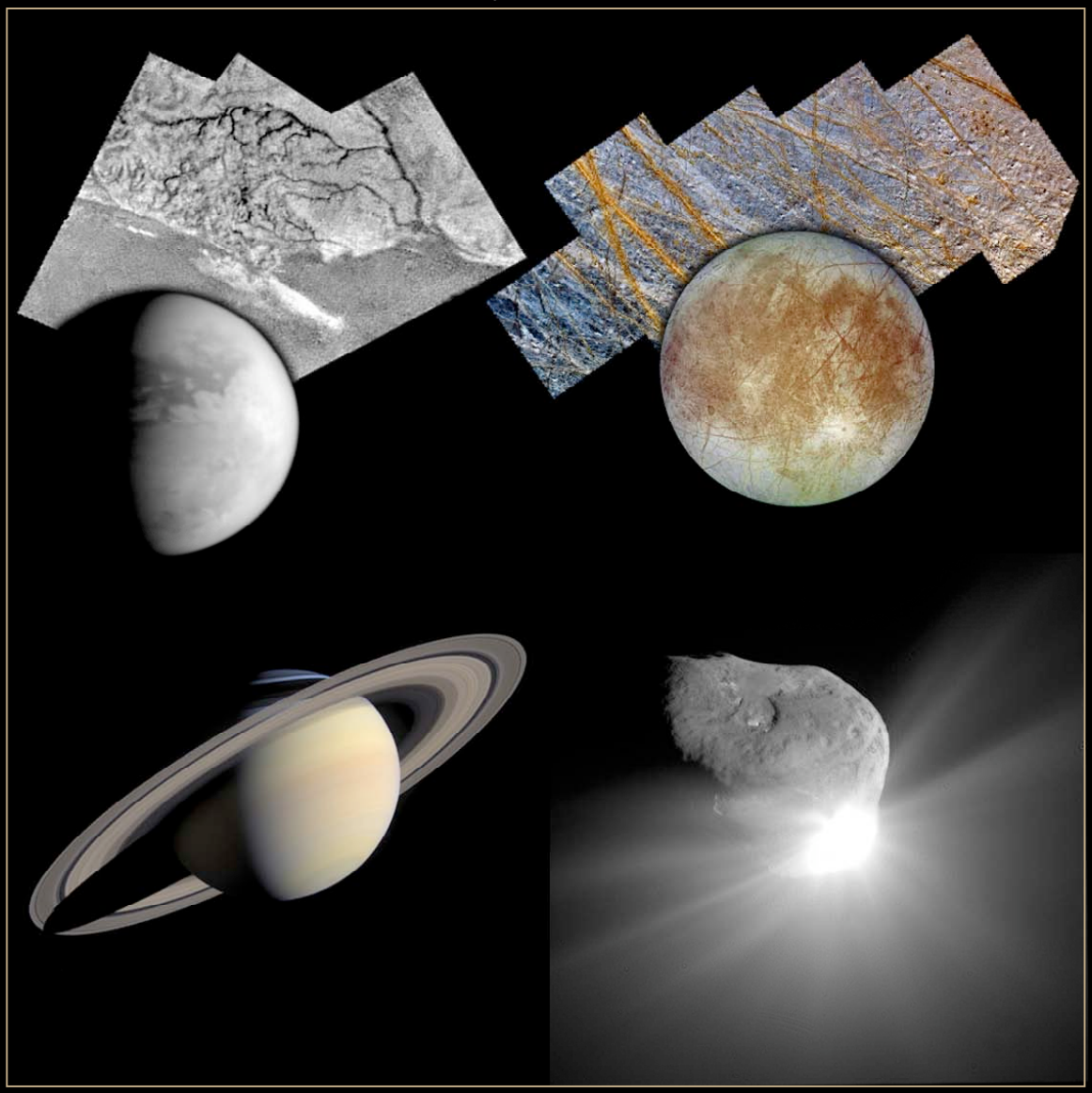
Scientific Goals and Pathways for Exploration of the Outer Solar System

A report of the Outer Planets Assessment Group (OPAG)
July 2006



OPAG is NASA's community-based forum designed to provide science input for planning and prioritizing outer planet exploration activities for the next several decades. It is chartered by NASA's Planetary Science Division and reports its findings to both the Division and at meetings of the Planetary Science Sub-Committee of the NASA Advisory Council. Open to all interested scientists, OPAG regularly evaluates outer solar system exploration goals, objectives, investigations and required measurements on the basis of the widest possible community outreach.

http://www.lpi.usra.edu/opag/

Front Cover (Graphics courtesy of Steve Bartlett):
Top Left - Cassini image of the disk of Saturn's largest moon Titan showing the Huygens landing site at dawn with (behind) Huygens images of surface channels. *Image credit: NASA/JPL/U of Arizona/SSI*
Top Right - Galileo images of Jupiter's moon Europa showing extensive fracturing of the moon's ice crust. *Image credit: NASA/JPL*
Bottom Left - Cassini image of Saturn. *Image credit: NASA/JPL/SSI*
Bottom Right - Deep Impact image showing the initial ejecta that resulted when the probe collided with comet Tempel 1 on July 4, 2005, taken by the spacecraft's medium-resolution camera 16 seconds after impact. Deep Impact showed that the comet was dusty, and contained complex materials such as clays, indicating it had been substantially processed. *Image credit: NASA/JPL-Caltech/UMD*

Executive Summary

The Outer Planets Assessment Group (OPAG) was established by NASA in late 2004 to identify scientific priorities and pathways for solar system exploration beyond the asteroid belt. The group consists of a 15-person steering committee which actively solicits input from the scientific community and reports its findings to NASA's Planetary Science Division and the Planetary Science Subcommittee of NASA's Advisory Council.

It is OPAG's goal that its findings represent the broad consensus of the scientific community. OPAG has held four meetings, in Virginia, Maryland, Colorado and California. Each meeting was attended by ~100 scientists. The meetings consisted of a broad range of presentations from NASA HQ representatives, mission PI's, individual scientists, and technology researchers. Each meeting included breakout sessions where scientists worked in small groups to prioritize scientific questions and mission requirements at specific destinations (e.g., Europa, Titan, giant planets, small icy bodies). Community input was solicited at the meetings and through the OPAG email list containing over 500 members.

This document is a summary of the consensus priorities, conclusions, and findings of those discussions. It expands and updates material relevant to the outer solar system presented in the National Research Council (NRC) Decadal Survey of 2003[*] and NASA's 2006 Roadmap for Solar System Exploration[**] (hereafter called the "Survey" and "Roadmap" and quoted in blue and green respectively). The major findings of OPAG's deliberations are:

Finding 1: Compelling Science – Important scientific discoveries continue to be made in the outer solar system through NASA missions and research programs. OPAG affirms the findings of the NRC Decadal Survey and NASA's 2006 Roadmap that the outer solar system provides critical clues to unraveling the mysteries of how solar systems form and evolve, how planetary systems become habitable, and how life has evolved in our solar system.

Finding 2: Steady, Balanced Strategy – Addressing these scientific questions requires a balanced strategy of outer solar system exploration that includes steady support for vigorous programs of basic research, data analysis, and technology development. Fundamental new discoveries are best made with a mixture of mission sizes that includes large flagship missions, along with small and medium-sized missions. A stable budget is crucial for continuity of scientific and technical capability. Such a strategy is most efficiently implemented as a coherent Outer Planets Exploration Program.

Finding 3: Mission Studies – OPAG encourages NASA to begin comprehensive mission studies toward destinations in the outer solar system in order to assess the technical feasibility, realistic cost and time frame of viable missions. OPAG affirms the findings of the Decadal Survey, COMPLEX, and SSES, that Europa is the top-priority science destination in the outer solar system. Titan and Enceladus are also important science destinations and OPAG urges NASA to evaluate potential missions to these targets.

---

[*] *New Frontiers in the Solar System: An Integrated Exploration Strategy*, National Research Council, 2003
[**] *The Solar System Exploration Roadmap*, NASA, July 2006

Several scientifically important destinations in the outer solar system require a flagship mission. Currently, there is a gap of 18 years and growing between the start of Cassini and the next flagship, a gap in which considerable scientific and technical expertise will be lost. OPAG strongly encourages NASA to complete concept studies of missions to important scientific targets in the outer solar system as soon as possible and with sufficient fidelity to inform a decision of the next flagship mission. Of particular importance for exploration of the outer solar system are radioisotope power systems (RPSs). Current availability of fuels and hardware for RPSs is extremely limited which severely limits NASA's ability to explore the outer solar system. OPAG urges NASA to support development of RPSs and to ensure supply of radioisotope fuels.

OPAG has organized an exploration strategy under the *theme* of "Making Solar Systems" - a short-hand phrase for the key issues of how solar systems originate and how such planetary systems become habitable. These same issues are highlighted by the Roadmap and the Survey.

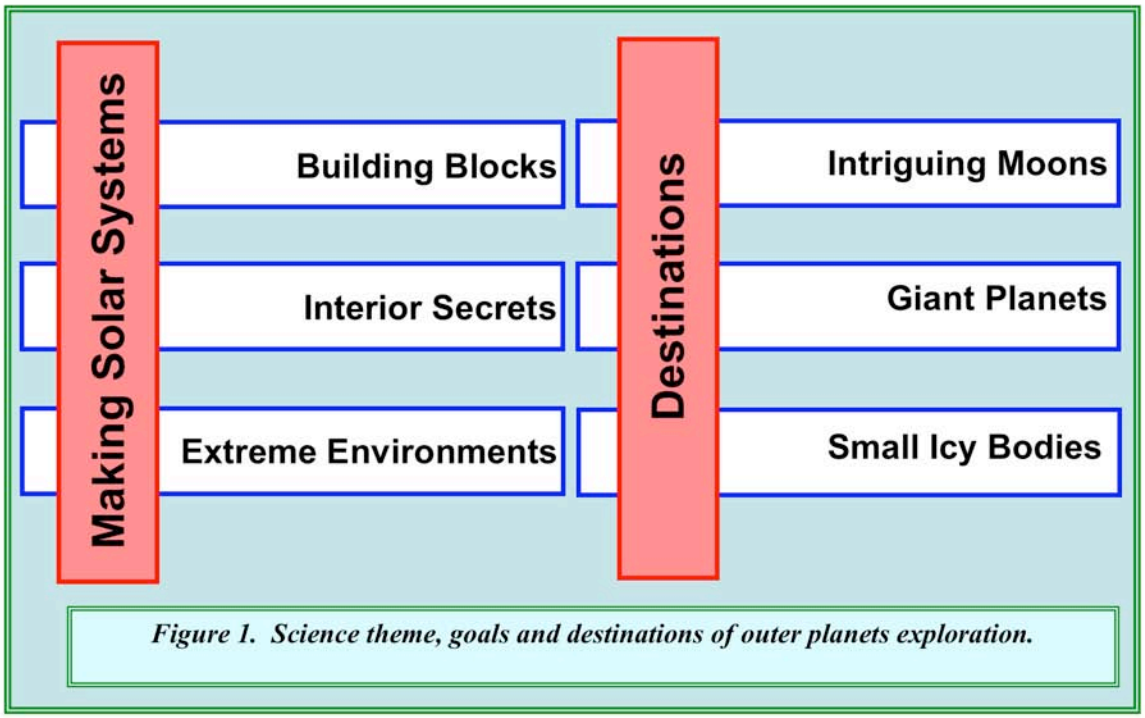


Figure 1. Science theme, goals and destinations of outer planets exploration.

Under the ***theme*** of Making Solar Systems, OPAG has identified three science ***goals***:

- ***Building Blocks:*** Characterize the locations, properties and history of small, relatively primitive bodies that may typify early solar system materials from which planets formed and may have supplied organic matter and volatiles that led to life.
- ***Interior Secrets***: Determine composition, structure, and other properties of the interiors of planetary bodies to provide vital clues about planetary formation and evolutionary processes.
- ***Extreme Environments:*** Ascertain the range of conditions that can support life and what planetary processes are responsible for generating and sustaining habitable worlds.

OPAG highlights three main types of ***destinations*** to address these science goals:

- ***Intriguing Moons:*** The larger moons of the giant planets are varied worlds whose interiors, surfaces and atmospheres reveal processes at different stages of planet evolution.
- ***Giant Planets:*** Comprising the bulk of the planetary mass of the solar system, the giant planets are key for understanding solar system formation and evolution.
- ***Small Icy Bodies:*** The smaller bodies of the solar system are thought to have undergone the least processing and comprise earliest materials that have been kept in "deep freeze."

1. Science Theme and Goals

Some of the most startling discoveries about our solar system have been made in the outer solar system. Currently, the Cassini/Huygens mission is opening up the Saturn system to us (see inset). Data from both the Cassini orbiter and Huygens probe revealed a remarkably Earth-like surface on the moon Titan, including evidence for a recent "hydrological" cycle. Cassini took images of the captured moon Phoebe that indicate it originated farther out and is a relic older than the planet it now orbits. At Enceladus, Cassini has discovered plumes of water vapor emerging from the south pole, indicating that this small moon possesses reservoirs of liquid water.

For nearly eight years in orbit around Jupiter, Galileo showed us that Jupiter is a complex, dynamic, interacting system. Europa's evidence for recent liquid water and subsurface oceans is well-known now, but was not even suspected before Galileo's high-resolution imaging of the surface in 1997. A warm, wet Europa led to the realization that Io is not the only moon being pushed and squeezed by Jupiter's tidal forces. One of the strongest pieces of evidence of liquid water beneath Europa's icy surface was the magnetic signature of electrical currents induced in a global ocean. Similar magnetic signatures were observed at both Callisto and Ganymede, suggesting they too may have convecting, saltwater oceans hidden beneath their surfaces. Galileo data revealed Ganymede as the first moon found to generate its own internal magnetic field. Galileo's probe performed the first-ever atmospheric sampling of a giant planet, and found the surprising result that Jupiter's composition is distinctly different than the Sun, enhanced in heavy elements by a factor of three. This has challenged modelers to explain how Jupiter and the Sun ended with different compositions, even if they started with the same raw components.

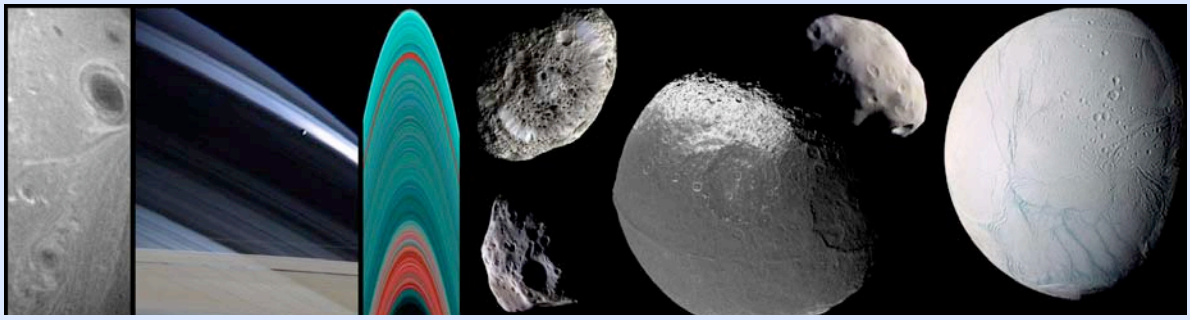
The Deep Impact mother-ship imaged Tempel 1 as the daughter-ship crashed into the comet in July, 2005. Results from this mission indicated two surprising things. First, the comet was not covered with blocks of ice and rock, as expected. Rather, the surface was almost entirely covered with thick deposits of microscopic dust. It is unknown what the history of this dust is, and how it could be retained on the surface in such large quantities. Second, spectra of the comet and its plume revealed a rich abundance of chemical species, including organic materials (called PAHs), carbonates, and clays. PAHs indicates substantial chemical processing, while carbonates and clays are tracers of liquid water on the surface. These findings are puzzling because comets are thought to have been in a "deep freeze" since their formation, and liquid water would not be present for any substantial length of time.

In January 2006 the Stardust mission returned to Earth samples of comet Wild-2, an object that was thought to have spent much of its history in the outer solar system until perturbations to its orbit brought it to the inner solar system. Grains of high-temperature-formed olivine have been found in the dust collected from comet Wild-2. This surprising result indicates that although comets spend most of their lifetime as cold bodies at the outer solar system, they managed to nevertheless integrate substantial components that condensed very near the Sun. This shows early solar system objects may have traveled much greater distances or that the original nebula had been stirred up more than imagined.

NASA missions of the past decade have shown us new, wondrous worlds in the outer solar system. They have provided pieces of the solar system formation puzzle. But exploration consistently yields just as many questions as it does answers. Future missions will address many of our open queries, but will almost certainly pose further questions for future generations.

Some of Cassini's science highlights include:

- Huygens probe revealed that Titan's surface has been remarkably Earth-like in the recent past, complete with evidence for methane rain, erosion, drainage channels, and dry lake beds.
- Cassini provided the first detailed global view of Titan's surface, including volcanoes, rain clouds, flow features, lakes, craters, and vast dune fields, as well as other still-puzzling terrains. A soup of complex hydrocarbons has been detected in Titan's atmosphere.
- The Cassini cameras took the highest resolution images ever of Saturn's rings and Cassini fields and particles instruments measured the in situ ring environment as the spacecraft skimmed above Saturn's rings just after Saturn orbit insertion. Discoveries included straw-like clumps several kilometers long in the A ring, an oxygen atmosphere just above the rings, signatures of marble-sized meteoroids impacting the rings, and evidence for slowly rotating ring particles.
- Saturn's F ring continues to change as we watch it. A nearby moon, Prometheus, was imaged stealing particles from its strands. A new moon was discovered lying in, and causing, the Keeler gap. Objects have been found (and lost) in the F ring, possibly transient clumps of debris. Clumpy ringlets in the Encke gap also evolve as they interact with Pan, the Encke moonlet, and probably other local objects.
- A new and completely unexpected radiation belt was discovered around Saturn between the inner edge of the D ring and the top of Saturn's atmosphere.
- Iapetus, the two-faced moon has an equatorial mountain range that is 20 km high in some places, twice the height of Mt. Everest.
- Phoebe is a crater-scarred world, with large landslides revealing bright water ice on crater walls and patchy clustering of silicate and organic material. The volatile ices tell us that Phoebe must have formed in the outer solar system and then was captured by Saturn's gravity - a survivor of objects much older than Saturn itself.
- At Enceladus Cassini found plumes of micron-sized particles propelled by a mixture of gases including water vapor, carbon dioxide, nitrogen, and methane emanating from bottoms of kilometer-wide troughs (“tiger stripes”) at the south pole. Near the tiger stripes the spacecraft saw fresh ice crystals and organics, with some area too warm to be heated by sunlight alone. An internal heat source of uncertain origin is necessary, and the steep subsurface temperature gradient implies water may be liquid within tens of meters below the surface.
- The magnetic field measured by Cassini in the environment outside Saturn seems to be drifting at a variable rate that is not tied to the rotation of the deep interior. These observations mean that we do not know the most basic property of the planet, its rotation rate, upon which such things as atmospheric winds are based.
- Infrared and radar images revealed a menagerie of atmospheric features below the upper layer of ammonia clouds - including "blocky" clouds, waves, donut-shaped clouds, a surprisingly large number of zone/belt structures.
- Storms on Saturn are rare but powerful. The electrostatic discharges from lightning bolts are a factor of 1000 times stronger than terrestrial lightening. During lightning storms, the discharges occur every few seconds. The storms are rare - only one or two storms occur on the planet per year – and typically last one to two weeks. Scientists are debating whether the rarity observed by Cassini are consistent with observations made by the Voyager spacecraft. Could there be seasonal variations in the occurrence rates?



These discoveries illustrate the wide variety of spectacular science offered by exploration of the outer solar system and lead to OPAG's first finding:

> **Finding 1: Compelling Science** – Important scientific discoveries continue to be made in the outer solar system through NASA missions and research programs. OPAG affirms the findings of the NRC Decadal Survey and NASA's 2006 Roadmap that the outer solar system provides critical clues to unraveling the mysteries of how solar systems form and evolve, how planetary systems become habitable, and how life has evolved elsewhere in our solar system.

Making Solar Systems

The Survey and Roadmap are substantial documents that lay out in great detail the outstanding scientific issues and the rationale for exploration of the solar system. The Roadmap lists five specific scientific objectives:

1. *How did the Sun's family of planets and minor bodies originate?*
2. *How did the solar system evolve to its current diverse state?*
3. *What are the characteristics of the solar system that led to the origin of life?*
4. *How did life begin and evolve on Earth and has it evolved elsewhere in the solar system?*
5. *What are the hazards and resources in the solar system environment that will affect the extension of human presence in space?*

The outer solar system plays key roles in all five objectives. The diversity of objects in the outer solar system spans a range of sizes, compositions, and evolutionary states that allow us to piece together the history of the solar system and its habitability.

The unmatched diversity of bodies in the outer solar system provides the opportunity for a wide variety of scientific investigations. The giant planets provide insight into solar system formation through studies of their atmospheric 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 comparably-sized worlds that have experienced very different geologic histories. The rings and magnetospheres of the giant planets illustrate currently-active processes (of collisions and momentum transfer) that played important roles in early stages of solar system formation. Smaller bodies, either in clusters (such as Trojans, Kuiper Belt objects, or captured irregular moons) or as individuals, provide clues about the raw planetary materials–including organic materials and pre-biotic chemistry.

The Survey provides a detailed summary of current theories of formation of the solar system as well as listing important academic references. Here we provide a précis of the major scientific issue of how solar systems – not just ours but also the 100+ other solar systems discovered to date – came to be the way they are, and the role of exploration of the outer solar system in helping us turn a rough sketch into a clear picture.

It is perhaps common to think of the formation of a solar system as a single, simple, rapid act. In fact a solar system is thought to come to a configuration such as that illustrated by our own example through a series of complex, currently poorly-understood processes, as illustrated in Figure 2. The very different natures of solar systems detected to date (generally with large planets close to the central star) indicate that important differences in initial conditions can produce totally different configurations.

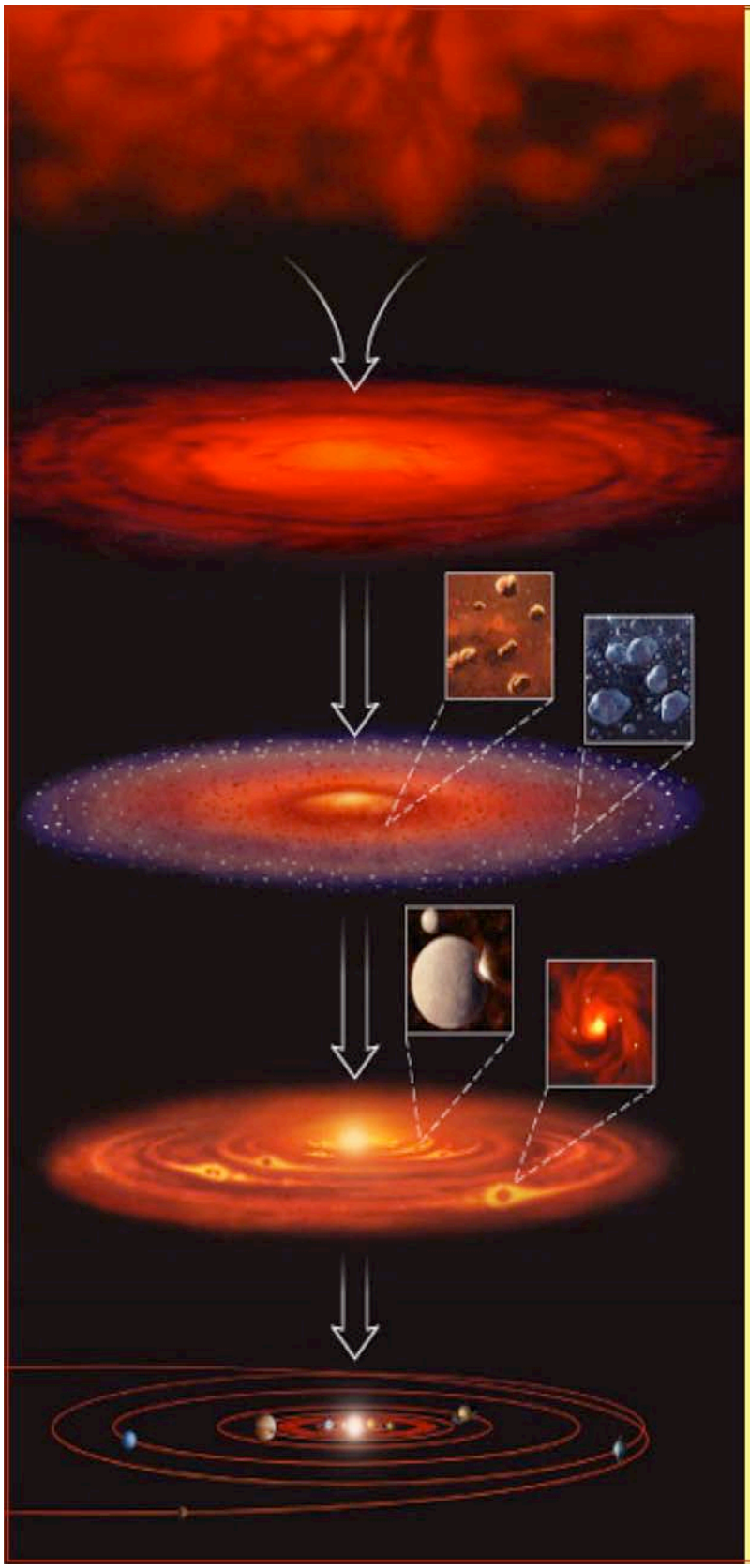


Figure 2 - Solar System Formation

Contraction of the Solar Nebula: A large, diffuse interstellar gas cloud contracts due to gravity. As it contracts, the cloud heats, flattens and spins faster, becoming a spinning disk of dust and gas. The Sun will form in the center. Planets will form in the disk.

Condensation of Solid Particles: The abundant elements hydrogen and helium remain gaseous, but other materials can condense into solid "seeds" for building planets. Warm temperatures allow only metal/rock "seeds" to condense in the inner solar system. Cold temperatures allow "seeds" to contain abundant ice in the outer solar system.

Accretion of Planetesimals: Solid "seeds" collide and stick together. Larger ones attract others with their gravity, growing bigger still. The small, terrestrial planets of the inner solar system are built from the less abundant metals and rocks. The abundant ices forming "seeds" of the jovian planets grow large enough (several Earth-masses) to attract hydrogen and helium - the most abundant elements in the nebula - making them into giant, mostly gaseous planets. Moons form in the disks of dust, ice and gas that surround these proto- giant planets.

Clearing the Nebula: The solar wind blows remaining gas into interstellar space. Small, rocky terrestrial planets remain in the inner solar system. Jovian planets remain in the outer solar system. "Leftovers" from the formation process become asteroids (metal/rock), Kuiper Belt objects (rock/ice) and comets (mostly ice).

Adapted from Bennett, Donahue, Schneider & Voit, "Cosmic Perspectives (4th Edition)", by permission of Addison Wesley.

Two critical factors control the character and location of planets that formed in the solar nebula: (a) the fact that the nebula is colder farther from the Sun, and (b) the relative abundance of elements in the nebula. The nebula was overwhelmingly dominated by hydrogen. When hydrogen combined with the next most abundant elements (oxygen, nitrogen, and carbon), molecules of water, ammonia, and methane were formed. The nebula contained relatively small amounts of metals and rock-forming elements. In the inner solar system, where temperatures were warmer, only metals and rocks initially condensed. At the low temperatures of the outer solar system the abundant water, ammonia and methane condensed as ices. Thus, at about 3 AU there formed a "snow line" inside of which relatively few rocky planetesimals formed and outside of which large masses of icy planetesimals grew into giant snowballs. This distinct separation of the solar system into two regions explains why there are two distinct types of planets: small, rocky inner planets and giant, gaseous outer planets and why the bulk of the mass of the solar system lies in the outer solar system, beyond the original "snow line."

Figure 2 describes the first main phases of solar system formation that lasted ~10 million years: contraction of the nebula, condensation of solids, accretion of planetesimals and clearing of the nebula. But the story does not end there. There is a complex endgame that involves (a) migration of the outer two giant planets, Uranus and Neptune, from somewhere closer to the Sun to their present locations; (b) giant planets scattering icy planetesimals into the inner solar system (delivering water and other life-critical volatile materials to the terrestrial planets); (c) scattering of planetesimals out to the Kuiper Belt and the Oort Cloud; (d) capture of planetesimals by the giant planets as irregular moons. The scattering of the leftover planetesimals seems to have died down quickly about 3.7 billion years ago (as shown by the impact craters on the Moon, the dates of which are revealed by the Apollo Moon rocks). Even with the leftovers of formation dispersed, the solar system continued to evolve–denser materials (e.g. iron, denser rock) settled down into the interiors of planetary bodies driving processes in the deep interior such as magnetic dynamos; heat from the interior of planetary objects (in the cases of moons sometimes further fueled by tidal interactions) driving geological re-working of their surfaces; gases escaping from the interior form atmospheres which interact with surface materials and are bombarded by photons and particles from space; gravitational perturbations by Jupiter continue to change the orbits of objects in the asteroid belt; comets are occasionally scattered in from the Oort cloud; and the ring systems around the giant planets exhibit dynamical evolution on timescales of a few million years. The dramatic impacts of the fragments of comet Shoemaker-Levy 9 into Jupiter in the summer of 1994 demonstrated that our solar system continues to change.

At what point in this business of making solar systems does life come in? The Survey notes "Life on Earth is thought to be a product of the confluence of the necessary materials and an event of origin. The necessary materials include liquid water, carbon-bearing molecules, and energy, all of which were present on early Earth. Life arose early in our planet's history. One widely held view is that life arose at least 3.5 billion years ago, and perhaps as much as 3.8 billion years, but the origin event or events remain unknown and the exact timing is uncertain. Organic molecular material carrying complex assemblages of carbon, hydrogen, oxygen, and nitrogen was delivered to the sterile early Earth by comets and asteroids, and some may also have been formed by impact events in the early ocean and atmosphere. Complex organic material exists in interstellar dust in our galaxy and others and thus predates the Sun and planets. However, as researchers survey the primitive bodies and planets of the solar system, they find compelling evidence not only of the preservation of ancient organic matter but also of the formation and destruction of organic molecules in modern environments. Water, too, is common both in interstellar space and throughout the solar system, though its presence in the liquid phase depends on special

circumstances of temperature and pressure. In several cases, however, even where water is not now a liquid, there is evidence that the liquid phase once existed. Thus, a search for organic matter in the solar system is an exploration of the range of environments in which life may have originated and a search for an understanding of our own origins as well."

To encompass this wide array of science, OPAG has adopted the over-arching ***theme*** for outer planets exploration of **Making Solar Systems** – a short-hand phrase for the key issues of how solar systems originate and how such planetary systems become habitable.

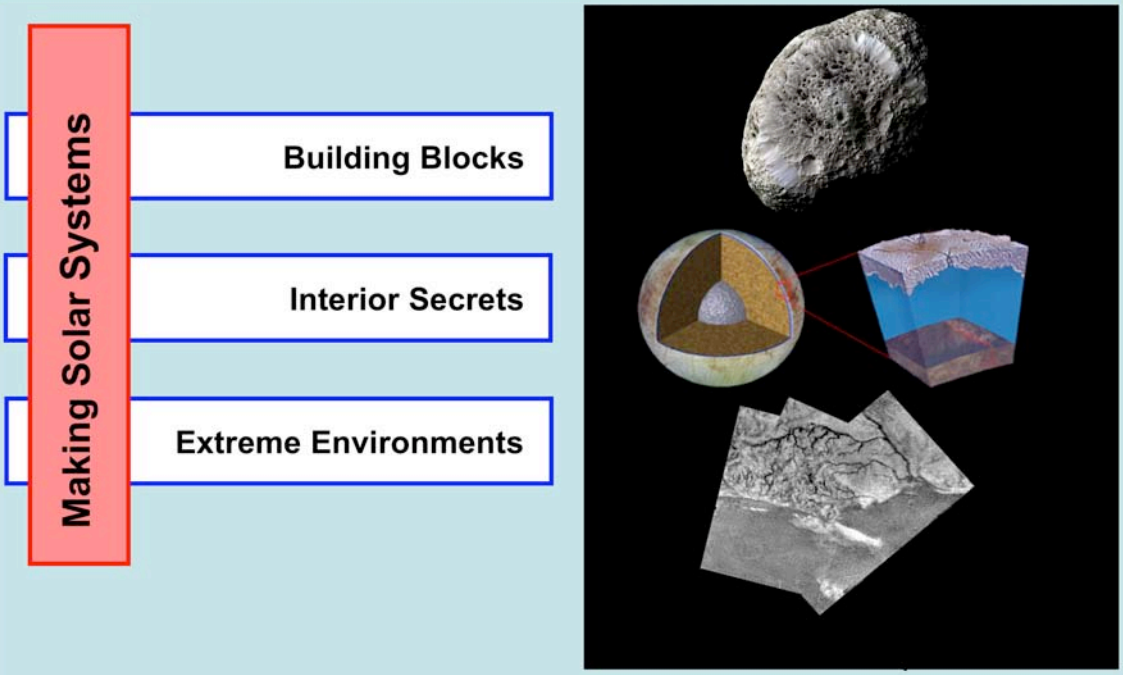


Figure 3 *- Under the theme of making solar systems, OPAG's three main scientific goals are to measure the properties of the building blocks of solar systems, to probe the interiors of planetary bodies, and to explore the extreme environments in which life may have developed.*

Under the **theme** of Making Solar Systems, OPAG has drafted three science ***goals***:

- ***Building Blocks:*** Characterize the locations, properties and history of small, relatively primitive bodies that may typify early solar system materials from which planets formed and may have supplied organic matter and volatiles that led to life.
- ***Interior Secrets***: Determine composition, structure, and other properties of the interiors of planetary bodies to provide vital clues about planetary formation and evolutionary processes.
- ***Extreme Environments:*** Ascertain the range of conditions that can support life and what planetary processes are responsible for generating and sustaining habitable worlds.

Below we elaborate on each of these three goals.

Building Blocks

The holy grail of planetary science is a piece of the raw solar nebula from which planets condensed. Spacecraft are dispatched in search of "primordial" or "primitive" materials. The Survey discusses the places where such materials may be found: "Primitive bodies are highly varied in size, surface properties, composition, and probably origin. Apart from interplanetary dust, these bodies range in size from a few tens of meters to 2,500 km (Pluto and Triton). Some

are snowy white, while others are charcoal black. Some have igneous and other minerals on their surfaces, while others have ices, and still others have combinations of ice and rock. Simple and complex organic chemicals are plentiful. The asteroids have highly varied compositions, with combinations of rock, metal, and organic compounds, while comets contain the same materials in a matrix of ices of various compositions. Some asteroids have been thoroughly melted, while others have not. Some comets have been externally heated, with consequent changes in internal structure, but others appear to have been entirely unchanged since they formed. Interplanetary dust near Earth appears to come from both comets and asteroids, and it contains minerals and organic solid matter. Triton, Pluto, Charon, and probably several large Kuiper Belt objects have icy surfaces and have probably been heated sufficiently for their interiors to differentiate. Pluto and Triton have significant atmospheres. Triton is geologically active; Pluto and other bodies in this region of the solar system may also be active, and volatile transport clearly takes places on bodies such as Triton and Pluto. Their surfaces record their bombardment histories, hence the collisional history of the Kuiper Belt population." This discussion shows that the search for truly primordial material may be elusive. On the other hand, it is the smaller, less processed objects of the outer solar system that provide the best opportunities for finding pieces of the complex puzzle of solar system formation. At the same time, the scenario for solar system formation presented above makes it clear that multiple samples from different regions will be needed to really complete the story. Under the label **Building Blocks** is the scientific goal to *characterize the locations, properties and history of small, relatively primitive bodies that may typify early solar system materials from which planets formed and may have supplied organic matter and volatiles that led to life.*

Interior Secrets

Of all the mass of planetary material in the solar system, 99.6% is hidden from view inside the giant planets. A few parameters (e.g. bulk density, shape, heat flux and subtleties of their gravitational fields) constrain models of the interior of planets but mostly scientists rely on their best ideas of plausible compositions and structures - plus the laws of physics - to construct their models. Without true understanding of the interiors of the giant planets it is dubious to claim understanding of the solar system and its formation. Did each giant planet form like a star, from an instability in the gaseous nebula, or from the accretion of a rock/ice core followed by gravitational capture of nebular gas? Did all four giant planets form the same way? What processes led to the differences between the Jupiter/Saturn pair and the Uranus/Neptune pair? Measurements that constrain the presence/absence and size of a core will help answer such questions. What is the abundance of water in each planet's deep atmosphere? Determining the water abundance would help distinguish between different formation scenarios, as well as provide clues as to how volatiles like water were delivered to the inner solar system. Probes carrying instruments that measure chemical and physical properties can tell us about the superficial gaseous layers of the giant planets while measurements of the gravitational, magnetic and thermal fields of a planet from multiple close orbits provide valuable constraints on interior models. Planetary objects with solid surfaces reveal clues about their interior workings from the geological processes evident from the outside. Volcanism and tectonics are evidence of reworking of outer layers of the planet while the density of craters in different geological regions give us some idea of how recently the geological activity occurred. Probing of the Earth's interior using seismology and other geophysical techniques has provided experience in at least how one planet is constructed. To date, the exploration of the interiors of other planets is largely limited to remote sensing techniques. Under the label **Interior Secrets** is the scientific goal to *determine composition, structure, and other properties of the interiors of planetary bodies to provide vital clues about planetary formation and evolutionary processes.*

Extreme Environments

The discovery of the presence of living organisms on Earth under extreme conditions of temperature, pressure and chemical environments has opened up the range of possible planetary environments that might lead to the persistence of life. The first issue to address is of habitability in planetary environments: how have specific planetary environments evolved with time, when and in what way were they habitable, and does life exist there now? Pragmatically, the primary investigation of habitability is a search for liquid water. In the outer solar system this means finding places where there is a source of heat to keep water from freezing. The secondary question is the availability of a reservoir of organic materials and stable conditions that provide the opportunity for complex chemistry to develop, without excessive disruption by planetary impacts or by high fluxes of energetic charged particles trapped in the magnetospheres of the giant planets. Under the label **Extreme Environments** is the scientific goal to *ascertain the range of conditions that can support life and what planetary processes are responsible for generating and sustaining habitable worlds.*

Mapping OPAG Goals to the Survey and the Roadmap

Of the six "continuing mysteries about the solar system" listed in the Survey, four are directly related to the outer solar system. It is not surprising, therefore, that all but two of 12 scientific questions that the Survey prioritizes to resolve these mysteries map onto the main scientific goals identified by OPAG under the basic theme of Making Solar Systems. Similarly, the five scientific objectives listed in the Survey also map to OPAG goals.

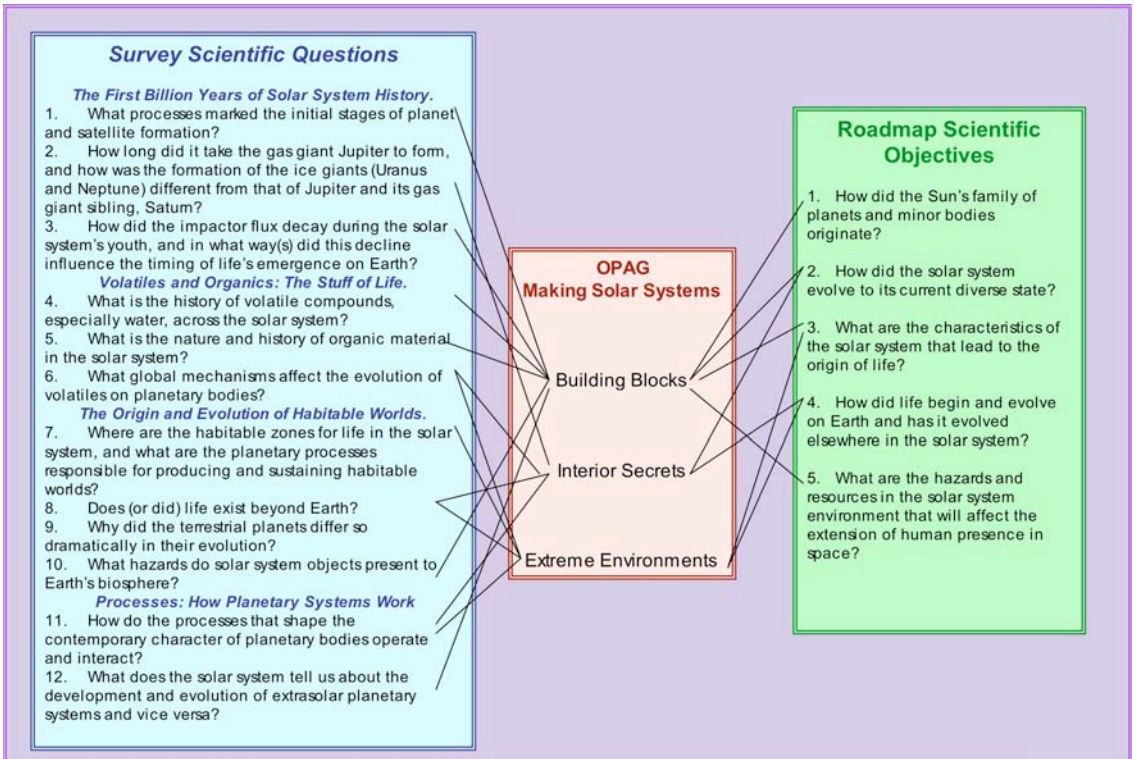


Figure 4 - Mapping of scientific questions from the Survey and scientific objectives of the Roadmap onto OPAG scientific goals under the theme of Making Solar Systems.

2. Outer Planets Exploration Strategy & Priorities

Several factors make exploration of the outer planets exceedingly difficult. The vast distances covered, the extreme environments encountered, and long duration of missions present unique challenges. The diverse bodies also complicate strategic planning. Past missions (Figure 5) have demonstrated that when we choose to meet these challenges the results consistently and radically alter our understanding of the solar system. The science described in the previous sections builds upon those results, and its pursuit will continue to improve our understanding of our solar system and others in fundamental ways.

A multi-pronged approach is needed to address the broad scientific goals and to meet the challenges of outer solar system exploration. The program elements required to provide this depth are (not in priority order):

- Mission size mix
- Periodic flagship missions
- Sustained and focused technology development
- Research & Analysis
- Mission concept studies
- Strategic planning

NASA has implemented some or all of these elements to varying degrees since the 1970s. As NASA moves beyond the initial discovery phase and into a phase of focused scientific enquiry we need a systematic approach that develops an exploration strategy, anticipates future technological needs, builds on investments in active/past missions, as well as takes advantages of opportunities as they arise. With the particularly long timescales of outer solar system exploration, NASA has to look beyond the current mission and start planning the next mission.

Currently, these elements are supported by disparate parts of NASA. There is no single program that unites these key elements into a cohesive, strong, and efficient program. These elements would be better integrated and more efficiently implemented by creating an Outer Planets Exploration Program at NASA. The purpose of this program is to make an orchestrated attack on the primary scientific theme of Making Solar Systems presented in Section 1 above. An Outer Planets Exploration Program will be responsible for optimizing resources by coordinating the different elements listed above on a coherent, productive path.

Exploration of the outer solar system operates on decade timescales. This means that planning, development, construction and operation of missions requires a budget that is stable for such timescales. A budget that lurches forward and back on an annual cycle greatly exacerbates execution of missions, raises net costs and wastes taxpayers' funds. OPAG urges NASA's Planetary Science Division to develop a long-range budget planning cycle that allows a stable platform for operating a successful scientific program. Below we elaborate on the roles of each program element in an Outer Planets Exploration Program.

Mission size mix

Figure 5 lists NASA missions to outer solar system targets and illustrates the graduated approach of exploration that starts with smaller spacecraft with limited capabilities making an initial foray (e.g., the Pioneers crossing the asteroid belt and traversing the radiation belts of Jupiter), followed by a larger, more complex spacecraft with a wide range of scientific

Past, Current and Future Missions to the Outer Solar System

NASA launched Pioneer 10, the first outer solar system mission, on March 2 1972. Pioneers 10 and 11 were rapidly developed, launched and reached Jupiter all within five years. As missions ventured into the outer reaches of the solar system, their durations have stretched into decades. In the case of Voyager 2, the mission made 10 years of planetary measurements at Jupiter (1979), Saturn (1980), Uranus (1986) and Neptune (1989). As the scale of missions grew with orbiters Galileo and Cassini, the time from inception to launch increased, they took longer to reach their primary targets of Jupiter and Saturn and the time spent gathering data in orbit around those planets increased. Exploration of a distant comet (Rosetta) and Pluto (New Horizons) involve cruise phases on the order of a decade. All missions since Cassini except for Rosetta (an ESA mission with NASA participation) are PI-led missions that were selected via a competitive process under either the Discovery or New Frontiers programs. Juno, a mission to explore the interior and polar regions of Jupiter, was selected in 2005 and is planned for launch in 2011. The next AO for New Frontier mission concepts is delayed until FY2008 at the earliest. The most recent flagship mission, Cassini, was started as a joint NASA/ESA venture in 1988, selected for flight in 1991 and launched in 1997.

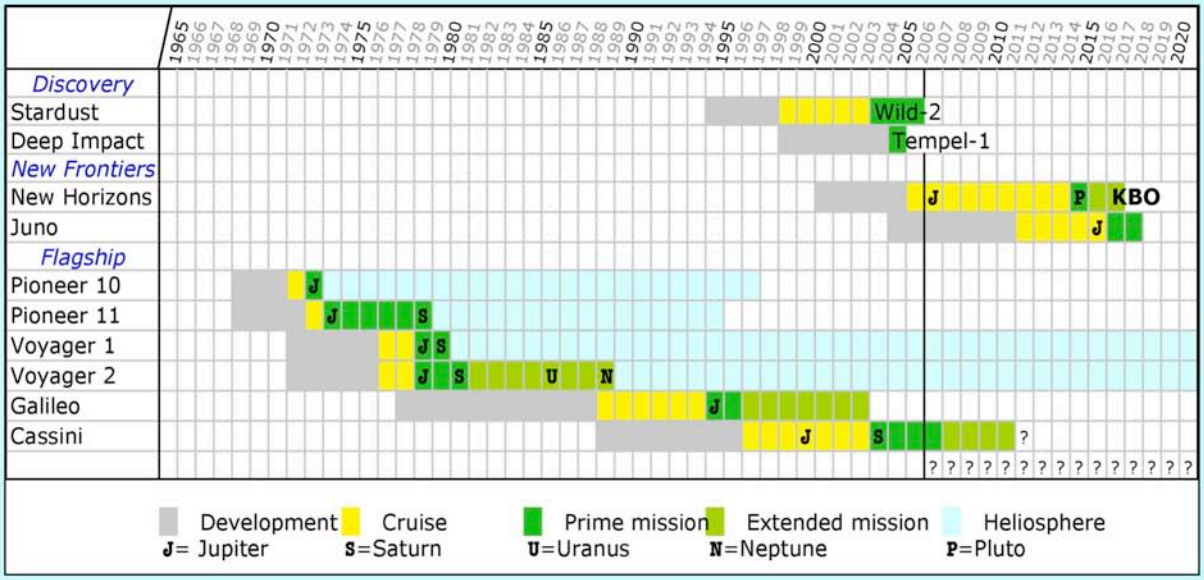


Figure 5 - NASA Missions to the outer solar system. Note the increase in development times, cruise durations, as well as extended lifetimes of missions. There are no flagship missions under development. The most recent flagship mission, Cassini, was started over 17 years ago. While the Pioneer missions are included under flagship missions, they were considerably smaller in scope and budget than the subsequent missions. There are also ESA missions (Ulysses, Rosetta) with NASA contributions. The New Millennium (technology) mission Deep Space 1 visited a comet at 1.5 AU.

instruments that makes a broad survey (e.g., the Voyagers flying past the giant planet systems), leading to an in-depth study of a particular system with a well-instrumented orbiter that spends several years investigating the many scientific aspects of a particular planetary system (e.g., Galileo at Jupiter and Cassini at Saturn). As we became more familiar with the outer solar system it became clear that smaller missions could address specific, focused issues. Discovery missions have explored two comets and New Frontiers missions are targeted at Pluto and Jupiter's interior/polar regions. Each type of mission has its virtues and NASA can optimize the scientific return on the taxpayers' financial resources by utilizing a mix of mission scales.

The Three Classes of Missions to the Outer Solar System

- ***Discovery:*** (~5 years, ~$425M) Quick implementation, addresses focused questions, innovative
- ***New Frontiers:*** (~10 years, ~$750M) Discovery-style missions to more challenging targets
- ***Flagship:*** (15-20 years, $1-3B) Missions to strategic targets and addressing broad scientific goals, high return from several coordinated scientific investigations, lowest cost-per-science-instrument, complex or multiple targets

Flagship Missions: Flagship missions are required to address important scientific objectives in the outer solar system. They either carry a large complement of instruments and dwell for longer periods of time in a planetary system or tackle a particularly challenging objective (e.g. orbiting Jupiter or Saturn). These missions address a broad range of major scientific goals and are the largest missions (total mission costs of $1-3B, end-to-end timescale of 15-20 years). Cassini is the archetype flagship mission – carrying 12 scientific instruments. The mission started development in 1989, was launched in 1997, and entered orbit around Saturn in 2004. The Cassini spacecraft carried the ESA-built Huygens probe with six additional instruments. Huygens was dropped into the atmosphere of Titan and returned pictures from the surface on January 14, 2005. The Cassini mission has been spectacularly successful. It is planned to continue through 2008 with a possible extension through 2012. As of May 2006 Cassini has returned over 140 gigabytes of data.

Currently, there are no flagship missions to the outer solar system under development. Thus, we are looking at a gap, unprecedented since the 70s, of over 18 years between flagship starts in which scientific and technical expertise will be lost. Even if a flagship mission were started today, it would be unlikely reach its target before 2020.

Findings on Flagship Missions

- Several scientifically important destinations in the outer solar system require a flagship mission.
- It makes every sense to take full advantage of having such a scientifically productive spacecraft as Cassini in orbit around Saturn. OPAG strongly supports an extended mission with appropriate support for analysis of data.
- Currently, there is a gap of at least 18 years between the start of Cassini and the next flagship, a gap in which scientific and technical expertise will be lost.

- Recognizing the recent trends of escalating costs of large missions within NASA's SMD, OPAG advocates that all studies of missions involve scientists working closely with mission engineers and that these studies must be subject to a review of technical, management and cost by an independent body. OPAG is concerned that any delays and/or cost over-runs of the next flagship mission might jeopardize the long-term goals for scientific exploration of the outer solar system.

New Frontier Missions: This mission line was initiated to address scientific objectives that require larger missions, costing ~$750M. New Frontier missions are PI-led and selected via competition. The list of targets are currently restricted to specific top priorities of the Decadal Survey (unlike the open solicitation for Discovery missions). The first two New Frontiers missions are the New Horizons mission to Pluto and the Juno mission to Jupiter. Some of the closer small bodies (e.g. Trojan asteroids, captured satellites, Centaurs) are also possible targets for a New Frontiers class of mission. A focused mission to Titan or a Saturn flyby with atmospheric probes might fit within the New Frontiers envelope.

Finding on New Frontier Missions:

- OPAG supports an AO for the 3rd New Frontiers mission in the 2008 timeframe and encourages NASA to make the scope of the AO broad. For example, some of the closer primitive bodies (e.g. Trojan asteroids, captured satellites, Centaurs) are possible targets for New Frontiers missions. OPAG encourages NASA to allow such missions within the next AO for New Frontiers missions.

Discovery Missions: Although most missions to the outer solar system involve vast distances, long durations and large budgets, there are some targets of focused science in the outer solar system that can be achieved within the Discovery program. The FY06 AO for Discovery mission concepts has a budget cap of $425M. With a cadence of approximately 18 months, generally two or three missions are selected for Phase A study of which one is selected for flight. Of the eight Discovery missions that have been selected for flight since 1996, two have successfully gathered data from objects originating in the outer solar system – Deep Impact and Stardust.

Findings on Discovery Missions:

- OPAG notes the value of Discovery missions in the exploration of the outer solar system.
- Given that radioisotope power systems (RPS) expand the opportunities for outer solar system exploration, OPAG recommends NASA explore ways to include the use of such power systems in the Discovery program.

Sustained and Focused Technology Development:

The outer solar system is a difficult place to explore: flight times are long, payload mass is limited, the flux of sunlight is low, atmospheres can be extremely deep or virtually nonexistent, surfaces are cold, and radiation environments can be high. For many missions specified in the Decadal Survey, advanced technology is required to either enable the mission, or enhance it by increasing its scientific return, or decreasing its cost/risk.

In the outer solar system few missions can operate with only solar power, making the development and testing of efficient radioisotope power systems a high priority. OPAG is particularly concerned that NASA procure an adequate supply of radioisotope fuels. Outer planet

missions intrinsically require high power because of their greater distances; a Europa mission could require 1 KW. However, providing this power for future missions may be difficult, for two reasons. First, the SiGe thermocouples used in RTG missions from Galileo through New Horizons are no longer produced. Sufficient parts are currently available for only 2-3 RTG units, each producing ~290W of electrical power using ~8 kg of Pu-238. Second, the amount of Pu-238 fuel available is severely limited. Domestic production of Pu-238 is estimated to start at Idaho National Laboratory no earlier than 2013, and the amount available to NASA would be no greater than 2.5 kg/yr. NASA is currently developing high-efficiency RPS systems that could have efficiency of up to ~4 times the Cassini-style RTGs. These are expected to be available for use by 2013. Exploration of the outer solar system depends critically on the availability of these power sources, and OPAG encourages NASA to continue to develop power systems.

OPAG also notes that NASA does not have a solar power research program, and recent missions such as Juno have demonstrated the feasibility of solar-powered outer solar system missions to targets previously considered out of reach. Development of higher-capability solar power would, amongst other benefits, ease pressure on the finite Pu-238 supply.

Outer solar system missions depend on robust and capable telecommunications provided by the Deep Space Network. Current DSN capabilities must be maintained (e.g. by replacing older antennas as necessary) to enable future outer solar system missions. Upgrades of DSN capabilities beyond their current level would significantly enhance future missions.

Findings on Key Technology

- Advances in technological capabilities can enable or greatly enhance scientific missions to the outer solar system. Of particular importance for exploration of the outer solar system is the developing and testing of radioisotope power systems as well as ensuring appropriate fuel supply.

Enabling Technology:

- High power, low mass radioisotope power systems (RPSs)
- Advanced propulsion systems (e.g. chemical, electrical, aerocapture, radioisotope)
- Technologies for extremely cold environments (e.g., surface packages for icy bodies)
- Unique enabling technologies for specific missions
    a. Titan: Balloons, aerobots or similar
    b. Probes into atmospheres operating at high pressures and temperatures
    c. Communication from deep atmospheric probes

Enhancing Technology:

- Low-power, low-mass, radiation tolerant components
- Advanced passive and active remote sensing instruments
- Low-power, low-mass in situ instruments
- Upgraded DSN capability

<u>Research and Analysis Programs</u>:

The scientific goals of exploring the outer solar system can only be accomplished with a vigorous research and analysis (R&A) program that includes robust programs in data analysis, modeling, theory, laboratory studies, ground-based astronomy, and data archiving. Not only are these supporting research programs key for development of productive new missions, but they

are also vital for maximizing the scientific return from past missions. The Outer Planets Program was started a couple of years ago and has been an important R&A program for the OPAG community. The majority of professional planetary scientists, particularly junior researchers and students, are supported via R&A programs.

Findings on Research & Analysis Programs:

- OPAG notes the findings and recommendations of the NRC's Space Studies Report on Research and Analysis supporting a balanced program for NASA's scientific research (http://www7.nationalacademies.org/ssb/)
- OPAG endorses the recommendations of the Planetary Science Subcommittee of the NAC (http://science.hq.nasa.gov/strategy/subcomm.html)
- OPAG is encouraged to see Cassini Data Analysis Program (CDAP) started. The initial budget of $2.5M is expected to double in subsequent years. However, the funding profile for the program is inadequate considering the expected science return of the Cassini mission.
- A Cassini Extended Mission is a fantastic opportunity to further science return. Cassini science teams as well as CDAP will both need to be funded to maximize scientific return.

What Planetary Science R&A Programs Do:

· Analyzes of data returned from spacecraft missions.
· Use telescopes, both from the ground and in space, to discover new objects in our solar system and to characterize known objects.
· Study in the laboratory Moon rocks, comet dust, and meteorites, and other materials that may make up the planets.
· Make theoretical and computer models to tie these data to our understanding of physics, chemistry and geology.
· Combine all these results to understand the histories of planets, moons, asteroids and comets.
· Use what we've learned to help plan where to send the next mission.
· Educate our youth - our future scientists and engineers.

Mission Concept Studies:

Recognizing the long timescales of exploration of the outer solar system, as well as the huge challenges of flagship missions, OPAG advocates an approach that develops options for exploring multiple targets which gives NASA flexibility in selecting a sequence of missions that optimizes science return. This is the same approach advocated in the Survey. To this end, OPAG has working groups looking at specific targets (Europa, Titan, giant planets–particularly their deep atmospheres–and primitive bodies) as well as defining feasible missions. Recognizing the recent trends of escalating costs of large missions within NASA's SMD, OPAG advocates that all studies of missions involve scientists working closely with mission engineers and that these studies must be subject to a review of technical, management and cost by an independent body.

OPAG is concerned that any delays and/or cost over-runs of the next flagship mission might jeopardize the long term goals for scientific exploration of the outer solar system. We emphasize that the scientific priority remains with a Europa orbiter. However, OPAG finds it important to study other missions in case a Europa mission is found to be unfeasible due to cost or technical reasons, as well as to have the next flagship mission well along in readiness following the launch of a Europa mission.

Finding on Mission Concept Studies:

- OPAG strongly encourages NASA to complete mission concept studies of missions to Europa, Titan and/or Enceladus, giant planets (particularly their deep atmospheres) and small bodies as important scientific targets in the outer solar system as soon as possible and with sufficient fidelity to inform a decision about the next flagship mission.
- **To inform decisions about a future flagship mission, concept studies of outer planet flagship missions must be with sufficient fidelity to ascertain whether missions realistically fit into a "flagship box" of a set timeframe (e.g. 15 years) and a set total mission cost (e.g. $2.5B).**

Strategic Planning:

Key to the success of a coherent, productive Outer Planets Program is a planned strategy based on (a) scientific results from missions and R&A programs, (b) results of mission concept studies, (c) development of enabling technologies. Such strategic planning for the outer solar system must tie closely to the Survey and Roadmap which have the broader perspective of the whole solar system. OPAG aims to provide NASA with community-based input on a coherent strategy for scientific exploration of the outer solar system.

Budget

The July 2006 Solar System Exploration Roadmap advocates a balanced program that should include a mix of missions. The Roadmap presents five options with different flight rates and corresponding costs. The lowest cost versions are their Options B and C, which we present here:

Mission Class	*Mission Cost ($FY06)*	*Flight Rate Per Decade*	*Investment Per Decade*
Discovery	$0.4B	7	$2.8B
New Frontiers	$0.7B	4	$2.8B
Small Flagship (C)	$1.4B	2	$2.8B
OR			
Large Flagship (B)	$2.8B	1	$2.8B

Such a mix of missions would entail, averaged over a decade, an investment of $8.4B per decade or $0.84B per year. This is about 50% of the current total Planetary Science Division budget (which also includes the Mars Program as well as R&A, technology development, etc).

Averaging the values published in NASA's FY2007 budget over the next six years, the total budgets of the Discovery and New Frontiers lines add up to ~$440M/yr, about 80% of the above budget for these two mission lines. Thus, an extra $400M/yr would be needed to fund the mix of missions at the above flight rate. Alternatively, the above mix of missions could be flown for $440M/yr with the above flight rate per 19 years (rather than per decade).

These simple calculations ignore the fact that mission costs are not constant, but there is a ramp-up and ramp-down period with the maximum spending during the few years of hardware construction. Thus, without temporary increases in funding to the Planetary Science Division, there will be a gap in support of other mission types in order to fund a flagship mission.

Steady, Balanced Strategy

To address the key scientific goals and meet the challenges of exploration of the outer solar system OPAG recommends consolidation of existing elements into a coherent Outer Planets Program following a steady, balanced strategy:

Finding 2: Steady, balanced strategy - Addressing these scientific questions requires a balanced strategy of outer solar system exploration that includes steady support for vigorous programs of basic research, data analysis, and technology development. Fundamental new discoveries are best made with a mixture of mission sizes that includes large, flagship missions, along with small and medium-sized missions. A stable budget is crucial for continuity of scientific and technical capability. Such a strategy is most efficiently implemented as a coherent Outer Planets Exploration Program.

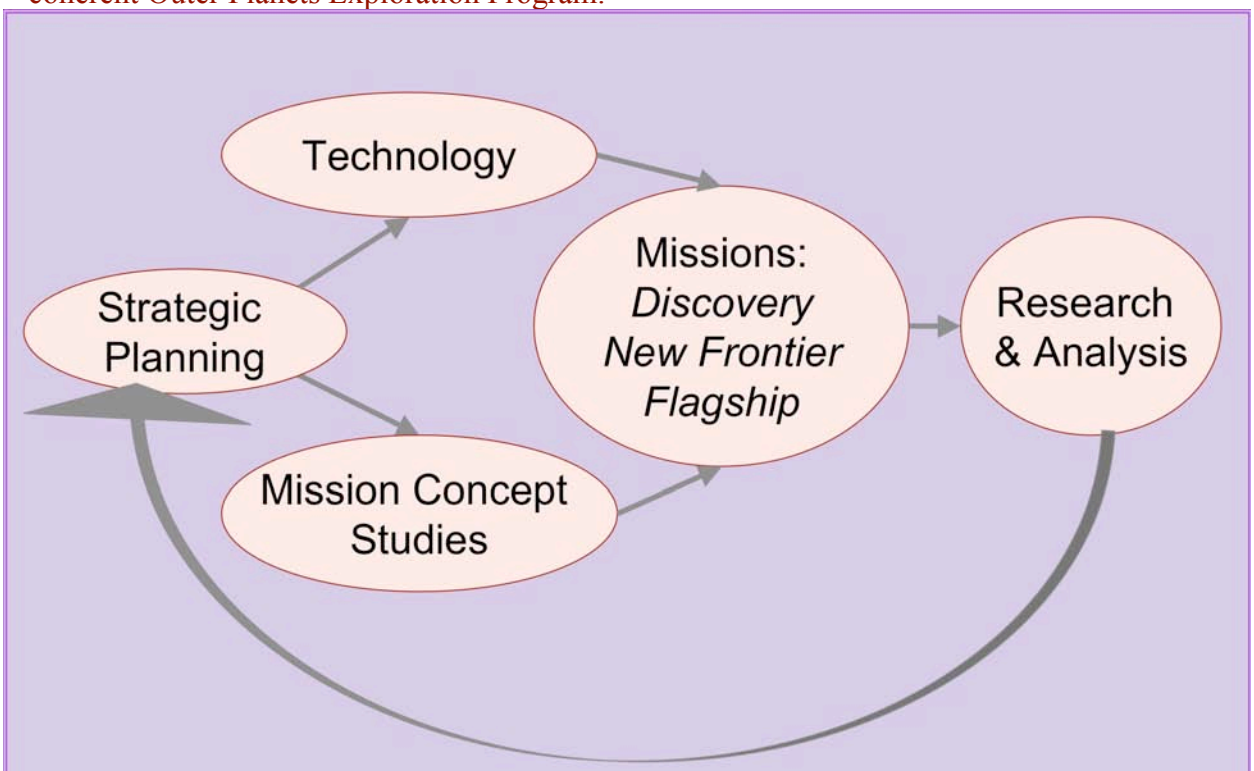


Figure 6 - Elements of an Outer Planets Program

3. Destinations and Mission Architectures

The outer solar system comprises many objects spanning a wide range of sizes, compositions and states of evolution. To address the main scientific goals of understanding how solar systems originate and how such planetary systems become habitable, OPAG has identified three main types of ***Destinations,*** illustrated in Figure 7. These same destinations were studied in detail by the Survey, and OPAG finds that they remain the top priority for outer solar system exploration. Both the Survey and Roadmap provide substantial arguments for why these objects are important scientific targets. Below we summarize the science addressed by visiting specific targets, and discuss potential mission concepts for exploring these planetary bodies.

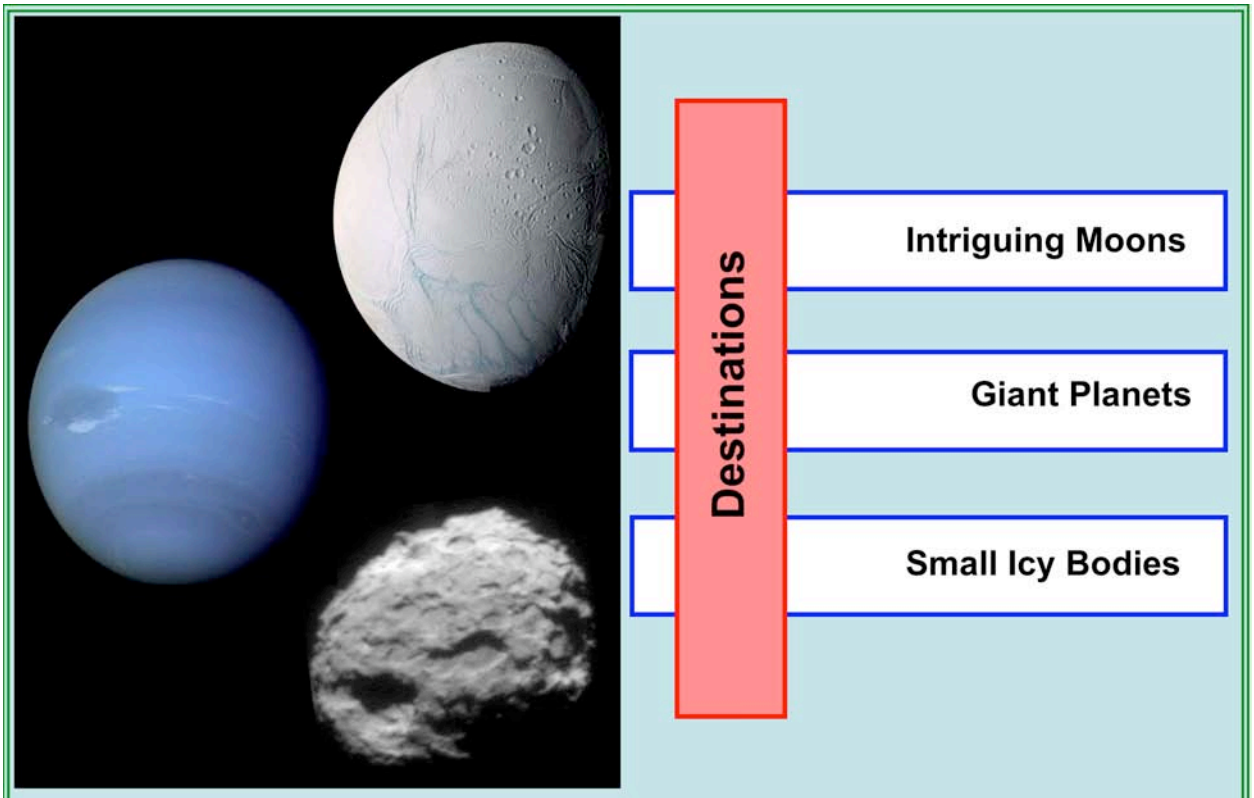


Figure 7 - The outer regions of the solar system offer many destinations where one might address OPAG's scientific goals – from the deep atmospheres of the giant gas planets, to the small icy worlds of comets and the Kuiper Belt, plus the many intriguing moons in between.

Intriguing Moons

The giant planets' retinue of moons are summarized by the Survey as follows: "Of the six large outer-planet satellites—Io, Europa, Ganymede, Callisto, Titan, and Triton—all are larger than Pluto and two are larger than Mercury; in addition, there are 11 medium-sized satellites. Each planet-sized satellite is unique:

- Io is intensely volcanically active,
- Europa may have a layer of subsurface water greater in volume than all of Earth's oceans combined,
- Ganymede has an intrinsic magnetic field,
- Callisto is largely undifferentiated,

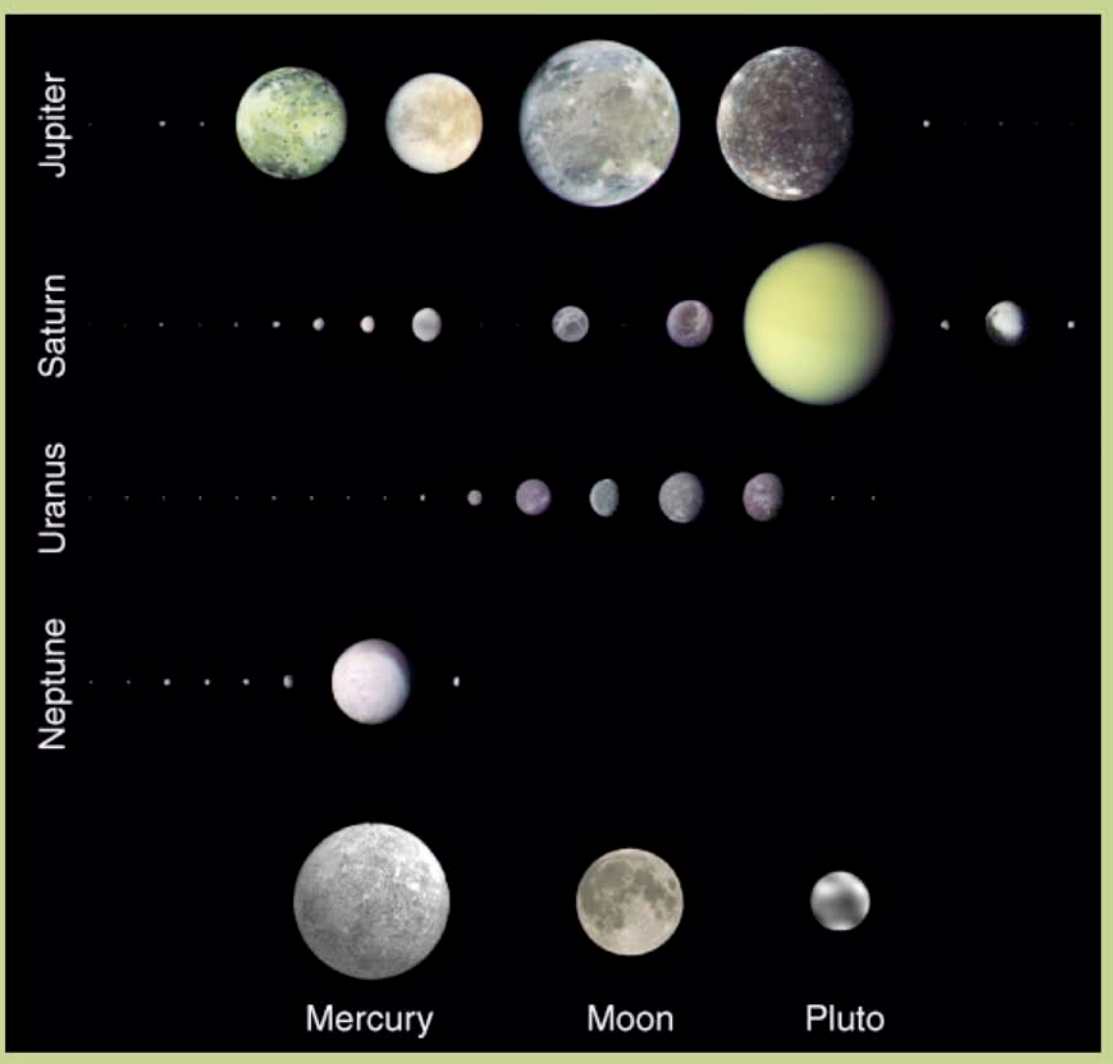


Figure 8 - The larger satellites of the outer planets are worlds in their own right. They are shown to correct relative size and order from the planet (on left) but their orbital distances are not to scale. The Galilean satellites of Jupiter are (from left) Io, whose surface is constantly renewed by active volcanoes tinged with sulfur allotropes; Europa, which probably possesses a liquid water ocean beneath its ruddy ice skin; Ganymede, a moon bigger than the planet Mercury, possessing a rutted surface of dirty ice and an internally generated magnetic field; and Callisto, a moon with an ancient cratered surface whose interior is only weakly differentiated. Saturn's family is dominated by cloud-shrouded Titan with an atmosphere rich in organics and possibly seas of methane. Saturn's bright icy moons consist of (inward from Titan) Rhea, Dione, Tethys, Enceladus and Mimas. Beyond Titan two-toned Iapetus shows one face as bright as snow and the other as black as coal. The five major uranian satellites are Miranda, Ariel, Umbriel, Titania, and Oberon. Each displays a dirty-ice surface and some tectonic activity, but the bizarre world of Miranda—with its exotic jumble of surface terrains suggesting that it may have been totally disrupted in the past and put back together at random—steals the show. Neptune's sole large satellite, Triton, is coated with exotic ices tinged pink by organic molecules; nitrogen geysers spew high into its tenuous atmosphere. In addition to the 17 large-medium satellites mentioned by name above, there 133 small moons that orbit the giant planets. *Courtesy of NASA/JPL.*

- Titan has a thick atmosphere rich in organic compounds, and
- Triton has active, geyserlike eruptions.

The large satellites have bizarre life cycles, influenced by orbital evolution and tidal heating, revolutionizing concepts based on the terrestrial planets. They are rich in volatile species such as H_2O, SO_2, N_2, CH_4, CO_2, and perhaps NH_3, creating a rich diversity of processes and environments. The 11 medium-sized satellites are also unique worlds, and they may provide essential information about the origin and evolution of satellite systems."

Of these many moons, Europa and Titan are the highest priorities for exploration. Cassini's recent detection of warm, active hydrological systems near the surface of Enceladus has added another intriguing moon to consider.

***Europa:* Oceans, Organics, and Habitability**

Europa has been a focus of scientific interest since 1997, when the Galileo orbiter found evidence for a global ocean beneath the satellite's thin icy crust. Images showed that liquid water must have been present on the surface in the moon's recent geological history. Organic material found near cracks in the crust suggested the possibility that biotic precursors could be created in Europa's warm, wet interior and delivered to the surface. The Galileo mission identified why Europa is so unique, but did not have the ability to explore the world in depth. A flagship mission to Europa is necessary to address the satellite's compelling scientific questions.

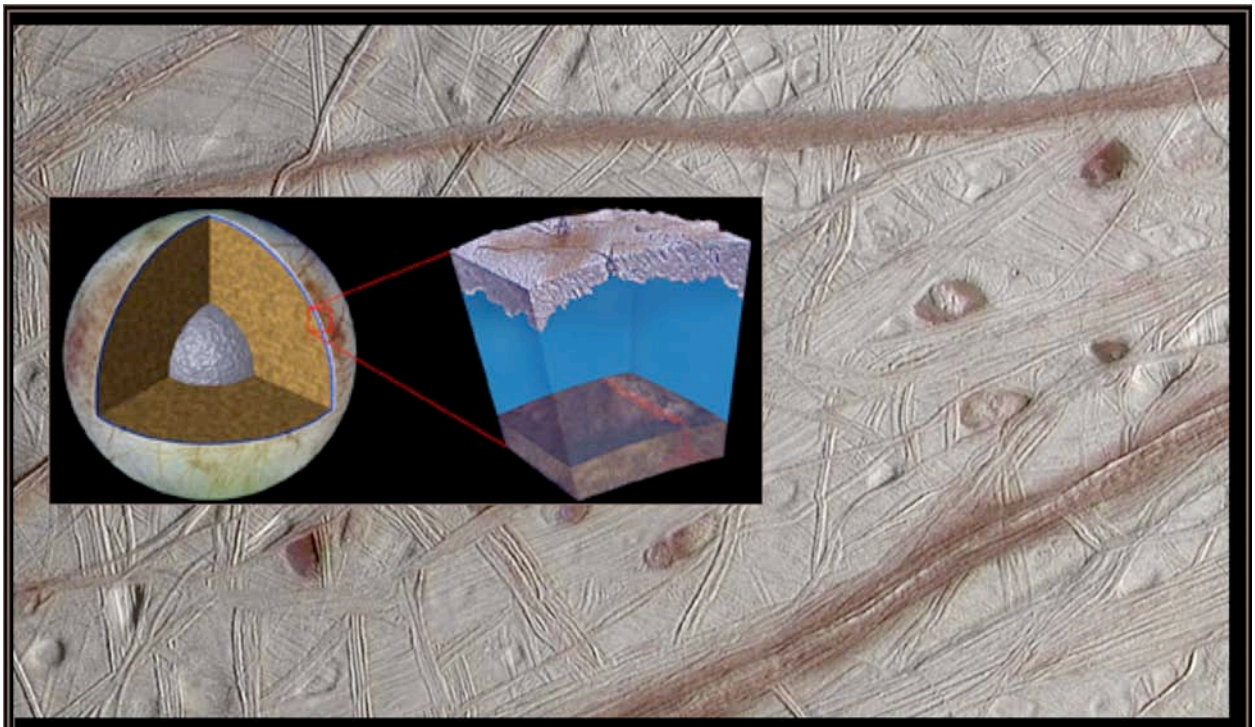


Figure 9 - *"Europa, tidally heated by Jupiter, is a warm rocky body possessed of an icy shell that is melted to some extent. That is, a global ocean of liquid water exists under an ice crust of indeterminate thickness. Yet the extent to which this subsurface ocean is endowed with organic molecules, the stuff of life, is unknown: the icy surface of Europa shows little evidence for carbon-bearing compounds, but few would survive for long exposed in the vacuum to the high radiation jovian environment." The Solar System Exploration Strategic Roadmap, May 2005.*

Below we list the science objectives of a mission to explore Europa and determine its potential for life. Each is considered part of the science floor, and all are intended to be of equal importance. For each objective, a set of sub-objectives are listed in priority order.

- Characterize the ocean through its effects on potential fields and its dynamic relationship with the ice shell.
  1. Determine the amplitude and phase of the gravitational tide.
  2. Determine the induction response from the ocean over multiple frequencies.
  3. Characterize surface motion over the tidal cycle.
  4. Determine the amplitude of libration.

- Characterize processes operating within the ice shell, and the nature of ice-ocean exchange.
  1. Characterize the distribution of any shallow subsurface water.
  2. Search for an ice-ocean interface.
  3. Correlate surface features and subsurface structure.
  4. Characterize the physical properties of the regolith and possible links to the interior.

- Determine surface composition and chemistry, especially as related to habitability.
  1. Characterize surface organic and inorganic chemistry.
  2. Relate composition to geological processes, especially communication with the interior.
  3. Determine the radiation effects on surface materials.
  4. Characterize exogenic material associated with the jovian plasma.
  5. Characterize magnetospheric sputtering interactions with the surface.
  6. Search for compositional indicators of past or present life.

- Understand the formation of surface features, including sites of recent or current activity, and identify candidate sites for in situ exploration.
  1. Characterize magmatic, tectonic, and impact features.
  2. Search for areas of recent or current geological activity.
  3. Investigate global and local heat flow.
  4. Assess surface ages.
  5. Assess processes of erosion and deposition.

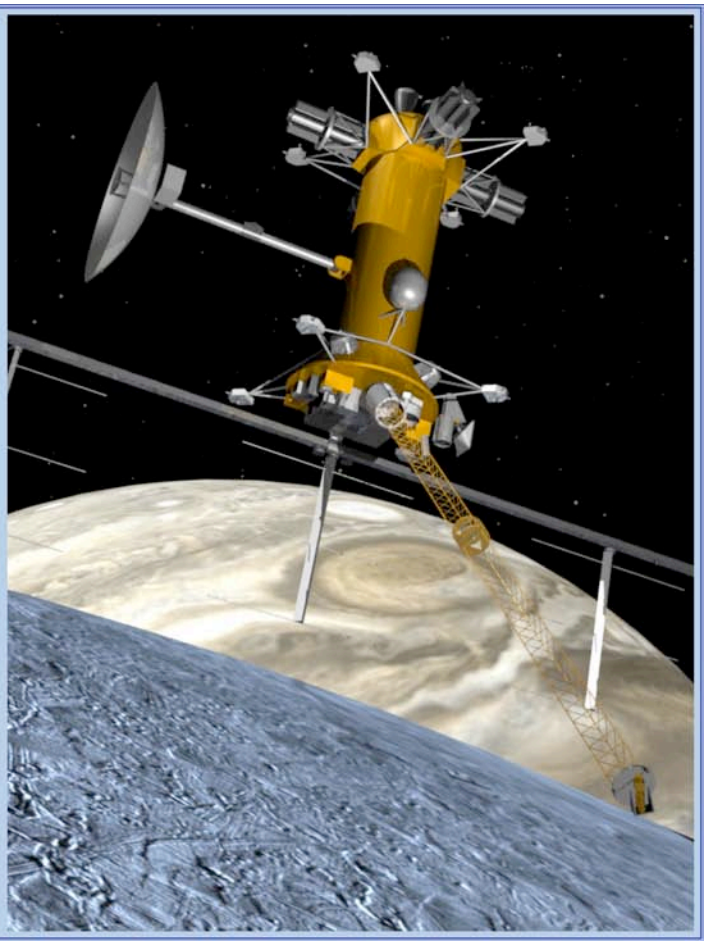
- Characterize the magnetic environment and moon-particle interactions.
  1. Characterize the magnetic environment at multiple frequencies.
  2. Determine the structure and dynamics of the ionosphere and neutral atmosphere.
  3. Characterize relationships between the magnetic field and plasma.
  4. Investigate the deep interior.
  5. Characterize the radiation environment.

- Determine how the components of the jovian system operate and interact, leading to potentially habitable environments in icy moons.
  1. Determine the nature and history of the internal heat sources and interior evolution of the Galilean satellite system.
  2. Investigate the geological processes and surface evolution of the Galilean satellite system.
  3. Study the jovian system as a model for other potentially habitable planetary systems.

Various mission concepts capable of achieving these primary science goals have been studied for over a decade. It is clear that it is necessary to put a spacecraft into orbit around Europa in order for radar and gravity measurements to determine the thickness of the ice shell. Yet, putting a spacecraft into orbit around Europa is a challenging technical task: the moon sits deep in Jupiter's gravitational well, it is embedded in Jupiter's radiation environment, and the flux of solar energy is limited. However, recent mission studies indicate that a Europa mission may be feasible with current technologies. In that mission study, a flagship-scale, RPS-powered orbiter carrying a suite of 10 scientific instruments (consists of a sounding radar and other remote sensing instruments) could be built using currently available radiation-hardened electronics. It is envisioned that the mission would entail a two-year tour within the jovian system using several gravity-assist maneuvers at the Galilean satellites to reduce the orbit capture requirements at Europa. The spacecraft would then orbit Europa for ~90 days. However, such a mission has not yet undergone a full Phase A study nor any review of technical feasibility, management and cost.

Figure 10 - Europa Explorer Mission Concept.

Building on experience and knowledge gained in designing previous mission concepts, and on recent dramatic improvements in radiation hardened electronics, this concept for Europa Explorer allows a thorough exploration of Europa with current technology. With gravity assists from one Venus flyby and two Earth flybys, Europa Explorer would reach Jupiter about six years from launch. The spacecraft would spend the next 1 to 1.5 years using gravity assists from Jupiter's moons to help it settle into orbit around Europa while conducting unique new observations of Jupiter and all four Galilean satellites. It would orbit Europa at an altitude of about 100 km, circling the moon every two hours. Europa Explorer would carry almost 200 kg of powerful science instruments. The planning payload of 10 instruments includes a high-resolution imaging system, an ice-penetrating radar to search for liquid water beneath the icy surface, and a Ka-band transceiver for precision gravity measurements. *Courtesy JPL.*



OPAG makes the following findings:

- Europa remains the consensus priority target of the OPAG community, as it is in the NRC Decadal Survey, in reports to NASA from both COMPLEX and SSES.
- OPAG encourages NASA to undertake a comprehensive Phase A mission study to assess the feasibility of a Europa mission that can achieve the priority science (as stated in the Decadal Survey and by the OPAG Europa Working Group) within an accurate and

realistic cost-cap and, most importantly, complete the primary mission by a timeframe of 2020-2022. OPAG reiterates the concern that SSES has stated about delays in starting a Europa mission (July 2003, March 2004, June 2004, October 2004, February 2005). A comprehensive study would allow a decision to be made about implementation of a Europa mission.

- OPAG is very concerned that any delays and/or cost over-runs of a Europa mission would jeopardize broader goals for scientific exploration of the outer solar system.
- The OPAG Europa Working Group will continue to work with the ESA-NASA Jupiter mission task force to assess international collaborations that enhance scientific return.

***Titan* – Exploring an Exotic Earth-like World**

Titan has fascinated scientists since well before Voyager 1 first characterized its thick atmosphere in 1980. Scientific community interest has grown since Huygens' 2005 landing on the surface near an apparent former shoreline, and Cassini's continued radar mapping of an exotic world of dunes, drainage networks, possible ancient seas, and observations of complex atmospheric chemistry and dynamics.

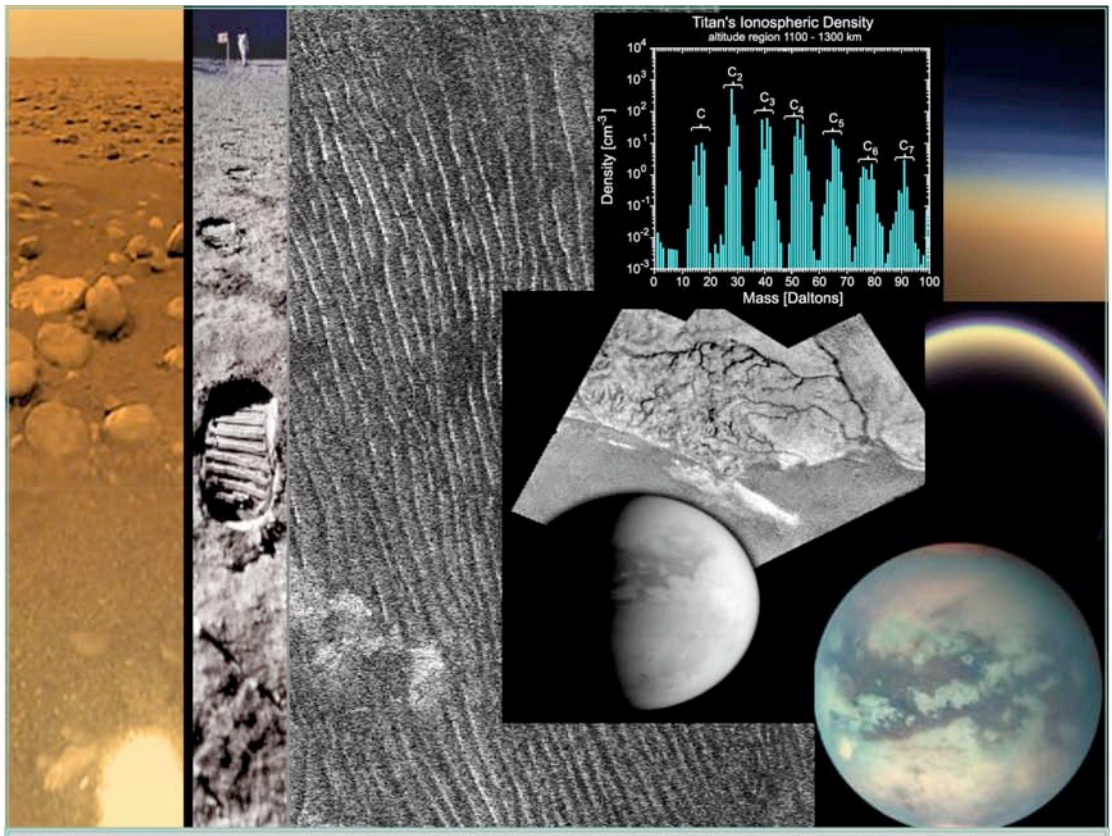


Figure 11 - Titan is a complex organic-rich world, inviting exploration of both its surface and atmosphere. Earth-like landforms such as river valleys and sand dunes result from methane rainfall and winds, while seasonal changes occur high in the organic smog-laden atmosphere. The view from the Huygens probe *(left)* is shown next to a vista of Apollo astronauts on the Moon to illustrate the scale of the Titan landscape.

Titan is a world that juxtaposes features from bodies across the solar system. Like Venus, its surface rotates slowly while its upper atmosphere is in super-rotation. Like Earth, condensable volatiles continually deposit atmospheric material on the surface. And like Ganymede and Triton,

Titan is a large, icy satellite with a complex geology exposed on its surface, driven from below by internal heat sources and modified from above by interactions with the atmosphere.

The Huygens probe studied only one point on Titan's surface. As of midway through the Cassini mission, Cassini's radar has mapped only 6% of Titan's surface at better than kilometer-scale resolution. The thick, mostly opaque atmosphere complicates remote-sensing of surface composition and geology. Exploration is desirable at multiple locations on the surface and in the atmosphere. The OPAG Titan working group lists the following scientific reasons for exploring Titan:

- Titan provides clues to the origin of life on Earth.
    1. Liquid water from transient cryogenic volcanism or impact melt could have interacted with complex organics from the atmosphere over thousands to millions of years; surface deposits might preserve a record of this interesting, transient, prebiotic or even biotic chemistry.
    2. Titan's current nitrogen-methane atmosphere could be similar to the early Earth's, and understanding organic chemistry on Titan could shed light on the origin and evolution of life on Earth.

- Titan has a dynamic and evolving atmosphere.
    1. Methane on Titan is near the triple point and thus behaves much as water does on Earth; interesting atmosphere-surface-subsurface interactions occur that remain to be characterized or understood.
    2. The carbon cycle, surface-subsurface liquid hydrocarbons, seasonal meteorology, winter polar hood and vortex, and atmospheric production, loss, and evolution all provide interesting puzzles and analogs to terrestrial processes.
    3. Titan has an upper atmosphere and ionosphere driven both by solar forcing (like terrestrial planets) and magnetospheric forcing (unlike terrestrial planets).

- Titan shows active recent geology.
    1. The geology of Titan is complex and dynamic. Cassini-Huygens data demonstrate that impact craters are relatively sparse, tectonic and cryovolcanic features are present, wind-blown dunes composed of fine-grained dark material (presumably coated in organics) are observed, and apparent dendritic "rainfall-driven" streams are located next to what resembles spring-fed drainage networks.
    2. The surface geology paints a picture of a relatively young, active world with complex interactions among tectonic, volcanic, "hydrologic," and atmospheric processes.

While Cassini-Huygens provided important observations of Titan, in many ways these glimpses of the cloud-covered moon mostly sharpened the scientific questions about the nature, origin and evolution of the object. The following are the outstanding questions that should be addressed by a future mission:

Origin and Evolution of Habitable Worlds:

- How did Titan's unique, thick N_2 atmosphere form and evolve?
- What is Titan's internal structure and composition and how do they reflect conditions in the early solar system?
- What is the composition and distribution of organic materials (liquids, solids, gases) on, beneath, and above Titan's surface, and what controls their distribution and chemistry?

- How far has organic chemistry proceeded on Titan?
- What are the volatile and geochemical cycles on Titan and how do they work?
- What can Titan tell us about the delivery of volatiles to the terrestrial planets?
- Isotopic ratios indicate the loss of a substantial fraction of Titan's atmosphere. How and why was it lost? How did it form in the first place?

Physical Processes of Complex, Planetary Bodies:

- What controls Titan's circulation and weather and how do these change with time?
- How does Titan's upper atmosphere interact with the solar wind and Saturn's magnetosphere, and how does this affect atmospheric chemistry and evolution?
- How did Titan's diverse geologic features form, what are their controlling internal mechanisms, at what rates do these operate, and are they currently active?
- What is the nature of the interactions between processes acting in the interior, on the surface, and in the atmosphere?

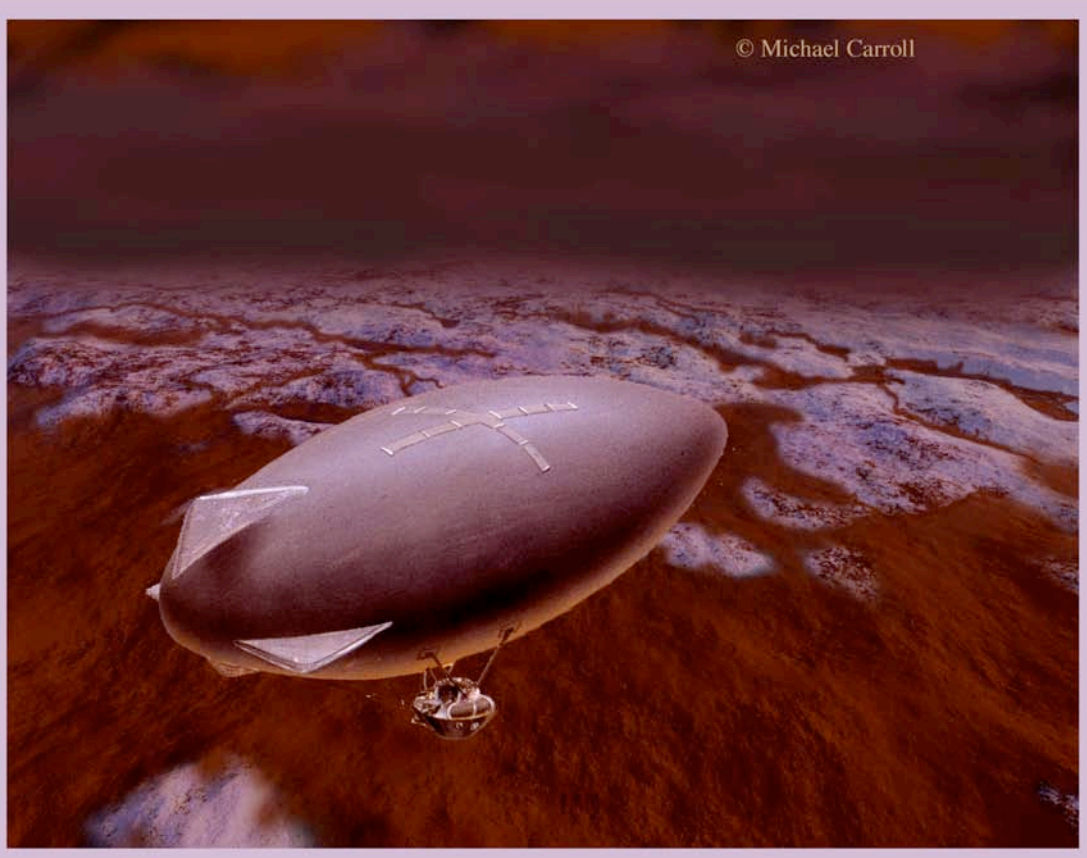


Figure 12 - Potential aerobot mission to Titan. *Courtesy Michael Carroll.*

Scientifically, a future Titan mission will build upon the observations of Cassini and Huygens. In addition to aerial imagery, made below the haze, of a much larger amount of terrain than was possible with the Huygens Probe, such a mission will conduct exploration of lower atmospheric winds, clouds and precipitation, and in situ measurement of ices and organic materials at the surface to assess pre-biotic/proto-biotic chemistry. The goal is to characterize those materials but also to contribute definitive observations concerning the origin of the diverse landforms identified in Huygens visual images and Cassini radar data. A preliminary mission concept

involves an aerial platform with repeated access to the surface for in situ sampling. Certain aspects of the extreme environment make in situ exploration much more challenging that the in situ exploration of Mars. The very cold temperatures (less than 100K) at Titan present challenges for materials, mechanisms and electronics. However, other aspects of the environment – specifically the high atmospheric density at the surface (4.5 times terrestrial) and very low surface winds – enable the use of a mobile buoyant platform that can move with much less energy and with much less risk of becoming immobilized than a surface vehicle; sampling is done in a fashion analogous to the acquisition of a sea floor sample by a submersible. Visual imaging and onboard machine vision implemented from a range of altitudes will play a key role in the scientific exploration and navigation. The mission described above (and sketched in Figure 12) is just one concept, other concepts are also worth consideration. Careful evaluation of mission concepts and their feasibility are needed to decide how best to explore Titan.

OPAG makes the following findings:

- Results from the Cassini-Huygens mission have demonstrated that Titan is a compelling destination. Titan is unique in its own right, but intriguing commonalities with Earth make it also valuable for comparison with Earth.
- The OPAG Working Group concludes: 1) exploration of Titan requires a flagship mission and 2) a flagship Titan mission should include an orbiter as well as a balloon/aerobot/probe.
- OPAG urges NASA to support studies of potential missions to Titan to evaluate the best approach to exploring this intriguing moon.
-

<u>Enceladus:</u> A Small, Geologically-Active World

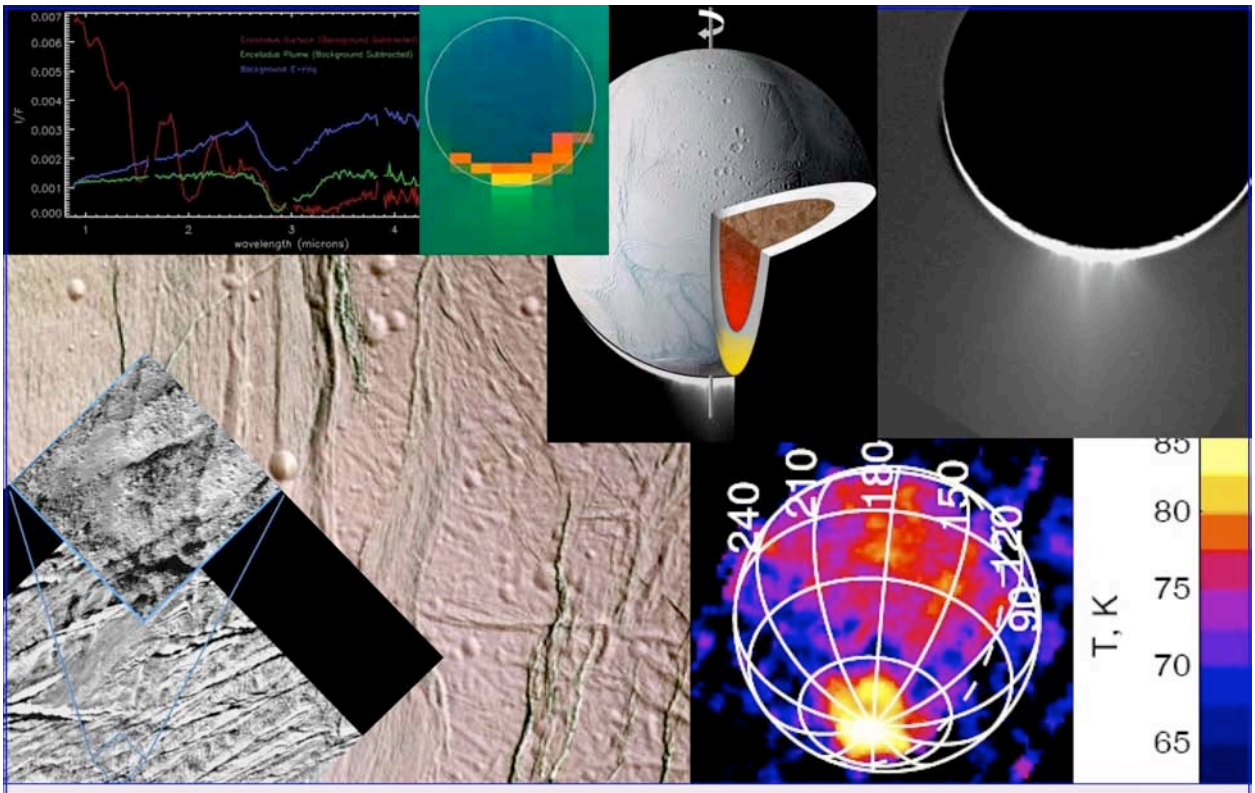


Figure 13 - Enceladus. The Cassini spacecraft shows that Saturn's small moon Enceladus has plumes of ice and gas rising from warm active fractures in its south polar region, probably the action of localized tidal heating. Water is the dominant plume constituent, and trace amounts of the simple organic molecules acetylene and propane are also detected. If water exists in the shallow subsurface of Enceladus, then this moon joins the shortlist of icy bodies that may be habitable environments.

The Cassini spacecraft shows that Saturn's small moon Enceladus has plumes of ice and gas rising from warm active fractures in its south polar region, probably the action of localized tidal heating. Water is the dominant plume constituent, and trace amounts of the simple organic molecules acetylene and propane are also detected. It is uncertain whether plume material is erupting like geysers, or sublimating from warm fractures. If water exists in the shallow subsurface of Enceladus, then this moon joins the shortlist of icy bodies that may be habitable environments. These new discoveries at Enceladus are pertinent to all four major science themes of large satellites, as recommended by the Decadal Survey: origin and evolution of satellite systems, origin and evolution of water-rich environments in icy satellites, exploring organic-rich environments, and understanding dynamic planetary processes. Thus, Enceladus is elevated to a high priority for continued examination by the Cassini spacecraft, to establish whether liquid water exists or is likely to exist near the surface, thereby making this a prime target for future solar system exploration.

OPAG has begun discussions of Enceladus as a potential mission target and will expand these discussions as it continues to be studied by Cassini.

Giant Planets: ***Keys to the Formation of Planetary Systems***

The giant planets are the keys to understanding formation and evolution of solar system. The giant planets comprise 99.6% of the mass of planetary material. They contain the raw components of the pre-planetary disk, sampled across a range of distances and construction times. By comparing the properties of these four planets we understand the different processes and conditions of their formation and thus piece together the history of the solar system. Jupiter and Saturn, made predominantly of hydrogen, are sometimes called the "gas giants." Because they have interiors with large amounts of water, ammonia and methane (chemicals that are sometimes misleadingly referred to collectively as "ices"), Uranus and Neptune are sometimes called "ice giants" or, more properly, "water giants."

Images from the Galileo and Cassini spacecraft as well as ground- and space-based telescopes have greatly increased our knowledge of the outer, atmospheric layers of Jupiter and Saturn. The Galileo probe sampled the atmosphere of Jupiter down to 22 bars. But the entry of the probe into a relatively uncommon region of strong, dry downdraft meant that we still do not have a good measure of the amount of water – and hence the important element oxygen – in the most massive planet in the solar system. The New Frontiers mission Juno aims to address this issue using the technique of radiometric sounding as it flies close over Jupiter's poles.

Neptune and Uranus remain unstudied by spacecraft except for their Voyager flybys, yet have major vexing issues that have only become more puzzling since their visits. Neptune and Uranus are therefore first-priority targets out of the giant planets.

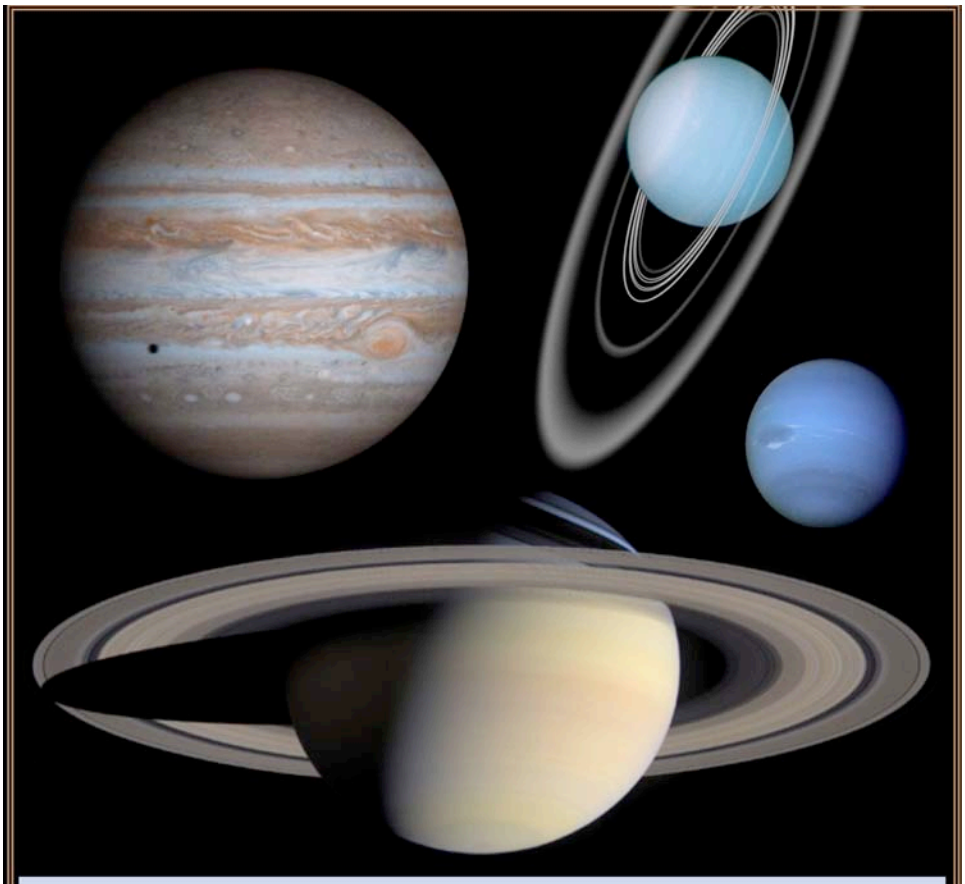


Figure 14 - The giant planets. For scale, Jupiter and Saturn are ~10 times the size of the Earth, Uranus and Neptune are ~4 times Earth's size. The images of Jupiter and Saturn were taken by Cassini (*courtesy of NASA/JPL/SSI*). The Neptune image was taken by Voyager 2 (*Courtesy NASA/JPL*). Uranus is a composite of images taken by the Hubble Space Telescope (*courtesy of NASA/Mark Showalter*).

Key scientific questions at all giant planets:

1. Over what period did the giant planets form, and what different processes produced the "water giants" Uranus and Neptune vs. the "gas giants" Jupiter and Saturn?
2. What is the history of volatile compounds, especially water, across our solar system?
3. How do processes that shape the contemporary character of planetary bodies operate and interact?
4. What does our solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?

Key measurement objectives at all giant planets (in priority order):

1. Determine the core mass and size.
2. Measure elemental and isotopic abundances (H, He, O, C, N, S, noble gases).
3. Investigate deep winds and internal convection.
4. Map the structure of the magnetic field and radiation environment.
5. Explore magnetospheres.
6. Determine the properties of planetary rings.
7. Map atmospheric properties as functions of depth, latitude, and longitude.

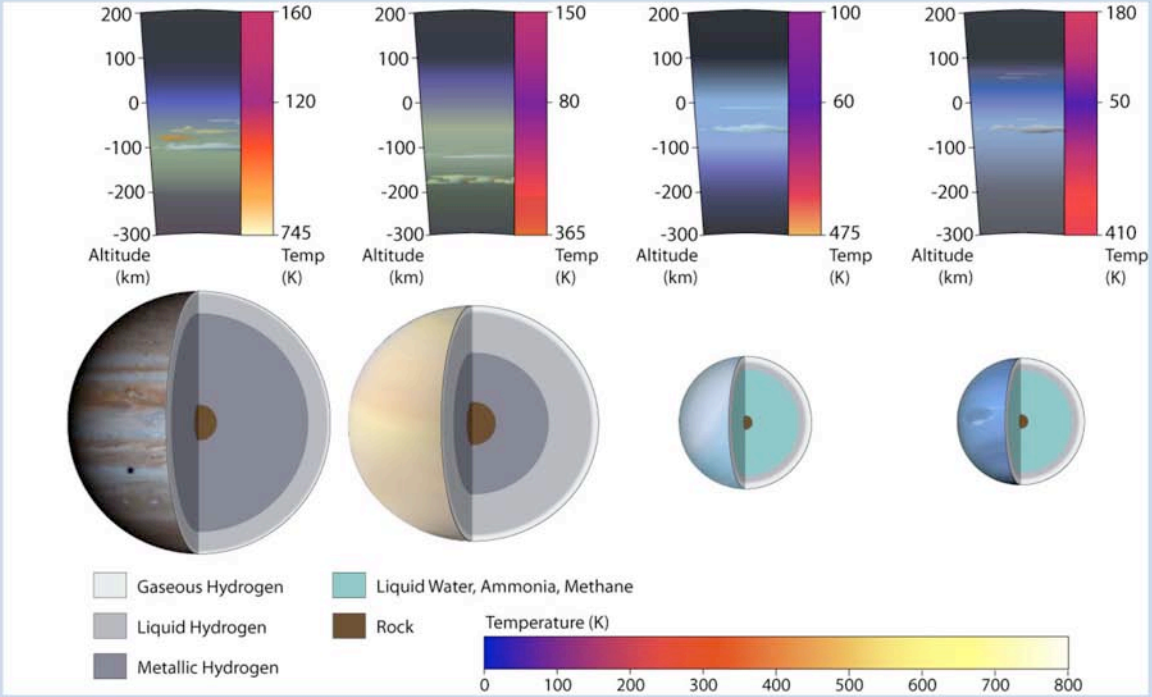


Figure 15 - Interiors and atmospheres of the giant planets. The giant planets form two distinct pairs. Jupiter and Saturn - primarily hydrogen: gaseous, liquid, then metallic at increasing pressures towards the planets' centers; Uranus and Neptune - hydrogen overlies a liquid layer comprising a mixture of water, ammonia and methane. It is not clear whether the planets have small rocky cores. The clouds that are visible from the exterior form distinct layers at specific pressures and temperatures in the thin outermost gaseous layer. The altitude scale is referenced to the locations where the atmospheric pressure is 100 mbar which is also the approximate altitude where atmospheric temperatures are a minimum (ranging from 50K at Neptune to 120K at Jupiter). Temperatures rise with higher pressures towards the interior of the planet. Absorption of sunlight also increases temperature in the upper atmospheres. None of these planets have been explored except for the thin layer above the clouds. These diagrams are based on theoretical models constrained by parameters such as bulk density.

Science goals for both Neptune and Uranus:

- Perform system-wide science, exploring interactions between atmosphere, magnetosphere, satellites and rings.
- Investigate the "salt water dynamo" responsible for the gas giants' magnetosphere.
- Explore the diversity of rings and ring arcs at Uranus and Neptune.

Science goals specific to Neptune:

- Understand the ice geysers and cryogenic activities on the surface of Triton.
- Study the effect of Neptune's tilted magnetic axis on interactions between its magnetosphere and atmosphere.
- Explore the processes creating and maintaining Neptune's ring arcs.

Science goals specific to Uranus:

- Investigate the role of Uranus' unique seasonal cycle and high obliquity in controlling its atmospheric structures.

It is now thought that the major scientific goals of understanding the volatile inventory of giant planets could be achieved with a combination of shallow probes (about 10 bars, rather than very deep probes, as initially thought) and radiometry at Jupiter or Saturn. Uranus and Neptune will probably need deeper probes, but the depth of penetration needs further study.

The following mission concepts (in priority order) have been identified by the OPAG giant planets working group as being potential missions to address these scientific questions:

1) Neptune Polar Orbiter with Probes: A comprehensive mission to perform system-wide science at Neptune. Uranus is a target of similar interest, but Neptune's moon Triton tips the balance in favor of it over Uranus.

2) Uranus Orbiter with Probes and/or Microwave Radiometry: A comprehensive mission to perform system-wide science at Uranus.

3) Saturn Multiple Probes with Microwave Radiometry Flyby: Saturn atmospheric probes are critical for determining elemental abundance. The Cassini orbiter has limited capability for determining key elemental composition. Only the ratio C/H (in CH_4) can be measured with confidence. For the noble gases, N, S, O and isotopes, probes are required. Measurement of O (in H_2O) requires probes to 50-100 bar depth. Water can be measured by microwave, in which case shallow probes to ~10 bar will suffice.

4) Jupiter Multiple Probes Flyby: The Jupiter system will have been studied to a large extent due to Voyager flybys, Galileo orbiter and probe, and the Juno orbiter. Nevertheless, simultaneous measurements of composition at multiple locations are still highly desirable, which would require probes to 50-100 bar. The Galileo Probe measured the abundance of noble gases and heavy elements, except oxygen (in water), in the well-mixed atmosphere in one, probably anomalous, location. Juno is expected to measure oxygen (water) and N, but no other elements. A Jupiter multiprobe mission should be considered after Juno, as Juno results will be an important guide to such a mission.

OPAG makes the following findings:

- OPAG encourages NASA to support development of deep probe technologies appropriate for research at all four giant planets, such as heat shields, telemetry, power systems, batteries, and instrumentation for high temperatures and pressures. OPAG encourages involvement of scientists in probe technology and mission studies to ensure that such technologies are keyed to needs of specific missions.
- Aerocapture is a non-proven technology that may enable substantially more mass to be delivered into orbit around Uranus and Neptune. OPAG encourages NASA to support continued study of aerocapture technologies.

Small Icy Bodies: ***Windows to the Past***

The small icy bodies in the outer solar system – including comets, Centaurs, Trojans, satellites captured by the giant plants, and Kuiper belt objects (KBOs) – are remarkable in their diversity. The smallest objects (500 km or less in diameter) have suffered relatively little modification since their formation, and thus serve as relics whose chemical composition and physical structure encode fundamental information on the genesis of the solar system. These objects are also thought to be critical to the process by which the cores of the giant planets formed. Cometary impacts transport water-laden, organic-rich material from the outer to the inner solar system, and play an important role in the formation and evolution of planetary atmospheres throughout the solar system. We include icy bodies that originated in the outer solar system but whose orbits have suffered perturbations that have brought them into the inner solar system.

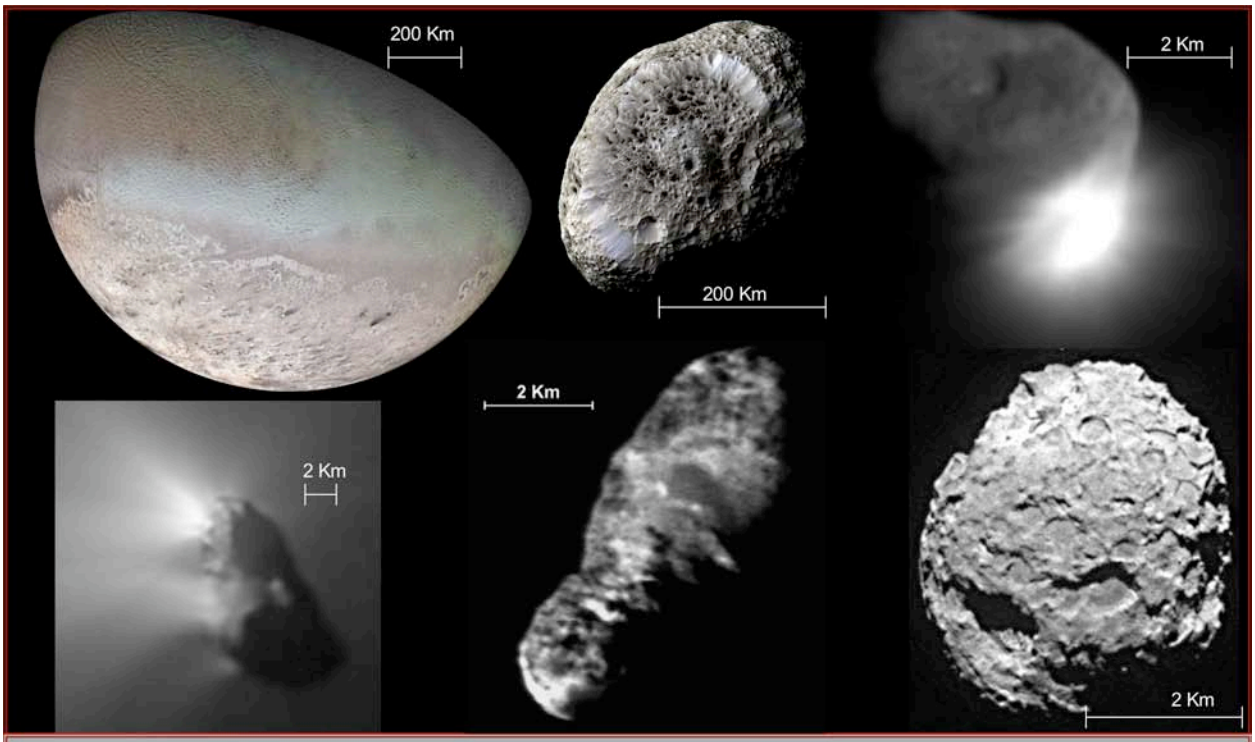


Figure 16 - Diversity of small icy bodies of the solar system. *Clockwise from top left:* Triton - Voyager 2 image of large, captured icy moon of Neptune; Hyperion - Cassini image of outer satellite of Saturn, likely captured; Comet Tempel 1 - Deep Impact image of daughter spacecraft crashing into the comet; Comet Wild 2 - Stardust image taken as the spacecraft flew by and picked up dust samples that were brought back to Earth; Comet Borrelly - image taken by the Deep Space 1 spacecraft; Comet Halley - image by ESA's Giotto mission. These diverse objects have common origins in a population of outer solar system planetesimals, from which the cores of giant planets accreted and which delivered organics and volatiles to the inner solar system. Their diversity reflects their very different histories that brought them to their current locations and produced their varied appearances.

The discovery in 1992 of the Kuiper belt, with its myriad of over 1000 "ice dwarf" objects, has revolutionized our view of the solar system. Pluto is no longer the enigma that it was for over 60 years, as it has been joined by a growing list of objects vying for planet status, and a far greater number of smaller objects. These icy dwarfs comprise a remnant debris disk whose dynamical structure is providing interesting new insights into the formation and radial migration of the giant planets during the solar system's early evolution. Collisions within the Kuiper belt have injected some of the smaller objects towards the Sun, where they became centaurs, captured satellites, or short-period comets. These various classes of objects display a wide range of sizes, shapes, albedos, and compositions, which have yet to be explained.

OPAG broadly endorses the Decadal Survey's priorities with respect to the small, icy worlds of the outer solar system. The Decadal Survey's fundamental issues remain the most relevant to study:

Small Icy Bodies: Fundamental Questions:

1. Where in the solar system are the small icy bodies found, and what are their bulk physical properties?
2. What processes led to the formation of these objects, and what processes have subsequently altered them?
3. How did small icy bodies make planets, and how have they subsequently affected the planets?

Small Icy Bodies: Measurement Objectives:

1. Obtain high resolution surface imaging to measure the size and shape, and to investigate topological features.
2. Map the global surface composition.
3. Determine physical attributes such as bulk density, internal structure, thermal inertia, cratering record, and magnetic field.
4. Characterize the local environment (e.g., atmosphere, outgassing, dust rings, charged particles).
5. Investigate multiplicity (e.g., presence or absence of one or more moons).

Small Icy Bodies: (Flagship missions, not prioritized)

1. Comet Nucleus Cryogenic Sample Return
    - Measure the volatile and non-volatile material from multiple site on a comet nucleus, enabling understanding of the origin of organics and water in the solar system.
    - Provide connections to the composition of planets and their atmospheres.
    - Provide connections to the interstellar medium.
2. Centaur or Trojan orbiter
    - Characterize in detail a large KBO escapee.
    - Determine the degree of evolution.
    - Search for and follow temporal changes.
    - Measure isotopic composition for comparison with values at the Earth and elsewhere in the solar system.

Small Icy Bodies: New Frontiers or Discovery missions (not prioritized):

1. Sample a diversity of KBOs, across a range of sizes, distances, colors, and single/binary systems.
2. Explore a Centaur and/or Trojan with flyby missions.
3. Return comet surface sample (non-cryogenic).

OPAG makes the following findings:

- Diversity of targets is the key to understanding the rapidly-increasing inventory of small bodies in the solar system.
- Spacecraft and Earth-based observations of small bodies are complementary. Spacecraft missions provide the "ground truth" needed to guide the interpretations of a wealth of remote sensing data; Earth-based data enables scientists to understand the broad population of objects. OPAG urges NASA to continue support of Earth-based telescopic studies as well as space craft missions.
- The smaller bodies of the outer solar system are potential targets of Discovery and New Frontiers missions. OPAG urges NASA to keep the AO of these mission lines open to such targets.
- Cryogenic sample return is a key technology required to meet the goals of the Decadal Survey. OPAG urges NASA to invest in studies of this important technology.

Appendix A. OPAG History

The Outer Planets Assessment Group was started in November 2004. Communication with the space science community is via an email list of about 500 people. Interested scientists and engineers can join the list via the OPAG website.

http://www.lpi.usra.edu/opag/

OPAG has held four meetings to date, each attended by ~100 people:

February 10–11th, 2005, Marriott Hotel, Rockville, MD
June 9–10, 2005, Hotel Boulderado, Boulder, CO
October 6–7, 2005, Key Bridge Marriott, Arlington, VA
May 4-5, 2006, Westin Hotel, Pasadena, CA

Charter: OPAG is NASA's community-based forum designed to provide science input for planning and prioritizing outer planet exploration activities for the next several decades. It is chartered by NASA's Planetary Science Division and reports its findings to both the Division and at meetings of the Planetary Science Sub-Committee of the NASA Advisory Council*. Open to all interested scientists, OPAG regularly evaluates outer solar system exploration goals, objectives, investigations and required measurements on the basis of the widest possible community outreach.

Outer Planets Assessment Group Steering Committee

Fran Bagenal, University of Colorado (Chair)
Sushil Atreya, University of Michigan
Kevin Baines, Jet Propulsion Laboratory
Frank Crary, Southwest Research Institute, San Antonio
Paul Geissler, US Geological Survey
Randy Gladstone, Southwest Research Institute, San Antonio
Ron Greeley, Arizona State University
Bill Hubbard, University of Arizona
Torrence Johnson, Jet Propulsion Laboratory
Bill Kurth, University of Iowa
Bill McKinnon, Washington University
Ralph McNutt, The John Hopkins University Applied Physics Laboratory
Bill Moore, University of California – Los Angeles
Julianne Moses, Lunar and Planetary Institute
Amy Simon-Miller, NASA Goddard Space Flight Center
Henry Throop, Southwest Research Institute, Boulder
Hal Weaver, The John Hopkins University Applied Physics Laboratory
Curt Niebur, NASA HQ (Executive Officer)

The Steering Committee is selected to represent the breadth of the scientific community. Each member typically serves for three years.

* *In spring 2006 NASA re-organized the divisions of the Science Mission Directorate as well as the bodies that advise NASA. The former Solar System Exploration Sub-Committee and the Space Science Advisory Committee were eliminated. A new advisory structure was created with a Planetary Science Subcommittee reporting to the Science Committee of the NASA Advisory Council.*