Astrobiology Priorities for Planetary Science Flight Missions

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Introduction

We have posited in another white paper that all of Planetary System Science can be seen through an astrobiological lens. In this paper we present priorities for flight mission investigations derived by applying that lens to the Planetary Science flight mission program.

Venus, Mercury and the Moon

Venus, Mercury and the Moon can all inform our understanding of the origin of habitable terrestrial planets, the robustness and longevity of habitable conditions under the influence of solar and planetary evolutionary processes, and the structure of terrestrial planet habitable zones around solar-type stars. As exploration targets they also present various opportunities to reconstruct solar system history and illuminate the origin and early evolution of terrestrial life.

Venus presents a unique opportunity to place the bulk properties, evolution, and ongoing geochemical processes of Earth in a wider context, as well as providing context for understanding any newly discovered extrasolar terrestrial planets. Although the original water inventory on Venus is highly uncertain (as is that of Earth), evidence and models (e.g. Taylor and Grinspoon, 2009; Raymond et al., 2006) strongly suggest that Venus formed with a water inventory similar to Earth's. It is likely that Early Venus had liquid water oceans during the time when life is believed to have begun on Earth (e.g. Grinspoon and Bullock, 2007). Thus the overall history of Venus is one of divergence from early more Earth-like surface conditions with loss of a habitable surface environment as solar luminosity increased. Selective loss of hydrogen from the photodissociation of water may also have created an oxygen-rich atmosphere during the late phases of ocean evolution on Venus, with possible implications for the biological emergence of aerobic respiration as well as potential false positives in spectroscopic searches for signs of life on extrasolar planets.

If Venus once had habitable oceans, how long did these conditions persist? What happened to any life that might have existed on Venus, and what observable signs might it have left behind? The possibility has been raised that Venus life might even have migrated to the clouds, which constitute a potentially habitable niche today (Grinspoon, 1997; Schulze-Makuch et al. 2004). Further exploration to understand cloud structure and processes and their role in the Venus climate system will serve to elucidate their biological potential. Determining early surface and atmospheric conditions on Venus and detecting chemical or isotopic signatures of early life are central astrobiological goals for Venus exploration (Venus Flagship Mission Science and Technology Definition Team Report – NASA 2009; available at http://vfm.jpl.nasa.gov/). *In situ* exploration of Venus to understand the loss of habitable conditions stands as one of the largest gaps in an astrobiology-focused planetary exploration program, and thus should be a very high priority for future missions.

Mercury is astrobiologically valuable as an end-member example of planetary evolution, containing important clues to planetary formation, the accretion of volatiles, and the overall bombardment history of the inner solar system in its ancient crust (Solomon et al., 2008). Important questions, vital to astrobiology, remain about the Late Heavy Bombardment (LHB) - whether it was a discrete episode or a gradual tailing off, and the composition and size distribution of the impactors. R&A investment for the continuing study of MESSENGER data from Mercury will be very important for maximizing astrobiological understanding.

Lunar exploration is astrobiologically important because of the Moon's role as a collector and preserver of information, particularly about conditions and processes on the early (Hadean) Earth, a poorly understood period during which prebiotic chemical evolution and the origin of life presumably occurred (Jakosky et al, 2004). In particular, the Moon presents a well-preserved record of the bombardment history in near-Earth space as well as the history of solar energetic particle and radiation fluxes and a record of the early intense solar wind. The Moon may also record evidence for extreme astrophysical events, such as supernova explosions or gamma ray bursts that could have affected life on Earth. It has been suggested that impact ejecta from the young Earth could have spread living organisms and re-seeded life on Earth after impact cataclysms. The Moon's ancient surface may preserve samples of these oldest rocks from Earth, and perhaps even from Venus and elsewhere. Understanding the chemistry of the Moon and its early bombardment history will also clarify important questions about the primordial delivery of volatiles and biogenic elements to the Earth. NASA's re-commitment to a program of Lunar Exploration, including future ambitious missions such as a South-Pole Aitken Sample Return, is vital for realizing this rich potential to learn the origin of life and the history of habitable conditions on Earth from our nearest planetary neighbor.

Mars

Much has been written about astrobiology and Mars exploration; therefore we will confine our comments here to a key set of specific recommendations.

We endorse the new Mars Exploration Program (MEP) theme "Explore habitable environments" to replace the "Follow the water" theme. "Explore habitable environments" embodies the capacity of astrobiology to coordinate biological, geological and environmental investigations to deepen our understanding of Mars as a complex, integrated, and potentially habitable system. Habitability requires liquid water with sufficient chemical activity to sustain metabolism; energy that can be harnessed by life; and biochemical building blocks. These attributes must persist long enough to allow life to arise, propagate and adapt to environmental changes. Accordingly, MEP should identify, explore and sample potentially habitable environments through a balanced strategy of orbital and rover missions.

NASA should support *immediately* an active MRO-based program to seek, characterize and prioritize landing site candidates regarding their potential past or present habitability. Diverse water-formed deposits of Mg sulfates, Ca sulfates, phyllosilicates, halides, silica and carbonates have recently been discovered from orbit. Promising physical features include spring alcoves, stream valleys, deltas, shorelines, and fresh gullies. We must determine which among these are the most promising for *hosting* and also *preserving accessible evidence* of habitable environments. Such locations, identified with reasonable confidence, would be prime candidate landing sites for future landers, including a sample return mission.

During the next decade MEP should deliver to a promising site a rover that is intermediate in size between the MER and MSL rovers and that includes an instrument suite that can evaluate *in situ* any evidence of water, energy and ingredients for life. To be responsive to astrobiology, future landed payloads must be able to prepare fresh rock surfaces (e.g., with a rock abrasion tool) and perform the following measurements: image at the macroscale and microscale (resolution ~30 μm or better), define mineral assemblages, and detect organics and carbonates. The payload must be able to identify candidate samples that might have captured and preserved biosignatures. Evaporites, hydrothermal deposits and fine-grained aqueous sedimentary rocks are examples of highly promising samples. Accordingly NASA should augment its programs to develop flight instrumentation and planetary protection systems.

During the coming decade NASA must move decisively toward returning a carefully selection suite of Martian samples to Earth. The greatest increase in understanding of Mars will come from collecting and returning a well-chosen suite of Martian surface materials. The caching rover must be able to analyze and cache a diverse suite of appropriate samples in a carefully selected landing site. This rover must satisfy planetary protection protocols for returning samples to Earth. The MEP should maintain a technology development program during the next decade to enable a caching rover to be launched preferably in 2018 (an *excellent* year for a Mars landing) but no later than 2020.

The Jupiter System

From extrasolar planets to subsurface oceans, the Jovian system is relevant to the full spectrum of astrobiology. Jupiter is our local analog for many of the planets discovered beyond our solar system, and its large moons may provide a Goldilocks scenario for subsurface habitable zones analogous to the Venus, Earth, Mars triad for the traditional habitable zone paradigm (Io too active and hot; Europa and Ganymede just right for potentially habitable subsurface oceans; Callisto's ocean (Zimmer et al., 2000) too chemically inactive to sustain life).

Europa, particularly, appears to best satisfy our criteria for habitability (Hand et al., 2009). Life exists on Earth anywhere liquid water, a suite of essential elements, and a source of usable chemical energy or light are found. With its rocky and potentially active seafloor, Europa's ocean may be the largest region in our solar system satisfying these conditions for habitability, greater by a factor of two to three than the volume of liquid water on Earth. Europa's relatively thin and possibly active ice shell opens exciting possibilities for astrobiological exploration.

The Jupiter Europa Orbiter (JEO), NASA's next Flagship Mission, will assess the habitability of Europa through a comprehensive geological and chemical investigation of this moon. It is critical to astrobiology that JEO be given top priority in an effort to achieve the proposed 2020 launch date. JEO must be capable of determining the presence or absence of complex organic molecules on the surface of Europa. The detection of carbon-, nitrogen-, sulfur-, and phosphorous-containing compounds is central to assessing the elemental constraints on habitability. *In-situ* surface measurements could greatly improve detection limits, advance our understanding of molecular structures, and provide ground truth for measurements from orbit.

The JEO mission is one component of the international Europa Jupiter System Mission (ESJM). The European-led component of ESJM is a Ganymede Orbiter (JGO) and is also a high priority for astrobiology. The JGO spacecraft will assess the planetary dynamics and habitability of Ganymede, and the coupled ESJM will provide partial imaging, spectroscopic, and magnetospheric coverage of Io, Callisto, and Jupiter. The resulting Jupiter system science will inform, and potentially revolutionize, our understanding of the habitability of the jovian system and the dynamics of similar planetary systems orbiting distant stars.

After the mapping mission and possible pathfinder surface science experiment of JEO, the next priority for astrobiology is a fully capable Europa lander equipped with the instrumentation needed to assess surface and near-subsurface biosignatures. This mission will need to provide full organic and microscopic analyses of multiple surface and near-subsurface samples.

The Saturn System

Recent Cassini-Huygens discoveries have revolutionized our understanding of the complex dynamics and liquid hydrocarbon cycle of Saturn's moon, Titan, and revealed clues to a possibly habitable sub-surface sea on another moon, Enceladus, thereby dramatically escalating interest in both Titan and Enceladus as premier astrobiology targets in the outer Solar System.

Titan is an intricate world that provides a fascinating, albeit much colder, analog to Earth. The similarities to Earth have been pointed out since Voyager days: a molecular nitrogen atmosphere like the Earth's, with a surface pressure just 50% larger than at sea level on Earth. It has an active climate and meteorological cycles where the working fluid, methane, behaves under Titan conditions the way that water does on Earth. Titan possesses methane lakes and seas (two of which are larger in absolute size than the North American Great Lakes), fluvial erosion, rounded pebbles and liquid methane in the soil at the Huygens site, and equatorial dunes shaped by winds and formed of organic particles derived from methane. Beneath this panoply of Earth-like processes an ice crust floats atop what appears to be a liquid water ocean. (Lunine and Lorenz, 2009)

Enceladus, a 504 km diameter moon of Saturn, is one of the most remarkable bodies in the solar system. The active plumes of the South Polar Terrain provide a way to sample fresh material from the interior; material that may be derived from a liquid water ocean. The plumes are known to contain water, CO_2, CH_4, and other organic molecules as well as small, dust size particles that contain Na, K, H_2O and other elements that are the source of Saturn's E-ring (Postberg et al., 2009). If the plume source region on Enceladus is liquid water, then it provides a plausible site for complex organic chemistry (Matson et al., 2007) and even biological processes.

These results emphasize the need to answer three profound astrobiological questions: Can life be sustained on one or both of these satellites? If not, did life exist on either of them in the past? And, if not, then how close did they come toward evolving life? Titan and Enceladus have thousands of micro-habitats with habitability potential.

The NASA/ESA Titan Saturn System Mission (TSSM) study, undertaken in 2008 proposed to begin addressing these questions. The study defined three well-established scientific goals for the next mission to the Saturnian System. *Goal A:* How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies? *Goal B*: To what level of complexity has prebiotic chemistry evolved in the Titan system? *Goal C:* What can be learned from Enceladus and Saturn's magnetosphere about the origin and evolution of Titan? The NASA Astrobiology Institute (NAI) Executive Council, in a letter on September 22, 2008 "reaffirms Titan to be in the list of highest priority astrobiological targets in the solar system." We recommend that the Titan-Enceladus mission be funded for a new start within a decade. Advance work, including technology development, for such a mission should be started in earnest now.

The Uranus and Neptune Systems

The ice giants Uranus and Neptune may host several active and chemically-rich moons of astrobiological interest. Voyager observations of Neptune's moon Triton revealed plumes of dark material rising several kilometers above the surface (Soderblom et al., 1990). The Uranian satellites, though considerably smaller than Triton, are larger than many of the Saturnian satellites and some models predict subsurface oceans in Titania and Oberon (Hussmann et al., 2006; Vance et al., 2007).

Along with the prospect of sub-surface oceans, these worlds also present intriguing chemical environments for astrobiology. As a consequence of forming in the cold outer regions of the Solar System, these moons are rich in ices of compounds that were too volatile to be retained by the terrestrial planets (McKay, 1991; Hand et al., 2009). Ground based observation of Triton's surface have revealed ices of CO, CO_2, CH_4, and N_2 (Cruikshank et al., 1984; Cruikshank et al., 1993). Many of these compounds, e.g. N_2, NH_3, CO, CO_2, CH_4, and H_2S, carry the baseline elementary inventory thought to be necessary for life as we know it (Wackett et al., 2004). Furthermore, compounds such as NH_3 serve to depress the freezing point of an aqueous solution, thus enhancing the prospect for liquid water regions on these relatively cold worlds.

Neptune's moon Triton and the Uranian satellites Titania and Oberon are the highest priority for future astrobiological investigation of the Uranus and Neptune Systems.

Small Bodies

Small bodies, including comets, asteroids and Kuiper Belt objects, are likely to have experienced less heating than other objects and may thus retain an imprint of the earliest primordial processes of our forming solar system. The origin of water on the terrestrial planets is a an unsolved problem of fundamental importance to assessing habitability (Mottl et al., 2007). It is likely that Earth and the other terrestrial planets acquired water from many sources (e.g., Owen and Bar-Nun, 2000) or as a consequence of chemical reactions on the surface of the early Earth. However, and whenever, volatiles were delivered to the terrestrial planets, there was likely a simultaneous delivery of organic material.

The breakthroughs of the past decade in small body science have enabled the initiation of astrobiologically relevant interdisciplinary investigations of the role of water in the early solar system and primitive organic material. These breakthroughs have included the in-situ exploration of comets (e.g., A'Hearn et al., 2005; Brownlee et al., 2006) and the discovery of the Main Belt Comets (MBCs). Investigating these objects improves our understanding of solar nebular models, and particularly the "ice-line" for volatile condensation, setting the stage for the development of planetary system architectures (Hsieh and Jewitt, 2006). In addition, the development of comprehensive dynamical models of planetesimal accretion that explore the migration of small bodies and have helped to constrain the source regions and timing for volatile delivery (Gomes et al., 2005).

Further out in the Solar System, observations of an increasing number of Kuiper Belt objects has moved the field from an era of discovery to one of characterization (Schaller and Brown, 2007). Finally, using the inventory of material transported to Earth, isotopic insights from meteorites have helped explain the chemical gradients in the early solar nebula that may have led to small body chemical differences (Sakamoto et al., 2007; Weaver and Stern, 2008).

These advances have laid the foundation for fundamental new insights into the early solar system and the development of habitable environments. Furthering our understanding of the interconnected relationships between small body chemistry and the dynamical architecture of the solar system requires several key measurements. Future exploration of small bodies should focus on characterizing the isotopic composition of small icy bodies, in particular D/H isotopes, which can be measured with sub-mm, UV, or near-IR measurements on very bright comets, or through in-situ investigation (e.g., required for MBCs). Additionally, the evaluation of the noble gas composition of icy reservoirs through observations in the vacuum UV or in-situ exploration is essential for understanding the origin and history of small bodies.

While recent comet flyby missions have demonstrated a wealth of diversity among comet surfaces, the most accurate way to determine the connection between cometary and terrestrial material is through Earth-based lab analysis. Key questions about the complexity of cometary matter and whether or not small icy bodies harbor the precursors of biological molecules may only be fully answered through the return of comet nucleus samples to Earth (Kuppers et al., 2009).

Extra-Solar Planets

The study of Earth-like worlds around other stars is on the verge of exploding. Planets have been discovered in the terrestrial regime, with minimum masses of less than 10 Earth masses and as small as 1.9 Earth masses (Mayor et al 2009; Butler et al 2006). One planet is known to have a solid surface (Leger et al 2009). Transit measurements have detected water vapor and methane in planetary atmospheres (Tinetti et al 2007; Swain et al 2008). Earth-like planets are at the brink of detection: both observations and formation models suggest that Earth-sized planets should be common and have a wide range in compositions (Raymond et al 2004; Mayor et al 2009). The primary goal of NASA's recently launched Kepler mission is indeed to determine the frequency of terrestrial planets in the habitable zone.

Several large-scale mission concepts have been proposed to serve as the “Terrestrial Planet Finder” to detect and characterize exo-Earths. From an astrobiology perspective the highest priority exoplanet measurements that should be made in the coming decade include measuring the the spectrum of an Earth-like planet with high-enough resolution to probe its atmosphere and search for potentially biologically relevant species such as O_2, O_3, CH_4, and CO_2 (e.g., Selsis et al 2002). Measuring the photometric light curve of an Earth-like planet – a simple brightness vs. time curve for an exo-Earth – may reveal the planet's rotation period and the approximate land vs. ocean distribution, modulo cloud and weather effects (e.g., Palle et al 2008). Finally, to infer the formation and composition of Earth-like planets around other stars, observations of the dust and gas components of planet-forming disks around young stars are critical (e.g., Eisner 2007). These goals should be considered as essential criteria in choosing upcoming exoplanet missions.

From a theoretical point of view, models of the formation and dynamics of gaseous and rocky/icy planets in a range of astrophysical environments are another key to our understanding of the context and environments of Earth-like planets around other stars. We also advocate continued observational and theoretical research efforts to a) determine the frequency of Solar System-like giant planets that are amenable to Earth-like planet formation and survival (e.g., Raymond 2006), b) determine the range of astrophysical conditions (e.g., the orbital and atmopheric limits) on terrestrial planets that might still be considered habitable, c) assess the viability of transit measurements to detect and characterize the atmospheres of habitable zone planets around low-mass stars, and d) improve models to interpret upcoming measurements such as transit timing variations (Agol et al 2005).

References

A'Hearn, M. F. *et al.* (2005). "Deep Impact: Excavating Comet Tempel 1", *Science* **310**, 258-264.

Agol, E., Steffen, J., Sari, R., & Clarkson, W. 2005. MNRAS 359, 567.

Borg, L.E., D.J. Des Marais, D.W. Beaty, O. Aharonson, S.A. Benner, D.D. Bogard, J.C. Bridges. C.J. Budney. W.M. Calvin, B.C. Clark, J.L. Eigenbrode, M.M. Grady, J.W. Head, S.R. Hemming, N.W. Hinners, V. Hipkin, G.J. MacPherson, L. Marinangeli, S.M. McClennan, H.Y. McSween, J.E. Moersch, K.H. Nealson, L.M. Pratt, K. Righter, S.W. Ruff, C.K. Shearer, A. Steele, D.Y. Sumner, S.J. Symes, J.L. Vago and F. Westall (2008) Science Priorities for Mars Sample Return. *Astrobiology*, Vol. 8. No. 3,489-535.

Brownlee, D. E. *et al.* (2006). "Comet 81P/Wild 2 Under a Microscope", *Science*, **314**, 1711.

Butler, R.P., et al. 2006, Astrophys. J. 646, 505.

Cruikshank, D. P., et al., 1984. Nitrogen on Triton. Icarus. 58**,** 293-305.

Cruikshank, D. P., et al., 1993. Ices on the Surface of Triton. Science. 261**,** 742-745.

Des Marais, D.J., B.M. Jakosky and B.M. Hynek (2008) Astrobiological implications of Mars surface composition and properties. In *The Martian Surface: Composition, Mineralogy and Physical Properties*, J. A. Bell, editor, Cambridge Planetary Science (No. 9), Chapter 26, 599-623.

Eisner, J.A 2007, Nature 447, 562.

Ford, E.B., Seager, S., and Turner, E.L.: 2001, Nature 412, 885.

Gomes, R., H. F. Levison, K. Tsiganis, and A. Morbidelli (2005), "Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets", *Nature*, **435**, 466-469.

Grinspoon, D.H. (1997) *Venus Revealed: A New Look Below the Clouds of Earths' Mysterious Twin Planet.* Addison-Wesley. Reading, Mass.

Grinspoon, D.H. and M.A. Bullock (2007), in "Exploring Venus as a Terrestrial Planet",

L. W. Esposito, E.R. Stofan and T.E. Cravens eds. AGU Geophysical Monograph Series, **176**: 191-206.

Hand, K. P., et al., Astrobiology and the Potential for Life on Europa. In: R. Pappalardo, et al., Eds.), Europa. University of Arizona Press, Tucson, 2009.

Hsieh, H. H., and D. Jewitt (2006). "A Population of Comets in the Main Asteroid Belt", *Science* **312**, 561-563.

Hussmann, H., et al., 2006. Subsurface oceans and deep interiors of medium-sized outer planet satellites and large trans-neptunian objects. Icarus. 185**,** 258-273.

Jakosky, B. (2004) Astrobiology Science Goals and Lunar Exploration: NASA Astrobiology Institute White Paper; http://nai.nasa.gov/about/lunar_astrobiology.cfm).

Kuppers, M. et al. (2009). "Triple F – A Comet Nucleus Sample Return Mission", *Experimental Astronomy* **23**, 809-847.

Leger, A., et al 2009, in preparation.

Lunine, J. I., Lorenz, R. D., 2009. Rivers, Lakes, Dunes, and Rain: Crustal Processes in Titan's Methane Cycle. Annu. Rev. Earth Planet. Sci. 37, 299-320.

Matson, D. L., Castillo, J. C., Lunine, J., Johnson, T. V., 2007. Enceladus' plume: Compositional evidence for a hot interior. Icarus. 187, 569-73.

Mayor, M. et al 2009. Astron. Astroph. in press, arXiv:0906:2780

McKay, C. P., 1991. Urey Prize lecture: Planetary evolution and the origin of life. Icarus. 91**,** 93-100.

Mottl, M. J., B. T. Glazer, R. I. Kaiser, K. J. Meech (2007). "Water and Astrobiology", *Chemie der Erde* **67**, 253-282.

Owen, T. C., A. Bar-Nun (2000). "Volatile Contributions from Icy Planetesimals" in *Origin of the Earth and Moon*, Ed. R. M. Canup and K. Righter, Univ. AZ Press, 459-471.

Palle, E., Ford, E.B., Seager, S., Montanes-Rodriguez, P., and Vazquez, M.: 2008, Astrophys. J. 676, 1319.

Postberg, F., Kempf, S., Schmidt, J., Brilliantov, N., Beinsen, A., Abel, B., Buck, U., Srama, R., 2009. Sodium salts in E-ring ice grains from an ocean below the surface of Enceladus. Nature. 459, 1098-1101.

Raymond, S.N. 2006. Astrophys. J. 643, L131.

Raymond, S.N., A. M. Mandell, S. Sigurdsson (2006) Exotic Earths: Forming habitable worlds with giant planet migration. *Science*, 313,1413 -1416.

Raymond, S.N., Quinn, T., and Lunine, J.I.: 2004, Icarus 168, 1.

Sakamoto, N. *et al.* (2007). "Remnants of the Early Solar System Water Enriched in Heavy Oxygen Isotopes" *Science* **317**, 231.

Schaller, E. L. and M. B. Brown (2007). "Volatile Loss and Retention on Kuiper Belt Objects", *ApJ* **659**, L61-L64.

Schulze-Makuch, D., D.H. Grinspoon, O. Abbas, L.N Irwin and M.A. Bullock. (2004). A sulfur-based survival strategy for putative phototrophic life in the Venusian atmosphere. *Astrobiology* 4. 11–18.

Selsis, F., Despois, D., and Parisot, J.-P.: 2002, Astron. Astroph. 388, 985.

Solomon,S.C., R. L. McNutt, Jr. T. R. Watters, D. J. Lawrence, W. C. Feldman, J.W. Head, S. M. Krimigis, S. L. Murchie, R. J. Phillips, J. A. Slavin, M. T. Zuber (2008). Return to Mercury: a global perspective on MESSENGER's first Mercury flyby. Science. 321. 59 – 62.

Soderblom, L. A., et al., 1990. Triton's geyser-like plumes: Discovery and basic characterization. Science. 250**,** 410-415.

Swain, M.R., Vasisht, G., and Tinetti, G.: 2008, Nature 452, 329.

Taylor, F.W. and D.H. Grinspoon (2009) Climate Evolution of Venus. *J. Geophys. Res.* In press.

Tinetti, G., et al 2007, Nature 448, 169.

Vance, S., et al., 2007. Hydrothermal Systems in Small Ocean Planets. Astrobiology. 7**,** 987-1005.

Wackett, L. P., et al., Microbial genomics and the periodic table. Vol. 70. Am Soc Microbiol, 2004, pp. 647-655.

Weaver, H. A., S. A. Stern (2008). "New Horizons: NASA's Pluto-Kuiper Belt Mission", in *The Solar System Beyond Neptune*, M. A. Barucci, H. Boehnhardt, D. P. Cruikshank, and A. Morbidelli (eds.), University of Arizona Press, Tucson, 592 pp., p.557-571.