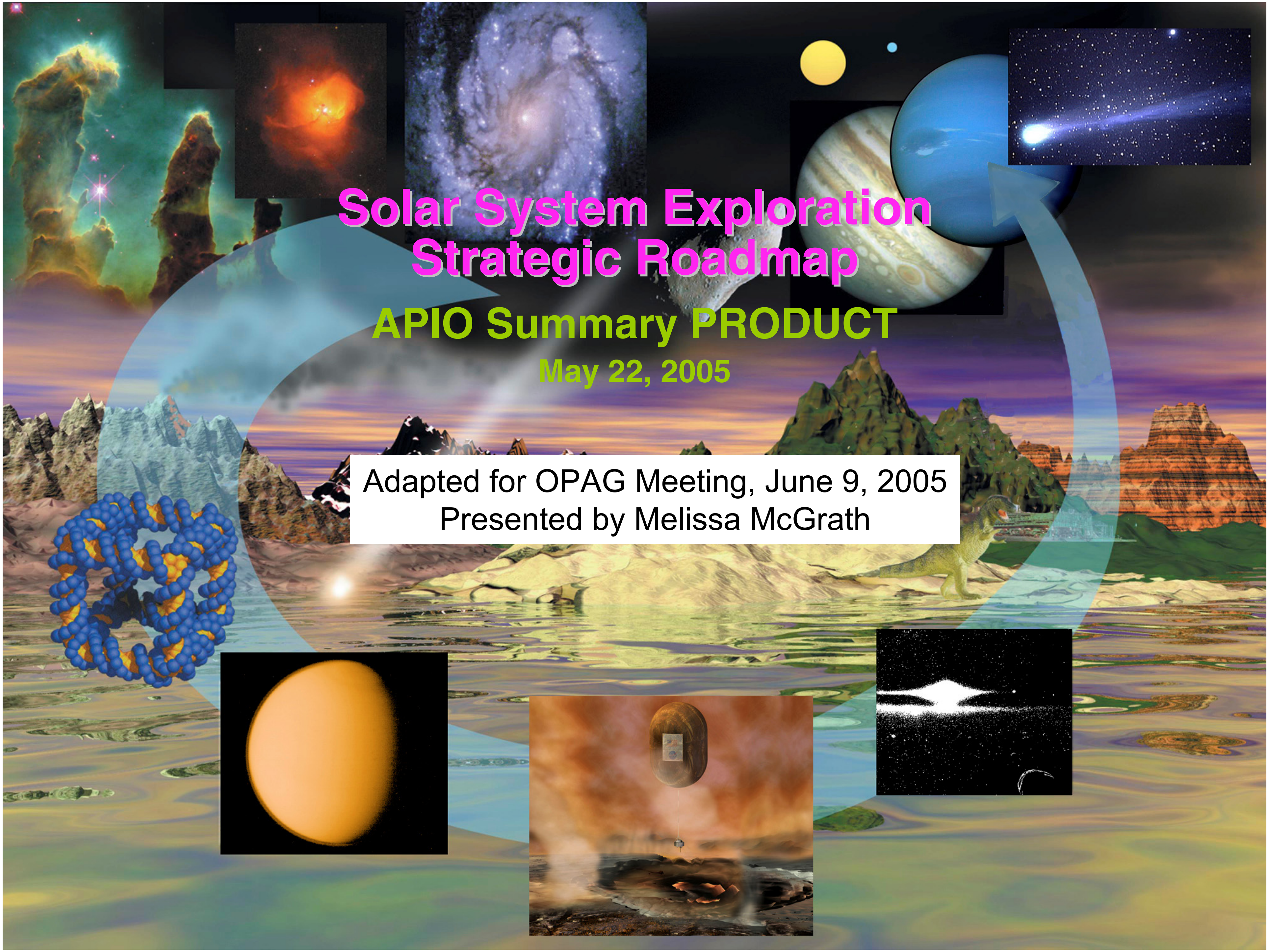

Solar System Exploration Strategic Roadmap

APIO Summary PRODUCT

May 22, 2005

Adapted for OPAG Meeting, June 9, 2005
Presented by Melissa McGrath

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Agency Objective

- Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore the moons of Jupiter, asteroids, and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources.

Deriving Roadmap Objectives

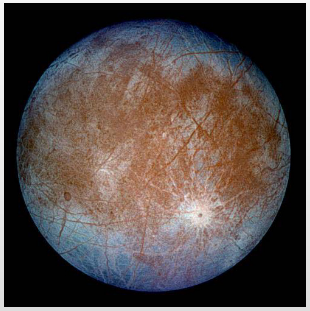
Roadmap Objectives

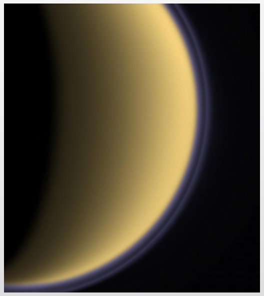
- Learn how the sun's family of planets and minor bodies originated
- Determine how the solar system evolved to its current diverse state including the origin and evolution of the Earth's biosphere
- Explore the space environment to discover potential hazards and search for resources that would enable permanent human presence
- Understand the processes that determine the fate of the solar system and life within it
- Determine if there is or ever has been life elsewhere in the solar system

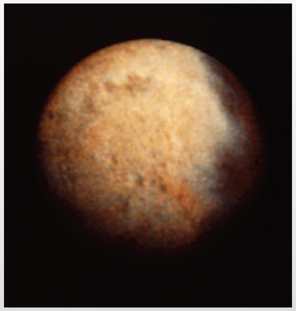
How does a planetary system become habitable?

The big “H”--Habitability

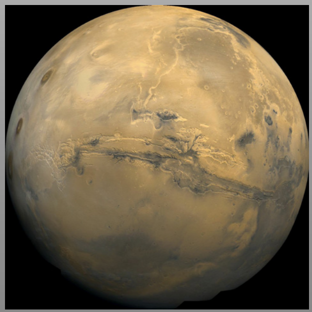
Habitability in planetary environments





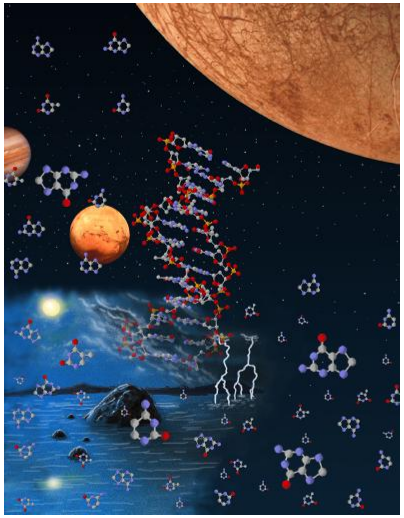


How does a planetary system become habitable?



Habitability in the architecture of planetary systems

Science Threads



- Habitability in planetary environments
  - Earth-like planets
    - Venus-Earth-Mars – Venus is a baked dry version of Earth; Mars is frozen solid
    - Venus & Earth are the same size; when did Venus become uninhabitable?
    - Mars – did life ever start and does life still exist?
  - Blue Moons: Habitable worlds around the giant planets
    - Europa-Titan-Triton: Another warm-to-cold trio
    - What does organic chemistry on Titan tell us about how life began?
    - Is there life on Europa?
- Habitability in the architectures of planetary systems
  - How do giant planets determine the arrangement of terrestrial planets near the habitable zone? (focus on Jupiter & Neptune)
  - Can giant planets in the habitable zones of other stars have habitable moons?
  - How were the ingredients for life supplied and when?
  - How have impacts affected the survival and evolution of life through time?

Roadmap Options and Alternatives

- Roadmap anchored on a balanced portfolio of Discovery, New Frontiers, Flagship class missions, and robust programs of R&A, critical technology developments, supporting ground observations, and EPO
- Three categories of flight missions
  - **Discovery ($300M to $500M)**
    - Open unrestricted competition to address broad solar system objectives
    - Budget projection supports flying 5 per decade
  - **New Frontiers ($500M to $800M)**
    - Open competition to address solar system objectives consistent with Decadal Survey recommendations
    - Objectives not achievable within Discovery Program constraints, but may not require flagship mission
    - Budget projection supports flying 3 per decade
  - **Flagship missions ($800M to $1400M or $1400M to $2800M)**
    - Major investigation campaigns to address fundamental questions in SSE consistent with Decadal survey recommendations
    - Investigations address distant and/or extreme environments
    - Budget projection supports flying two $800-1400M or one $1400-2800M mission(s) per decade.

Roadmap Options and Alternatives

- **New Frontiers**
  - Kuiper Belt/Pluto
  - Lunar South Pole Aitken Basin
  - Comet Surface Sample Return
  - Venus In Situ Explorer
  - Jupiter Polar Orbiter with Probes
- **Flagship Missions**
  - Europa Geophysical Orbiter
  - Europa Astrobiology Lander
  - Titan Orbiter/Lander
  - Neptune Orbiter with Probes
  - Comet Cryo Nucleus Sample
  - Venus Sample Return

Decision Points

- Decision Points are influenced by the congruence of 3 major factors: scientific priorities and knowledge, technological readiness or capability, and programmatic considerations
- What we learn from precursor missions could influence not only the destination(s), but the architecture of the investigation campaign, the approach, and what we do once we get there
- The competed nature of the Discovery, New Frontiers programs prevent us from assuming their outcome beyond missions already selected, but it is clear that as a significant part of the portfolio of missions, they will influence scientific knowledge and perhaps priorities
- A focused investment in critical technologies and capabilities will enable the missions, and will dictate the timetable for their implementation.

Key Decision Points

- **2005 to 2015**
  - 2007 New start for Europa Geo-Physical Orbiter
    - Decadal Survey highest priority new start flagship mission
    - The Vision for Space Exploration, supported by the objectives of the Solar System Exploration roadmap and its emphasis on habitability, reinforce this recommendation.
    - Launch in the 2014 timeframe, with arrival at Europa ~ 7 years later.
    - Assumes NASA investment in the $800M to $1400M, offering an opportunity for significant international collaboration.
  - 2012/13
    - Phasing and start of one of the two flagship missions envisioned in the $800M to $1400M range for the second period (2015 to 2025).
    - Cassini/Huygens findings, and technology readiness leads to a Titan Surface In-Situ Explorer ahead of a Venus Surface In-Situ Explorer, but phasing will be rexamined later.
    - Both missions offer an opportunity for significant international collaboration

Key Decision Points

- **2015 to 2025**
  - 2018/19
    - Start of the second of two missions envisioned in the $800M to $1400M range for the second period (2015 to 2025), a Venus Surface In-Situ Explorer if today's assessment holds.
    - Offer an opportunity for significant international collaboration
  - 2023/24
    - Start of a flagship mission in the $1400M to $2800M range
    - Heavily dependent on early technology and capability investments
    - Scientific priorities and knowledge will guide decision
    - Options include Europa Astrobiology Lander, Titan Orbiter/Lander, Neptune Orbiter with Probes, Comet Cryo Nucleus Sample, Venus Sample Return

Decision Points

Roadmap Options and Alternatives for Flagships

Magellan, Galileo

Europa Geophysical Orbiter
(f)

Decision 1

Decision informed by
Cassini, MEP, LRO,
India/Chandryan, JAXA/Selene
Discovery missions
ESA/Venus Express
Technology readiness
Budget

2015

Titan (f)
Surface in situ

--and--

Venus (f)
Surface in situ

Decision 2

Decision informed by
Europa, Cassini, MEP,
Discovery missions
New Horizons missions
ESA/Rosetta
Technology readiness
Budget

2025

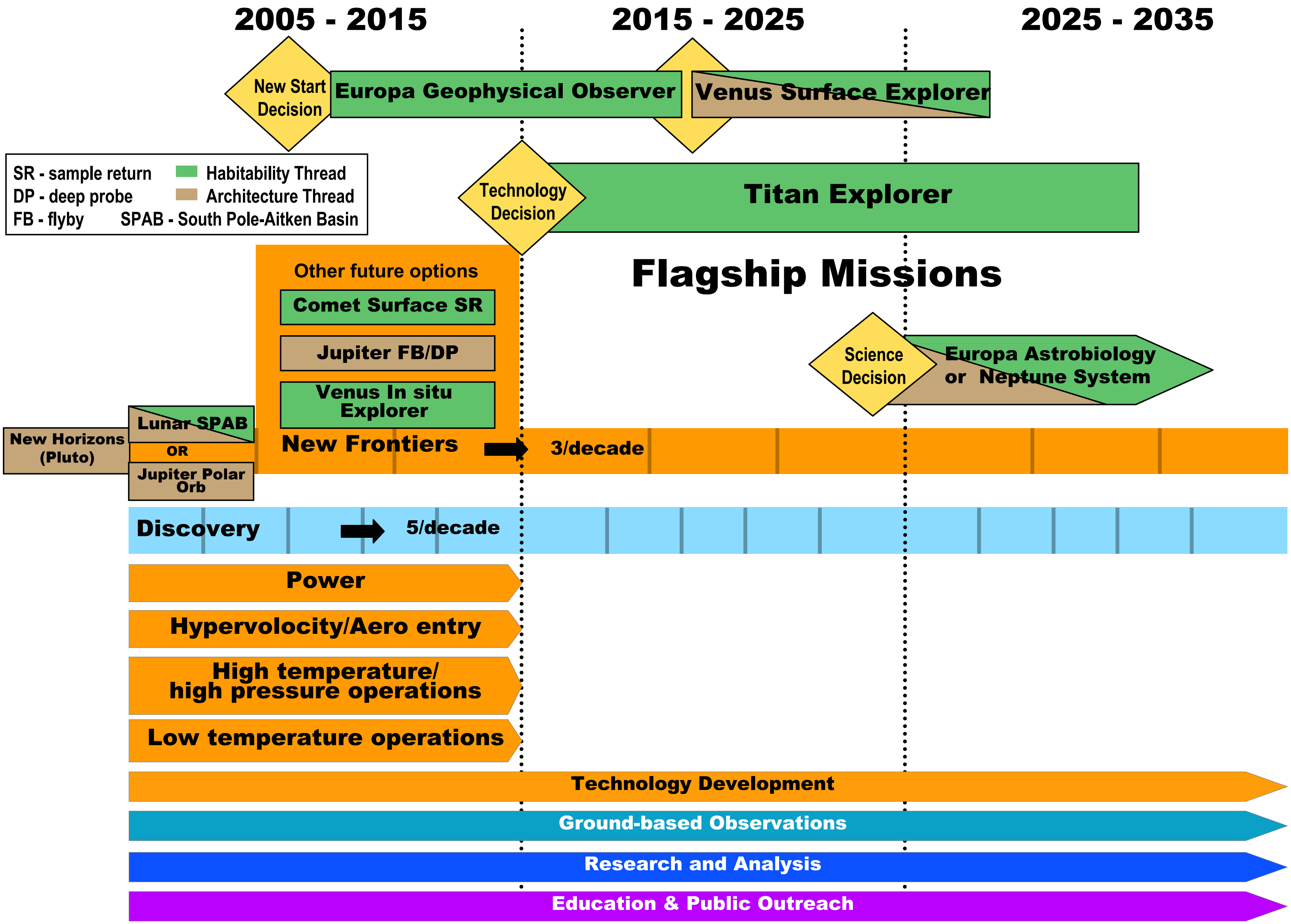
(f) or (F)

Europa Astrobiology
--or--
Titan Orbiter/Lander
--or--

Neptune Orbiter w Probes
--or--
Comet Cryo Nucleus Sample
--or--
Venus Sample Return

(f) = $800M - $1400M
(F) = $1400M-$2800M

Solar System Exploration Roadmap



SRM3 - SSE Education and Public Outreach

What works already and should be continued

- Developing collaborative programs that include both active scientists and EPO professionals, to effectively integrate science results in the educational realm
- Mandating a fraction of mission funds for EPO
- Highlighting "hot" topics (e.g., NASA Science Updates)
- Providing context materials for existing products

What could be done better

- Commit to providing understandable results quickly from missions (Mars, Moon, Europa, etc)
- Permit more flexibility for scientists and technologists to engage in EPO activities
- Assess processes and programs on regular basis to ensure productivity

Decision Points for SSE-EPO Implementation

When a truly spectacular discovery is made
(e.g., life is found elsewhere in the solar system)

When a major technological innovation occurs
(e.g., Moore's Law)

Roadmap Options and Alternatives

- **Paradigm Shifting Events**
  - Investigation timeline, architecture, and approach may be altered significantly by breakthrough findings or the availability of the following capabilities
    - Confirmation of life or pre-biotic activity anywhere in the solar system other than Earth
    - Maturation of AFFORDABLE technologies to reduce trip time to outer solar system bodies
    - Detection and confirmation of a Near Earth Object (NEO) with high probability of Earth impact

Roadmap Requirements - Technology

- **Highest priority investments**
  - Radioisotope Power Source Technologies (100’s and 10’s watt high efficiency to milliwatts)
  - Technologies for extreme environments
    - Very high (Venusian surface) and very low (Titan mid-atmosphere) temperatures
    - Extreme pressure (hundreds of bars: Venus, Jupiter, Neptune)
    - Atmospheric entry probes for Outer Planets and Venus (very high heating rates in He/H atmosphere for OP and high heating rates in CO2 for Venus)
    - High Radiation (Europa, Jupiter)
- **Further assessment of the following technology areas**
  - Continued assessment of supporting propulsion technologies
  - Closer evaluation of optical communications, ultra-high bandwidth and ultra-high pressure communication/survival technologies which could enhance and possibly enable deep giant planet probes
  - Further study to determine specific needs for technologies in Autonomous Systems, Science Instruments, Nanotechnology or Advanced Modeling and Analysis to enhance SSE missions.

Roadmap Requirements - Technology

Continued funding of RPS and supporting Technologies

- Radioisotope power supplies are critical for missions at extreme distances or in extreme environments
- Ongoing evaluation of efficient RPS designs (e.g., Stirling cycle rather than RTG)
- Some supporting technology to be investigated
  - Low Power Electric Propulsion may be enabling for a Jupiter Polar Orbiter or Neptune/Triton Orbiter Probe.

Roadmap Requirements - Technology

Extreme Temperatures

High: 700 K

Low 70-90 K (Titan near-surface/surface)

- Extremely high temperature technologies are needed for Venus Atmosphere with surface access missions
  - Electronics and surface mobility at ~500 degrees C
- Extremely low temperature technologies are needed for Comet Surface Sample Return missions, Titan Explorer
  - Implies low temperature technology for Titan atmospheric and surface mobility
  - Low temperature surface access and sample preservation for Comet Surface Sample Return

Roadmap Requirements - Technology

Extreme Pressures (Hundreds of bars)

- Missions which require operations at ≥100 bars
  - Deep atmosphere of Neptune (up to one kilobar)
  - Surface of Venus (90 bars)
  - Deep atmosphere of Jupiter (100 bars)
- Implies special attention to structure and design of surface vehicles and pressure vessels in hazardous environment (hydrogen in outer planet atmospheres, high temperature corrosive chemicals in Venus)

Roadmap Requirements - Technology

Technology for Outer Planet and Venus probes

- Extreme entry velocity/heating rates in H/He atmosphere for Jupiter and Neptune probes and very high heating rates in CO_2 atmosphere for Venus
  - Requires extreme environment thermal protection systems (TPS) and testing in relevant environments
- Extreme depth for Venus, Jupiter, Neptune probe missions
  - Requires special attention to entry probe design including pressure vessel structure to deal with ≥100 bar pressures (cf previous chart) and thermal management of sensors, electronics and battery
  - Communications technology needed for data transfer from extreme depths
- Aerocapture for a Neptune/Triton Orbiter Probe
  - Requires targeting precision and extreme environment TPS

Roadmap Requirements - Technology

High Radiation

- High intensity radiation environment around Jupiter near Europa poses special problems
  - Different energy, particle distribution distinct from military applications
  - Implies need for electronics, structures, shielding which can provide minimum 30 day to many months of operations

Maintaining Priorities

p. 192 of the Decadal Survey

Many discoveries occur in the planetary sciences over the course of a decade, and for a decadal strategy to maintain a course consistent with ongoing discoveries, the need to reconsider the priorities recommended by this Survey may arise. NASA should issue Announcements of Opportunity for New Frontiers missions that are consistent with the priorities given in this Survey. Only in the case where a new discovery changes the Survey's fundamental understanding should these priorities be reconsidered, in which case **the SSE Survey recommends that the National Research Council's Committee on Planetary and Lunar Exploration conduct a review to confirm or modify decadal survey recommendations and priorities for the New Frontiers flight program.**

Supporting Material

Decision Points Considerations I

Scientific	Impact
- Do comets have complex layered structures?	- Sample return strategy
-Cometary and meteoric particles the same?	- Sample return strategy
- Strong differences between comets?	- Multiple comet flyby mission(s)
- NEO's with significant probability of Earth impact?	- Hazard mitigation
- Strong differences among asteroid surfaces?	- Multiple asteroid flyby mission(s)
- Evidence of non-basaltic geochemistry on Venus?	- Driller/mobile platform lander
- Continents, plate tectonics on Venus?	- Sample return strategy
- Subsurface ocean at accessible depths on Europa?	- Lander/drill strategy
- Diverse organic deposits on Titan?	- Mobile platform/organics explorer
- Atmospheric and surface evolution on Triton?	- Return missions with landers(?)
- Strong diversity among Kuiper Belt objects?	- Multiple KBO strategy
- Organics found in Europan ocean?	- Life search strategy for Europa
- Life processes found on Europa or Titan?	- Large scale bio laboratory

Decision Points Considerations II

Technological	Impact
- Cryogenic sampling and storage	- Cryo Sample Return
-Nuclear electric propulsion	- KBO/Asteroid belt survey, Icy Moon tour, Triton
- Aerocapture	- Titan exploration, Triton orbiter
- Extreme environment technology (cold)	- Titan long duration mission
- Extreme environment technology (hot, high pressure)	- Venus long duration surface exploration
- Aerial vehicle technology	- Titan regional exploration
- Surface mobility	- Europa, Titan, Venus
- High radiation environment	- Europa long duration
- Ultrahigh pressure communication/ survival technology	- Deep giant planets probes
- Nuclear fission or other high power technology	- Venus, Titan sample return, NEO mitigation
- High thrust/payload rockets	- Deep outer solar system exploration
- High bandwidth communication	- Outer solar system exploration, high data rate throughout

Decision Points Considerations III

- **Programmatic**
  - Human presence beyond cislunar space
  - Emphasis on search for life elsewhere
  - Emphasis on Earth evolution
  - Emphasis on Earth Hazards
- **Impact**
  - Asteroid resource exploration, hazard mitigation
  - Mars, Europa, Titan, comets
  - Venus, Moon, Mars, asteroids
  - Hazard mitigation

Expected Achievements

Agency Strategic Objective: Conduct robotic exploration across the solar system for scientific purposes and to support human exploration.			
	Phase 1: 2005-2015	**Phase 2: 2015-2025**	**Phase 3: 2025-beyond**
Roadmap Objective 1: Learn how the sun's family of planets and minor bodies originated.	Expected Achievements: a) Probe the interior of a comet (Deep Impact) b) Return samples of dust from a comet's coma (Stardust) c) Conduct detailed studies near a differentiated and a primitive asteroid (Dawn) d) Conduct detailed studies of a cometary nucleus (Rosetta)	Expected Achievements: a) Complete the reconnaissance of the solar system with a flyby of Pluto b) Explore the diversity of small bodies with missions such as multiple comet flybys and Trojan/Centaur asteroid flybys c) Study individual small bodies intensively by means of sample return missions	Expected Achievements: a) Return cryogenically preserved samples from a comet b) Characterize the diversity of KBOs

Expected Achievements (cont.)

Roadmap Objective 2: Determine how the solar system evolved to its current diverse state including origin and evolution of the Earth's biosphere	Expected Achievements: a) Conduct an intensive orbital study of Mercury to understand how and where it formed (Messenger) b) In conjunction with the expected achievements for Roadmap Objective 1, investigate the origin of Earth's water, organics, and other volatiles d) Investigate the earliest life on Earth through studies of Earth's oldest rocks as well as modern analogue microbial communities	Expected Achievements: a) Land on Venusian highland to search for granitic or andesitic rocks consistent with an early earth-like tectonic evolution b) Search for evidence of past massive oceans of water on Venus c) Characterize the past and present population of asteroidal impactors to understand the impact history of the terrestrial planets	Expected Achievements: a) Drill into various places on Venus to determine the mechanisms by which Venusian highlands were formed. b) Return selected geologic samples from Venus

Expected Achievements (cont.)

Roadmap Objective 3: Explore the space environment to discover potential hazards and search for resources that would enable permanent human presence	Expected Achievements: a) Complete (>90%) the inventory of NEOs larger than 1-km diameter b) Characterize potentially hazardous objects via telescopic remote sensing c) Study remotely the resource potential of a sample of accessible small bodies	Expected Achievements: a) Precisely track and characterize any NEO with an Earth impact probability of concern b) Explore near-Earth asteroid mineralogy in situ to determine resource potential	Expected Achievements: a) Develop technologies to alter trajectories of potential large Earth-impacting bodies. b) Study an L2 and NEO human-visit capability to understand need for robotic and piloted extraction of asteroidal resources for use in space and on Earth.

Expected Achievements (cont.)

Agency Strategic Objective: Conduct robotic exploration across the solar system for scientific purposes and to support human exploration.			
	Phase 1: 2005-2015	**Phase 2: 2015-2025**	**Phase 3: 2025-beyond**
Roadmap Objective 4: Understand the processes that determine the fate of the solar system and life within it	Expected Achievements: a) Determine the nature of interactions and balance of processes on/in Titan's surface, interior and atmosphere b) Quantify the nature of changes in Saturn's atmosphere d) Understand the evolution of satellite surfaces and ring structure	Expected Achievements: a) Study the nature of Pluto's surface and its evolution over time. b) Look for clues to the origin of the Pluto-Charon system c) Determine the composition of the surface of a typical Kuiper Belt object and hence constrain the origin of the Belt.	Expected Achievements: a) Determine the range of detailed properties of Kuiper Belt objects b) Quantify the composition and conditions within the deep envelopes of the giant planets, particularly Jupiter and Neptune c) Determine the origin of Triton's volatiles and the origin of this body's apparent early episode of melting/resurfacing

Expected Achievements (cont.)

Roadmap Objective 5: Determine if there is or ever has been life elsewhere in the solar system	Expected Achievements: a) Through the astrobiology program, determine plausible pathways for the origin of life on the Earth. b) Determine if there are organics on Titan distinct from those made by photochemistry, and accessible for study.	Expected Achievements: a) Determine if material from Europa's subsurface ocean is accessible to surface or near-surface-drilling study b) Deploy a mobile platform to study the detailed structure and composition of biogenically-relevant organics on Titan.	Expected Achievements: a) Determine if there is evidence of biological activity in selected materials sampled directly on Europa b) Drill into cryovolcanic flows on Titan for organic material evolved in the presence of liquid water c) Explore for life throughout the outer solar system.

Roadmap Requirements - Strategic Links

LUNAR

- Lunar sample analysis and field studies to understand the record of solar system processes preserved in the lunar surface materials is critical in understanding the process under which the solar system developed.

MARS ROBOTIC AND HUMAN EXPLORATION

- Understanding Mars from both a historical and current perspective will be part of understanding the full story of the development of the entire Solar System.
  - Understand the current state and evolution of the atmosphere, surface, and interior of Mars as part of understanding the development of the Solar System
  - Determine the nature of any habitable environments on Mars and if life exists or has ever existed on Mars

Roadmap Requirements - Strategic Links

EARTH-LIKE PLANETS & HABITABLE ENVIRONMENTS

- Studying both the Giant planets in our Solar System and understanding how they effect habitability
- Studying extrasolar planetary systems and understanding how they become habitable.

EXPLORATION TRANSPORTATION

- Exploration of the outer Solar System will necessarily require longer transit times and as more sophisticated science data is gathered, instruments with larger launch mass and volume will be required.
  - Heavy Lift Launch for high mass robotic missions
  - Precision Entry/Descent and Landing
  - In Space propulsion
  - In Space Automated Rendezvous and Docking (depending on design of launch and transfer vehicles)
  - Pre-Deployed surface/orbit assets (fuel, power, instruments, etc)
  - Surface Launch and Ascent/ sample Return to Earth

Roadmap Requirements - Strategic Links

SUN-SOLAR SYSTEM CONNECTION

- Specify and predict space weather at solar system destinations and along interplanetary routes. To include planetary atmospheric state (ascent, aerobraking, aerocapture, descent, landing) and ionospheric state (communications, navigation), and energetic radiation morphology and spectral content (reliability of electronics and materials).
  - Solar and Galactic Radiation environment prediction, detection, warning
  - Upper atmospheric characteristics (e.g., Titan, Neptune) for aerocapture
  - Magnetospheric science

Roadmap Requirements - Strategic Links

AERONAUTICAL TECHNOLOGIES

- Future Atmospheric vehicles

NUCLEAR SYSTEMS

- Radioisotope power supplies are critical for missions at extreme distances or extreme environments. Both in providing propulsion to/from the outer Solar System, and in communications and planetary surface investigations.
- Low Power Electric Propulsion may be enabling for a Jupiter Polar Orbiter or Neptune/Trition Orbiter Probe.