over time and whether life has ever existed on the red planet. However, large strategic knowledge gaps (SKGs) still exist in our understanding of the evolution of the Solar System (e.g. the Lunar Exploration Analysis Group, Small Bodies Analysis Group, and Mars Exploration Program Analysis Group). Sending humans to these bodies is a critical part of addressing these SKGs in order to transition to a new era of planetary exploration by 2050.

Background: The Apollo missions are the only example of conducting crewed in situ science on another planetary body. These were characterized by careful traverse planning and execution, sample collection with basic technologies (e.g. scoops, rakes, bags, etc.) and deployment of in situ science experiments (e.g. Apollo Lunar Surface Experiment Package). Although these missions were a resounding success by collecting samples and other data that improved our understanding of the lunar geologic history, multiple technological advancements in the four decades since Apollo will enable higher-resolution analyses in situ during future exploration missions.

These technology developments will enable increased mobility, communications structures, and real-time data processing and viewing capability. All of these factors introduce not only the potential for increased science return, but also operational complexity that must be accounted for and incorporated into mission concept and procedure development. Technology development and the associated procedural development for future science operations is already underway through multiple operational campaigns that build off both Apollo and ongoing integrated operational tests, and it is these tests which will close outstanding SKGs (for Science, Technology, and Science Operations) and enable human planetary exploration before 2050.

RATS (Research and Technology Studies) and NEEMO (Extreme Environments Mission Operations (NEEMO) testing have identified crucial Science Operations knowledge and technology gaps that must be closed prior to future planetary exploration. The complementary RIS[4]E (Remote, In Situ and Synchrotron Studies for Science and Exploration) project focuses in on one important area: the use of high-resolution field portable instruments in crewed exploration.

Planetary Surface Mission Operational Testing: The RATS tests (1997-2012) provided an ongoing testing platform for technology (e.g. habitat rovers, space suits, tools, etc.), operational concepts development, and science operations procedures. From 1997-2011, RATS testing took place in the San Francisco Volcanic Field, AZ, testing procedures for the exploration of both Mars and the Moon. In 2012, RATS testing moved to NASA Johnson Space Center (JSC) to the Space Vehicle Mockup Facility, testing technology and procedures for the exploration of small bodies. Major lessons were learned from the RATS tests:

(a) A science backroom is crucial for supporting scientifically-driven Extravehicular Activities (EVAs);
(b) A crew combining both astronauts (or operational engineers) and geologists is valuable for testing exploration technologies and operational procedures;
(c) It is extremely valuable during EVA to have a crewmember supporting the surface operations from an IV (intravehicular) capacity. However, more work is needed to determine exactly what assets are needed for the intravehicular activity (IVA) crew and how the communications pathways are structured and governed between the EVA crew, the IVA crew, and any terrestrial science support;
(d) Field portable instruments are highly valuable in a planetary exploration mission. Arizona RATS testing included instrumentation in a habitat laboratory to support crews on long duration missions and indicated that field portable instruments can play a valuable role during an EVA to inform scientific discovery.

Science Operational Concepts Development: 21 NEEMO missions have taken place off the coast of the

Florida Keys at Aquarius Reef Base. Crews have lived in Aquarius for as many as 18 days at a time, testing both IVA and EVA objectives as an analog for the exploration of the Moon, Mars, and small bodies. Most recently, NEEMO 21 was run in July/August 2016, and tested a variety of objectives that will have implications for the future of planetary exploration:

(a) It is possible to conduct scientifically-motivated EVA operations under a Mars-appropriate communications latency, with the crew receiving actionable intelligence about science sampling priorities during a single EVA;

(b) The IV crewmember workload is extensive, it is therefore crucial to develop appropriate supporting technologies for an IV crewmember supporting an EV crew;

(c) A ñflexible executionò methodology provides the crew with enough latitude to make deviations from an original traverse plan if real-time feedback indicates added-value, thereby enhancing the science return of an exploration EVA.

Field Portable Technology on EVA: The RIS^{4}E project is a Solar System Exploration Research Virtual Institute (SSERVI) team led by Dr. Timothy Glotch at Stony Brook University. A primary goal of the RIS^{4}E project is to investigate the utility of field portable instruments for planetary surface exploration and provide recommendations to NASAõs Human Exploration Operations Mission Directorate (HEOMD). RATS and NEEMO testing indicated that portable technologies could play a valuable role in exploration, but the logistics of integrating high-resolution instruments are poorly understood. RIS^{4}E is working to close this SKG by identifying a science question of interest, selecting an instrumentation suite to collect critical data, answer the science question, and providing recommendations to HEOMD on how portable instruments are best incorporated into an EVA timeline (Figure 1).

The instrumentation suite chosen for future exploration missions has not yet been determined, so RIS^{4}E has chosen a suite comparable to the types of data and instruments that are likely candidates: an x-ray diffraction instrument, a handheld x-ray fluorescence spectrometer, a multispectral imager, a light detection and ranging instrument, ground penetrating radar, and an aerial-based imager for context and terrain modeling. Field deployment of these instruments is modeled after the 2010 RATS test and is analogous to a likely architecture to be used in future surface exploration:

1. Crewed rover parks at target of interest.
2. Crew initiates remote measurements (including LiDAR, visual imaging, and multispectral imaging). These will be used as context for all other in situ data collected on EVA.
3. Crew egresses and conducts an EVA, deploying portable instruments, and assimilates new data into future EVA and real-time mission planning.
4. Crew ingresses rover, analyzes all collected data from EVAs, and discusses future plans for subsequent EVAs as impacted by real-time data.

While the future science operations architecture has not been finalized, it is probable that the operational concept will look like what is described here, regardless of the target body being explored.

Figure 1: The RIS^{4}E Methodology, focusing on answering science questions about planetary processes through the use of field portable instrumentation, as well as seeks to understand how these technologies would fit into an Exploration EVA architecture.

Conclusions and Moving Forward: Human exploration will be a crucial part of planetary exploration by 2050. While work has begun exploring science operations architectures for a crewed expedition, much more work is needed to test these architectures and develop both the technologies and the operational procedures needed to implement them. One crucial role that has been identified and needs more investigating is the role of an IVA crewmember in support of EVA operations, especially when integrating field portable technologies. Real-time data analysis will be critical and figuring out the crew time and assets needed to do this is a critical knowledge gap that must be closed. Additionally, the range of crew autonomy in exploration scenarios must be considered, with varying degrees of interaction with science support teams playing a potential role in a missionõs science return. Only when these various science operations gaps are closed will we as a community be ready to send human crews out in the Journey to Mars, as is the hope by 2050.

NASA Planetary Science Division Vision 2050 through Human Exploration

Paul Yun, El Camino College, CA

Abstract

Understanding the origin and history of the solar system, the potential for life elsewhere and thus habitability, and the hazards and available resources in space are critical to make human space exploration and human base establishment on celestial bodies possible. The success of PSD missions depends on the success of human exploration. Human exploration of our entire solar system by the end of this century can be achieved through successful PSD missions using commercial solutions and international partnership. The space exploration will result in the technological advancement that becomes a new driving force of economic growth and improves human living condition.

Next 34 years PSD should play the role of the 21st century-version Lewis and Clark Expedition to gather critical information about carefully chosen target celestial bodies in our solar system, to study the possible bio-signatures and habitability, geography, and geology, in situ resources such as propellant methane, oxygen and nitrogen, resources for food growing, and building materials for human bases, and to determine human landing sites and locations for human bases. Next 34 years PSD missions should be a ground work for space exploration in the 2nd half of the 21st century and following centuries so that our future generations can continue to explore space successfully in order to secure the future of humanity.

If the spacecraft can be launched from the Moon human base, Deimos, Phobos or Mars human base, Europa human base, Enceladus human base, Charon human base instead of the Earth, then we can explore the entire solar system more efficiently and economically. PSD missions should be coordinated with the following human missions. PSD missions will make human exploration possible and in return human exploration will justify next level PSD missions and make them more efficient and cost-effective.

Vision and Voyages for Planetary Science in the Decade 2013-2022(2011) identified cross cutting themes, key questions, and missions. In my oral presentation, I would like to propose the following decadal-focus missions in order to achieve PSD sub-goals as well as NASA's goals and eventually national space goals.

2020s focus missions on the Moon and Mars:

(i)Lunar Geophysical Network and other future lunar missions to answer the crosscutting theme building new worlds, to prepare the establishment of human lunar base, to target resource mining sites and to understand what it takes to terraform the Moon

(ii) Mars 2020 mission to find bio-signature and to prepare sample return and human exploration

(iii) OSIRIS-Rex sample return and other future ABO missions to understand available resources, including propellants, to colonize and terraform Mars

2030s focus missions on Mars and Europa:

(i) Mars Astrobiology Explorer-Cacher (MAX-C) or other future Mars missions to assist human exploration on Mars, tentatively scheduled in 2035
(ii) Jupiter Europa Orbiter (JEO) to answer multiple crosscutting themes key questions, to find bio-signature, and to prepare human exploration

2040s focus missions on Europa and Trojan asteroids:

(i) Europa rover and submarine missions to answer multiple crosscutting themes key questions, to prepare human exploration, and to build human underwater base,, which provides warmth and radiation-protection

(ii) Trojan Tour and Rendezvous to answer multiple crosscutting themes key questions, and to find resources to build, operate, and maintain Europa underwater human base and eventually to terraform Europa

I propose that PSD primarily focus on the Moon, Mars, Phobos, Deimos, Jupiter, Europa, and Trojan asteroids in the 1st half of the 21st century and go beyond Jupiter in the 2nd half of the century. In the 1st half century, the small Discovery missions and medium New Frontiers missions may be carried out beyond Jupiter if funding and affordable commercial solutions are available. A substantial amount of success in exploration up to Jupiter in the 1st half century will increase a chance to succeed in the following explorations beyond Jupiter in the 2nd half century, and thus the human exploration of our solar system by the end of this century.

2050s Enceladus Orbiter to answer multiple crosscutting themes key questions, to find bio-signature, and to prepare human exploration

2060s Uranus Orbiter and Probe to understand the properties of exoplanets and to prepare our future generation's exploration to exoplanets

2070s Neptune Orbiter and Probe to understand the properties of exoplanets and to prepare our future generation's exploration to exoplanets

2080s Charon Orbiter to answer multiple crosscutting themes and to prepare human exploration and human base establishment in order to explore KBO

2090s Makemake/KBO Orbiter to answer multiple crosscutting themes, to prepare human exploration and human base establishment in order to explore KBO and to reach out the edge of our solar system

Furthermore, in my oral presentation, I will discuss necessary technologies to make the missions mentioned above possible.

STATUS AND FUTURE OF PLANETARY SAMPLING TECHNOLOGIES. Kris Zacny and Gale Paulsen, Honeybee Robotics (398 W Washington Blvd., Pasadena, CA 91103, zacny@honeybeerobotics.com).

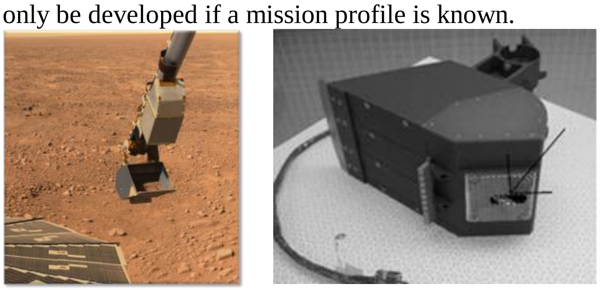
Introduction: Over the past decades, NASA, Industry and Academia have been developing various sampling systems for planetary exploration [1-10]. Sample acquisition is required for numerous missions and especially those seeking signs of present or past life, and mapping geologic history of planetary bodies.

In general, sampling systems can be divided based on required sampling depth. Using a log scale to actually differentiate between sampling systems is quite a reasonable approach. Hence the depth categories are:

- 1 cm scale
- 10 cm scale
- 100 cm (1 m) scale
- 10,000 cm (10 m) scale
- 100,000 cm (100 m) scale
- 1,000,000 cm (1 km) scale

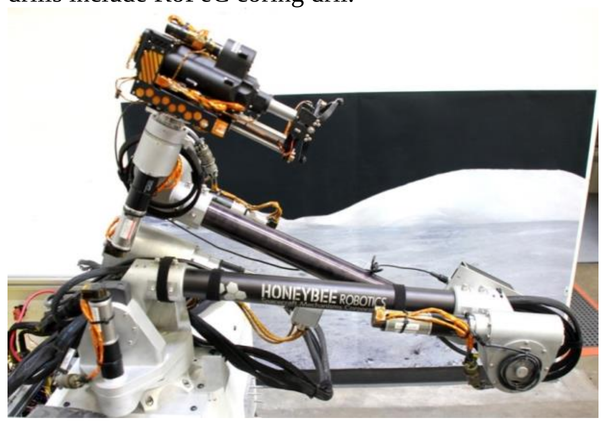
Sampling system has two critical functions: sample acquisition (i.e. excavation and capture) and sample delivery. It is therefore extremely important to consider both of these functions for the mission. Very often sample delivery in fact will drive how a sample can be acquired. Seemingly obvious excavation and sample capture approaches are deemed inappropriate if sample delivery also has to be taken into account. The paragraphs below give examples and current technology status of various sampling systems.

1 cm scale: These systems capture or excavate very near surface material. Since depth is quite shallow, excavator could have numerus shapes. It could be a scoop for loose materials, a harpoon, rotary-brush, a saw or double saw, piercing blades (post-hole digger style), abrading tool, drills and so on. The exact type depends what material will be excavated and what is the required sample type. Flight examples include Mars Phoenix scoop and Venera drill. New systems in this category are mission specific – that is, a system can only be developed if a mission profile is known.



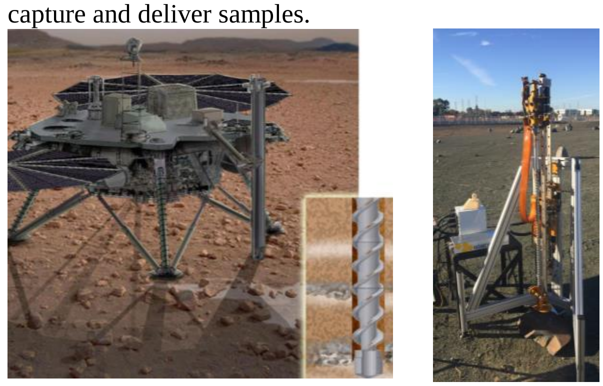
Phoenix Icy Soil Acquisition Device with a Rasp bit.

10 cm scale: At that scale, it is critical to start considering excavation energy. Going deeper means more material needs to be excavated. If material is loose, a scoop could be employed. However, if material is competent and hard, the least energy intensive system is a drill. The drill bit is long and slim and thus can penetrate relatively deep with minimal energy dissipation into a formation. Flight examples include Curiosity drill and Luna16 drill. Examples of current high TRL drills include RoPeC coring dril.



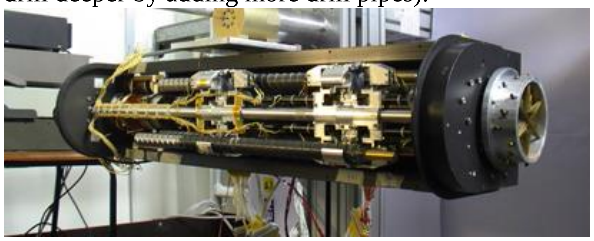
RoPeC Coring drill

100 cm (1 m) scale: These systems have to be in the form of a drill (long and slender); otherwise excavation energy becomes extremely high. In very loose materials, impact moles such as one on the InSight mission could be deployed as well. Flight examples include Luna24 drill and Rosetta Philae drill. The 1 m scale drills are characterized by having one drill string. This significantly reduces drill mass and volume, as well as mission risk. Luna24 was a 2 m drill, but had a single 2 m coring auger. The currently highest TRL drill in this category is Resource Prospector Drill at TRL6. The drill can be used on any planetary body to capture and deliver samples.



Icebreaker/Resource Prospector Drill

1,000 cm (10 m) scale: The drilling systems in this category are characterized by using traditional Oil&Gas drilling approach – they have a carousel to feed drill pipes that form longer drill string. The maximum depth using this approach is highly limited though. Auger torque quickly becomes extremely high and cannot be overcomes easily just by increasing drill power at the drill head. There are solutions to deal with that, but add complexity to the system. Flight example includes Apollo drill which was manually deployed by astronauts. ExoMars drill also falls in this category even though it is rated for 2 m depth (it could feasibly drill deeper by adding more drill pipes).

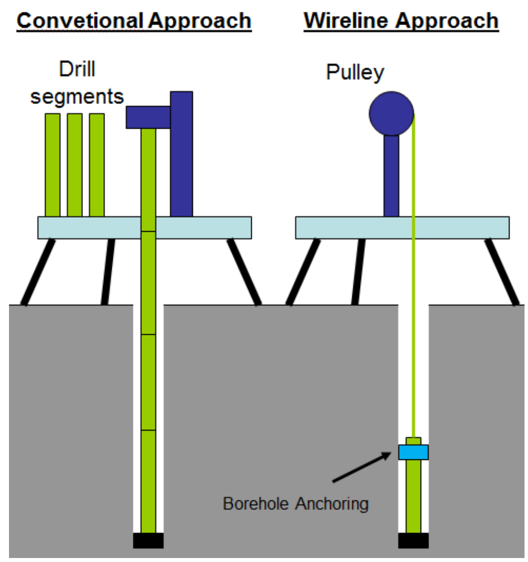


ExoMars Drill

10,000 cm (100 m) scale: This depth range becomes quite significant. To reduce mass and volume of the drilling system, a wireline approach needs to be deployed. A wireline drill is essentially drilling system that is suspended on a tether. To drill deeper, the tether is unspooled from a drum. The drill needs to come out of the hole every so often to deposit cuttings (which can be analyzed). There are no flight examples of such a system. The highest TRL drill is AMNH drill at TRL 4; the system successfully drill to a depth of 13 m. Currently AutoGopher and Watson drills are being developed to reach TRL 5/6. Watson drill has integrated M2020 Sherlock instrument for analysis of borehole while the drill is below the surface (this is a new paradigm in exploration where an instrument is brought to a sample as opposed having a sample being brought to an instrument). For ice drilling, Valkyrie melt probe is also possible provided sufficient power is available.

AMNH Deep Drill

100,000 cm (1 km) scale: This depth range (and beyond) can be captured as the last category. Drills in this depth range need significant surface support. Unfortunately 'clever' design will no substitute proven 'brute' force approach that requires power and mass. Subsurface is an unforgiving environment – it doesn't take much to get stuck. The deepest hole in ice (Vostok) is 3.7 km deep; this took 20 years to complete. The deepest hole in the ground (Kola) is 12 km - this also took ~20 years to complete. It is therefore safe to assume that a deep drilling mission on another planet is equivalent to the Apollo program and impossible with the current technology level.



How will deep drill look like?

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VOLATILE EXTRACTOR (PVEX) FOR PLANETARY IN SITU RESOURCE UTILIZATION (ISRU). K. Zacny[1], P. Morrison[1], V. Vendiola[1], A. Paz, [1]Honeybee Robotics, 398 W. Washington Ave, Suite 200, Pasadena, CA 91103, zacny@honeybeerobotics.com, [2]NASA Johnson Space Center,

Introduction: In Situ Resource Utilization (ISRU) is a term given to any activity that uses local resources to offset or enable the cost of bringing all the resources from Earth. In fact, numerous studies related to human exploration of Mars and the Moon indicated that sustainable human presence cannot be achieved without ISRU [1]. In addition, ISRU plays a significant role in commercial market; numerous companies are eager to mine space resources for commercial gain.

A low hanging fruit with respect to ISRU is volatiles and in particular water. Water can be relatively easily extracted just by heating the material. Water vapor can be captured on a cold finger and either processed or cleaned for different applications or electrolyzed into its constituent components: Hydrogen (H2) and Oxygen (O2). Liquid H2 and Liquid O2 can then be used in rocket thrusters as fuel (H2) and oxidant (O2). If the rocket uses different fuel (e.g. methane), O2 can still be used as primary oxidant.

In a conventional mining approach, feedstock is mined, transported to a processing plant, and valuable resource is extracted. This process is energy intensive and requires significant surface assets to perform different functions. Here, we present an alternative approach. Planetary Volatiles Extraction (PVEx) is an approach that combines mining and extraction into one step and eliminates energy intensive and time consuming “transport” step.

We developed three PVEx approaches: “Sniffer”, Mobile In Situ Water Extraction (MISWE)/Auger, and Corer. All three are drill based, which helps with penetration of frozen material [2].

Sniffer: The Sniffer, shown in Figure 1, is a deep fluted auger with perforated walls. The Sniffer auger is drilled into subsurface to the target depth and left in place. The heaters embedded within the auger wall and flutes are then switched on to heat up and subsequently melt and/or sublime trapped volatiles. The idea is that the volatiles from the surrounding material would then flow through the holes within the auger, into the hollow auger and up into a cold trap on the surface. Hence volatiles would be ‘pumped’ directly from the borehole into a cold trap; akin to natural gas or oil recovery.

The main advantage of this approach is that the extraction occurs in-situ and in turn there is no need to capture or transport material. The main disadvantage is that a fraction of heat will be lost by unnecessarily heating surrounding material.

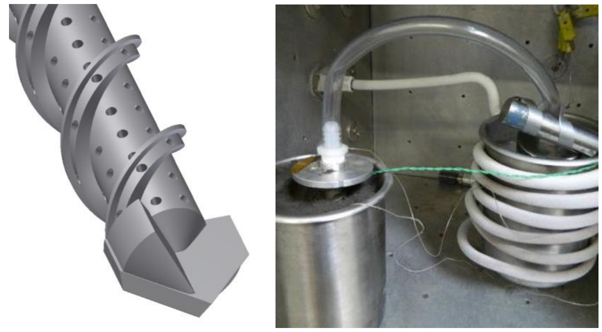

Figure1. PVEx: Sniffer.

MISWE: MISWE system¸ shown in Figure 2, consists of the Icy-Soil Acquisition and Delivery System (ISADS) and the Volatiles Extraction and Capture System (VECS) [3]. The ISADS is a deep fluted auger that drills and retains material on its flutes. After capture of volatile rich material, ISADS moves back into the VECS. VECS consists of a cylindrical heat exchanger (a cylindrical trap) and volatiles transfer system (a reactor).
The material on the deep flutes is then heated, water melts/sublimes and travels down the pressure gradient into a water collection canister (cold finger), where it re-condenses. After water extraction, the ISADS is lowered towards the ground and spun at high speed to eject the dry soil via centrifugal action.

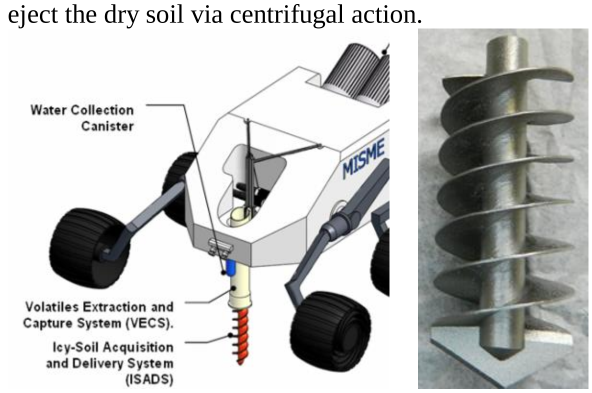

Figure 2. PVEx: MISMWE/Auger.

Corer: A Corer based volatiles extractor, shown in Figure 3, is a dual wall coring auger [4]. The outer wall is an auger with shallow flutes. It’s made of low conductivity composite material (e.g. carbon fiber). The inner wall is perforated and covered with heaters. The corer penetrates subsurface and captures a core inside. Heaters are then turned on and heat up the core within the core. As a result ice melts and sublimes; volatiles then flow within the annual space between the inner conductive cylinder and the outer insulating cylinder (auger), down the pressure gradient into a cold trap on the surface.

The main advantage of this approach is that heat is concentrated within the auger, and because the outer auger surface is insulating, the efficiency is high. Since the coring system cuts only a small annulus, the drilling efficiency is higher than those of the full faced drills.

Figure 3. PVEx: Corer.

Test Results: We conducted hundreds of tests inside a vacuum chamber using JSC-1a soil simulant (Table 1, Figure 4). We found that Sniffer does not work because volatiles tend to escape up the soil and into the vacuum. The MISWE is a distant second in terms of water extraction efficiency and energy conversion efficiency. The Corer is the best in terms of volatiles extraction and energy efficiencies. The Corer also requires less energy to penetrate subsurface (than MISWE or Sniffer) since it uses coring bit and not full faced bit.

Table 1. Trade study

		Sniffer	MISWE	Corer
Data Points		5	16	15
Energy Efficiency [Whr/g]	**Min**	1.8	1.3	1.5
	Max	83	5.4	4.4
	Avg	**36**	**2.6**	**2.2**
	StDev	30	1.0	0.8
Water Recovery [%]	**Min**	0.1	18	31
	Max	4.6	78	87
	Avg	**1.2**	**44**	**65**
	StDev	1.7	16	17
Rankings		**3**	**2**	**1**

Figure 4. Captured water from Corer.

PVEx Corer Design: The Corer system takes advantage of TRL6 Resource Prospector (RP) drill for its deployment. The drill head itself is arranged in such a way as to allow for volatiles to flow straight up through the drill head and into a cold finger (no swivels are needed).

For example, to meet the 30 kg/day water goal for Mars ISRU, the system would need one rover with four Corer systems assuming in-situ material has 12 wt% water saturation. In an ideal scenario (no losses), the needed energy per daily operation would be approx. 3.7 kWh. Of this 3.7 kWhr, 3.4 kWhr would be in the form of heat and in turn could be provided by a Radioisotope Thermal Generator or RTG [4]. The exact power needs would need to be worked out based on the mission profile.

Currently, the system is being developed to reach TRL 5 by 2018, via NASA SBIR Phase 2 funding. One of the goals of the Phase 2 research is to leverage existing heat energy from the rover's RTG power supply.

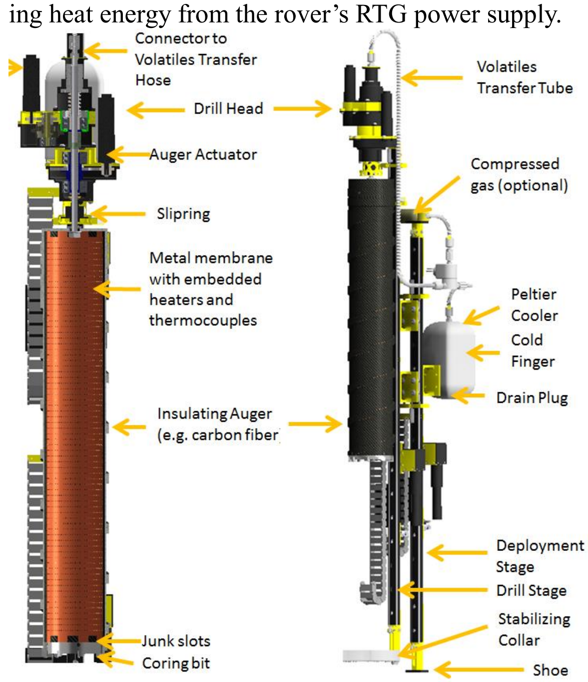

Figure 5. PVEx-Corer Design.

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Acknowledgements: This work has been supported by NASA SBIR program.

ADVANCED CURATION ACTIVITIES AT NASA: PREPARING FOR THE NEXT WAVES OF ASTROMATERIALS SAMPLE RETURN. R. A. Zeigler, J. H. Allton, C. A. Evans, M. D. Fries, F. M. McCubbin, K. Nakamura-Messenger, K. Righter, M. Zolensky, and E. K. Stansbery, NASA Johnson Space Center, 2101 NASA Parkway, Mail Code XI2, Houston, TX 77058. ryan.a.zeigler@nasa.gov.

Introduction: Astromaterial sample return missions from other planetary bodies (e.g., the Moon, asteroids, the Sun) and astromaterial sample collection missions here on Earth (e.g., Antarctic Meteorites, Cosmic Dust) have been a vital part of NASA's science vision since nearly its inception. Beginning with the Apollo missions to the Moon and extending to the recent launch of the OSIRIS-REx asteroid sample return mission, these astromaterials collections have been an invaluable resource to scientists and educators around the world. Sample studies continue to provide fundamental insight into how our solar system and its constituent bodies formed and evolved over the past 4.5 billion years. As evidence of their utility, there are currently over 19,141 samples on loan to 433 Principal Investigators in 24 countries.

As we plan for exploration missions through 2050, sample return missions will continue to play a vital role in NASA's science vision. Returned samples truly are the gift that keeps on giving. Having the samples accessible on Earth allows new generations of scientists and new generations of instrumentation to answer ever evolving scientific questions. For example, the Apollo samples were collected ~50 years ago, yet recent studies of these samples have fundamentally changed our view of how the Earth-Moon system formed, the role of volatiles in the early inner solar system, and even the positions of the gas giants in the outer solar system.

Vital to the long term viability of any sample return mission is the careful curation of the samples. Curatorial efforts need to begin early; not with the return of the samples, but rather at mission conception. The Astromaterials Acquisition and Curation Office at NASA Johnson Space Center (hereafter JSC Curation) is responsible for curating all of NASA's current and future extraterrestrial samples. Looking at possible sample return missions over the next 35+ years [1], many samples would require curation efforts a step beyond our current capabilities, e.g., cold or cryogenic curation, organically and biologically clean curation, curation of gases and ices, and curation of samples with extreme pressure, temperature, or redox requirements. Below we discuss the current curatorial efforts in JSC curation, as well as efforts that are underway (or need to be undertaken) to prepare for the challenging curation conditions required by future sample return missions.

Present Curation: Currently, JSC Curation curates all or part of nine different astromaterial collections, with two more on the way soon: Apollo samples (1969), Luna samples (1972), Antarctic meteorites (1976), Cosmic Dust particles (1981), (4) Microparticle Impact Collection (1985), (5) Genesis solar wind atoms (2004); (6) Stardust comet Wild-2 particles (2006), (7) Stardust interstellar particles (2006), (8) Hayabusa asteroid Itokawa particles (2010), Hayabusa 2 asteroid Ryugu particles (2021), and OSIRIS-REx asteroid Bennu particles (2023). We also curate spacecraft coupons and witness plates for multiple missions (e.g., OSIRIS-REx). Thus, we currently curate large rock samples (Apollo, Meteorites), bulk regolith and core samples that are intimate mixtures of particles ranging from submicron to 1 cm (Apollo), micron-scale individual particles (Cosmic Dust, Hayabusa), micron-scale particles embedded in aerogel (Stardust), atoms of the solar wind implanted in various materials, physical pieces of spacecraft that have astromaterials embedded in them (Microparticle Impact Collection), and materials that capture contamination knowledge for returned extraterrestrial samples (Genesis, Stardust, OSIRIS-REx).

The samples are stored in eight different clean room suites containing 22 different rooms, ranging from ISO class 4 to 8 (i.e., Class 10 to Class 100,000). Most samples are stored under dry nitrogen conditions, and the larger samples (e.g., Apollo, meteorite) are processed in isolation cabinets under dry nitrogen conditions. The smaller samples requiring fine manipulation are processed in air on flow benches (e.g., Cosmic Dust, Stardust). The majority of the samples are stored and processed under room temperature conditions (~20° C), although a subset of the meteorites and lunar samples are stored frozen at -5° C, though they are not processed at that temperature (Fig. 1).

In addition to the labs that house the samples, a wide variety of facilities and infrastructure are required to support the clean-rooms and centralized curation takes advantage of the economies of shared resources for more than 10 different HEPA-filtered air-handling systems, ultrapure dry gaseous nitrogen systems, an ultrapure water (UPW) system, and cleaning facilities to provide clean tools and equipment for the labs. We also have sample preparation facilities for making thin sections, microtome sections, and even focused ion-beam (FIB) sections to meet the research requirements of scientists across the globe.

In order to ensure that we are keeping the samples as pristine as possible, we routinely monitor our clean rooms and infrastructure systems. This monitoring includes measurements of inorganic or organic contamination in processing cabinets [2-3] and weekly airborne particle counts in most labs. Each delivery of liquid N_2 is monitored for contaminants (typically <6 ppm Ar, and <1 ppm all others combined), and the stable isotope composition of the gaseous N_2 is measured monthly. The quality of our UPW system is monitored daily.

In addition to the physical maintenance of the samples, resources are pooled to achieve economies in documenting detailed handling histories and physical states of samples and subsamples. Databases record the current and ever changing characteristics (weight, location, destructive analysis spots, etc.) of >250,000 individually numbered samples across our various collections. Similarly, there are 100s of thousands of images associated with the samples that are stored on our servers. Collectively, these digital and paper records contain each sample's history in curation, information that could be of vital importance to future researchers.

Advanced Curation: As each new sample collection is returned, new facilities are added to accommodate them. The next missions returning samples to JSC are Hayabusa 2 and OSIRIS-REx, in 2021 and 2023 respectively (the Hayabusa 2 samples are being provided as part of an international agreement with JAXA). Two large suites of ISO class 5 clean rooms to house these samples are currently in the planning stages and should be completed in 2020.

In addition to adding clean-rooms to house samples, we are augmenting our analytical facilities as well. A micro-CT laboratory dedicated to the study of astromaterials will be coming online this spring within the JSC Curation office, and we plan to add additional facilities that will enable non-destructive (or minimally-destructive) analyses of astromaterials in the near future (micro-XRF, confocal imaging Raman Spectroscopy). These facilities will be available to: (1) develop sample handling and storage techniques for future sample return missions, (2) be utilized by PET for future sample return missions, (3) for retroactive PET-style analyses of our existing collections, and (4) for periodic assessments of the existing sample collections.

Part of the curation process is planning for the future, and we also perform fundamental research in advanced curation initiatives. Advanced Curation is tasked with developing procedures, technology, and data sets necessary for curating new types of collections as envisioned by NASA exploration goals. We are (and have been) planning for future curation, including cold curation, extended curation of ices and volatiles, curation of samples with special chemical considerations such as perchlorate-rich samples, and curation of organically- and biologically-sensitive samples. In the relatively near term, these efforts will be useful for Mars Sample Return (including Phobos samples), sample return from a cometary surface, and volatile-rich samples from the lunar poles, all of which were named in the NRC Planetary Science Decadal Survey 2013-2022. Looking farther out, these advanced curation efforts will begin to lay the groundwork for other challenging samples that might be returned: (1) mercurian or venusian surface sample return (requiring extremes in pressure, temperature, and redox); or (2) ice and/or volatile samples from outer solar system locations like Ceres, Saturn's Rings, Enceladus, or Europa.

Concluding Remarks: We are fully committed to pushing the boundaries of curation protocol as humans continue to push the boundaries of space exploration and sample return. However, we must never forget our founding principle that curation begins at the conception of a sample-return mission or campaign (in the case of Mars 2020), not at the time of sample collection or return. The return of every extraterrestrial sample is a scientific investment. Our primary goals are to maintain the integrity of the samples and ensure that the samples are distributed for scientific study in a fair, timely, and responsible manner.

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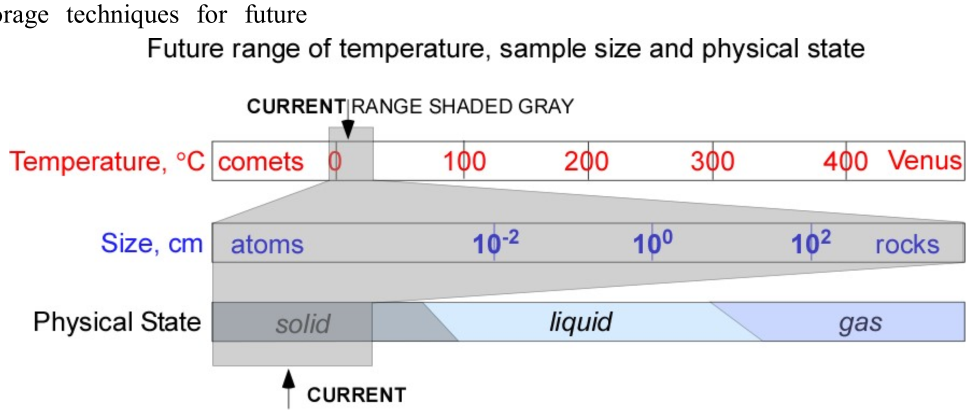

Figure 1: Schematic diagram showing the current conditions that astromaterials are stored at in JSC Curation, as well as likely future conditions that will be required.

FROM COPERNICUS TO NEWTON TO EINSTEIN: TOWARD A DYNAMICAL UNDERSTANDING OF THE SOLAR SYSTEM. Maria T. Zuber[1], David E. Smith[1], Erwan Mazarico[2], Jonathan I. Lunine[3], Gregory A. Neumann[2], Frank G. Lemoine[2], Antonio Genova[1,2], Sander J. Goossens[4,2], Xiaoli Sun[2]. [1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02129-4307, USA (zuber@mit.edu); [2]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; [3]Dept. of Astronomy, Cornell University, Ithaca, NY 14853 USA; [4]CRESST, Univ. of Maryland, Baltimore County, Baltimore, MD 21250, USA.

Introduction: It has been five centuries since it was established that the Sun was at the center of our solar system [1], three centuries since the basic laws that govern our solar system were formulated [2], and one century since those laws were modified to include relativistic effects [3] to bring us to our present understanding of how our solar system works. What new insights will the next 35 years bring? At the heart of our planetary system is the Sun that controls our planetary destiny and which is slowly but inexorably converting hydrogen into helium and slowly losing mass.

Measurements that could confirm the fundamental processes that govern our solar system are approaching the realm of possibility. Accurate monitoring of the motions of the planets about the Sun will answer certain basic questions, some which are essentially theoretical, about the evolving nature of individual planets, and the processes that are changing our Sun.

Measuring the Solar System: If we are able to accurately measure the distances of the planets with respect to each other over decadal timescales, we will have the data needed to understand their smallest motions and, by implication, the forces that are controlling their movement with greater accuracy. All solar system bodies are responding to the primary force of gravity, particularly that of the Sun, the gravitational interaction between them, as well as many other small forces. Monitoring of their motions enables us to estimate the forces that cause them; and central to everything is the Sun. Its gravity controls planetary orbits, its internal nuclear processes and expulsion of material in the solar wind reduce its gravitational mass that leads to an expected expansion of the solar system.

The magnitudes of many of these forces and their effects on the planets are small, but in some cases accumulate with time and in others introduce periodic signals of known frequency, enabling their recovery. For the fundamental scaling of the solar system the product of the gravitational constant, G, and the solar mass, M, is the principal term and the possibility that both parameters are changing is a well-known question. If we assume that the more recent estimates of the change in G [4, 5] suggest it is of order 10^{-12} to 10^{-13}/yr [8] and the change in M due to the conversion of hydrogen to helium in the solar interior [6] and the emission of protons in the solar wind [7] is also of order 10^{-13}/yr, then the implied change in the distance of Earth from the Sun is several centimeters per year, which will accumulate with the square of time, t^2.

Although neither the change in G or M have actually been measured, the consequences of such changes are important. Today there is no fully understood reason why G would not be a constant, and a change in M is inferred from nuclear reactions taking place in the solar interior together with measurements of the flux of solar wind by spacecraft in Earth orbit. There is also the possibility that the change in M is not constant. Fig. 1 shows the predicted change in distance between Earth and Mercury over 4 years between March 2011 and April 2015 as a result of a change in the solar GM of 10^{-13}/yr [8]. The observed change might be smaller as some compensation in the orbit may occur. The oscillation is the synodic orbital motion of Mercury with respect to Earth and amplitude steadily increases as the separation between Mercury and the Earth increases.

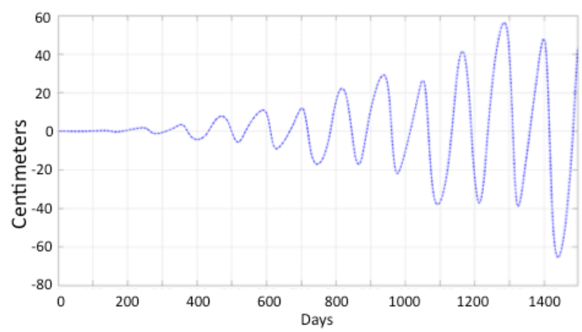

Figure 1. *Predicted direct effect due to changes in solar GM in the distance between Earth and Mercury over the 4-year period that the MESSENGER spacecraft orbited Mercury, March 2011 to April 2015* [8].

Although the changes shown in Fig. 1 are small, they are measurable today as has been demonstrated by Lunar Laser Ranging [9], the LLCD [10] on the LADEE mission to the Moon, and by an asynchronous transponder experiment [11] between the Mercury Laser Altimeter (MLA) on MESSENGER and Earth. In the latter experiment range was measured to 20 cm over a distance of 24×10^6 km, where the limiting factor was the 10-cm range accuracy of MLA.

But the real strength of the concept comes from the multiple combinations of baselines between many planets, effectively forming a grid that connects all the planets together into a single network. Each baseline provides a constraint on the solar system and the forces involved. A 5-planet network, for example, provides 24 baselines that contribute to a very robust solution.

A planetary dynamics network contributes to every aspect of solar system science. Table 1 is a brief list of the science and measurements that we expect will be obtainable after several years of observations. One of

Loss of solar mass by internal nuclear reactions and solar wind
Change in the gravitational constant, G
Test of equivalence principle
Expansion of the solar system
Lense-Thirring precession of reference frame
Relativistic parameters, beta, gamma
Gravitational flattening of the Sun, J2
Precession, nutation and rotation of host planets
Obliquity, tides, moment of inertia of host planets
Low degree gravity, seasonal change on host planets
Inferences on interior structure, sun and host planets
Orbits of host planets/bodies

Table 1. *List of some of the science measurements and parameters that will be possible with a planetary-scale laser ranging network.*

the important solar parameters is the gravitational flattening, J_2, that can provide information about the radial distribution of mass within the Sun, observable in the motions of the inner planets but almost indistinguishable from the relativistic Lense-Thirring effect.

Gravitational flattening provides information about the radial density distribution within the Sun. At present, there are two methods of estimating solar flattening: planetary dynamics and helioseismology. The former is derived from planetary perturbations, principally Mercury, and the latter from observations of the rotation of the outer layers of the Sun. Table 2 summarizes recent estimates for the sun's J_2.

Source	Solar J_2, 10^-7	Reference
Dynamics	1.96 (2.11 ± 0.7)*	DE430, DE431,Folkner et al., 2014
Dynamics	2.13 (2.40 ± 0.2)*	MESSENGER, Verma et al., 2013
Dynamics	2.24 ± 0.1	MESSENGER, Genova et al., 2016
Helioseismology	2.20	Mercheri, et al., 2004
Helioseismology	2.206	Roxburgh, 2001
Helioseismology	2.22 ± 0.06	Amstrong and Kuhn, 1999
Helioseismology	2.22	Paterno et al., 1996
Helioseismology	2.18	Pijpers, 1998

()* Prior to a reduction of 7% to account for Lense-Thirring effect

Table 2. *Recent values for the solar flattening, J_2.*

It is conceivable that the solar J_2 is changing on an 11-year period with the solar cycle and a planetary geodetic network would be able to detect it. This would indicate subtle changes in mass distribution in the solar interior.

***Trilogy*, A Proposed First Step:** Geodetic / geophysical spacecraft are placed in orbit about several planets or major solar system bodies; *Trilogy* [12] is an example of an initial concept that would place spacecraft in orbit about Earth (or Moon), Mars and Venus. The distances between the spacecraft are measured at the few centimeter level regularly over a period of 5 to 10 years from which the motion of the center of mass of the planets are inferred and *G*, *G-dot*, *GM* of the Sun, etc. are estimated. Fig. 2 shows the *Trilogy* configuration of planets and spacecraft. A possible alternative to using spacecraft could be landers on the Moon, or Mars, though dynamical perturbations at the planetary surface would need to be considered.

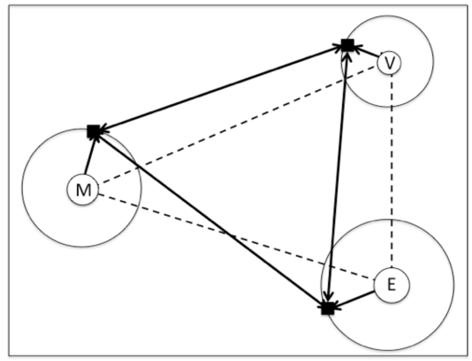

Figure 2. *Trilogy concept with Earth, Mars & Venus.*

Technology readiness: Measurements over planetary distances have been routine for decades at microwave frequencies, but such technology requires large antennae on the ground and on the spacecraft. Laser tracking and ranging over planetary distances has been demonstrated over the last decade and the telescopic instrumentation is smaller as, for example, laser altimeters that have operated at planets for years, with the laser altimeter (LOLA) on LRO continuing to operate in lunar orbit after nearly 8 years [13]. *Trilogy* envisages laser ranging terminals on small spacecraft, possibly cubesats, that can make range and/or range-rate measurements over several astronomical units at sub-μ/s precision. The required technology is here today. Let's do it!

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LUNAR COTS: USING THE MOON'S RESOURCES TO ENABLE AN ECONOMICAL AND SUSTAINABLE PATHWAY TO MARS AND BEYOND. A. F. Zuniga[1] and D. J. Rasky[1], R. B. Pittman[2], [1]NASA Ames Research Center, Moffett Field, CA (allison.f.zuniga@nasa.gov), [2]Lockheed, NASA Ames Space Portal Office, Moffett Field, CA.

Introduction: To support NASA's goal of sending humans to Mars, a new plan was constructed to develop and demonstrate cislunar and lunar surface capabilities and services in partnership with commercial industry using the well-proven Commercial Orbital Transportation Services (COTS) Program acquisition model. The NASA COTS Program was a very successful program that developed and demonstrated cost-effective commercial cargo transportation services to the International Space Station (ISS). As a result of NASA's COTS program, two new launch vehicles and spacecraft (including SpaceX's Falcon 9 rocket and Dragon spacecraft and Orbital's Antares rocket and Cygnus spacecraft) were developed and have been successfully performing cargo transportation missions to the ISS since 2012. The COTS acquisition strategy utilized a new model than normally accepted in traditional procurement practices. This new model used Space Act Agreements where NASA entered into partnerships with industry to jointly share cost, development and operational risks to demonstrate new capabilities for mutual benefit and later provide low-cost commercial space transportation services. This model proved to be very beneficial to both NASA and its industry partners as NASA saved significantly in development and operational costs, as much as a factor of ten has been reported, while industry partners successfully expanded their market share of the global launch transportation business for significant economic benefit and gain.

Using the COTS acquisition model as a basis, a new plan, notionally referred to as Lunar Commercial Orbital *Transfer* Services (or Lunar COTS), has been developed to determine the potential benefits and challenges of a new Lunar COTS plan[1]. The proposed plan includes low-cost, commercial-enabled missions to prospect for resources, determine the economic viability of extracting those resources and assess the value proposition of using these resources in future exploration architectures such as Mars. These missions would be accomplished in partnership with industry to meet these exploration goals but will also have the capability to carry payloads to meet science goals as well.

As noted in several references, there are a wide variety of lunar resources in the lunar regolith that can be useful to NASA's long-term human exploration missions to Mars and beyond. One major example is water-ice concentrations in the permanently shadowed regions of the lunar poles. Several remote-sensing, lunar missions in the last two decades including DOD's and NASA's Clementine mission launched in 1994; NASA's Lunar Prospector mission launched in 1998; NASA's Lunar Reconnaissance Orbiter (LRO) [2] launched in 2009 and NASA's Lunar Crater Observation and Sensing Satellite (LCROSS) [3] mission launched in 2009 have all indicated the presence of water-ice deposits at the lunar poles. Although these data are strong indications that the presence of water-ice is abundant at the poles, ground truth data is needed to validate these results and determine the composition, distribution, depth and accessibility of these areas with high concentrations of lunar ice.

Several studies have also examined the In-Situ Resource Utilization (ISRU) processes and facilities necessary to extract and convert the lunar water into LO2 and LH2 propellants. These studies have also provided cost estimates for putting the infrastructure in place for creating the propellant and then delivering it to a cislunar propellant depot for use in a future Mars architecture. Although these studies have provided an excellent strategy and approach for creating propellant on the lunar surface, ground truth data from the Moon is needed for a more refined cost estimate of the exact methods, tools and machinery that will be needed to extract the lunar ice and create the propellant. It is also best to obtain this ground truth data and develop extraction techniques in partnership with industry to share cost and risk as well as leverage on industry's capabilities and innovativeness in a competitive environment employing the COTS acquisition model.

Over the past few decades, several architectures for the Moon and Mars have been proposed and studied but ultimately halted or not even started due to the projected costs significantly exceeding NASA's budgets. Therefore a new strategy is needed that will fit within NASA's projected budgets and takes advantage of commercial industry along with its creative and entrepreneurial attributes. The Lunar COTS plan presents a cost-effective approach to partner with industry to establish low-cost cislunar capabilities and services, such as, lunar transportation, lunar mining and lunar ISRU operations. These capabilities and services may enable development of an affordable and economical exploration architecture for future missions to Mars and beyond. This paper will describe a plan for a proposed Lunar COTS program, its potential impact to an eventual Mars architecture and its many benefits to NASA, commercial space industry and the science community.

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