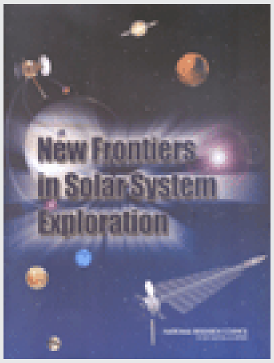

New Frontiers in Solar System Exploration

DETAILS

32 pages | 8.5 x 11 |
ISBN | DOI: 10.17226/10898

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New Frontiers in Solar System Exploration

NATIONAL RESEARCH COUNCIL
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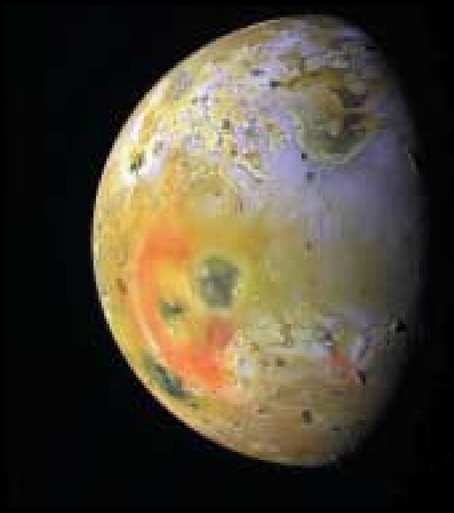

THE NATIONAL ACADEMIES PRESS
Washington, D.C.

www.nap.edu

This booklet is based on the Space Studies Board report *New Frontiers in the Solar System: An Integrated Exploration Strategy* (available online at <http://books.nap.edu/html/newfrontiers /0309084954.pdf>). Details about obtaining copies of the full report, together with more information about the Space Studies Board and its activities, can be found at <http://www7.nationalacademies.org/ssb/>.

New Frontiers in the Solar System was authored by the Solar System Exploration Survey.

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Support for this publication was provided by the The Presidents' Circle Communication Initiative of the National Academies.

The Space Studies Board acknowledges Brian Dewhurst, Bethany Ehlmann, and David H. Smith for drafting the text of this booklet.

Cover design by Penny Margolskee; booklet design by Anne Rogers.

Printed in the United States of America

Contents

A montage of some of the diverse planetary bodies explored by spacecraft in the last 40 years.

Solar System Exploration Today

Over the last four decades, robotic spacecraft have visited nearly every planet, from torrid Mercury to frigid Neptune. The data returned by these Pioneers, Mariners, Vikings, and Voyagers have revolutionized our understanding of the solar system. These achievements rank among the greatest accomplishments of the 20th century. Now, at the opening of the 21st, it is appropriate to ask, where do we go from here?

The scientific potential is limitless; the text on page 4 highlights just a few of the mysteries our explorations have turned up to date. We could send spacecraft to roam Mars's surface, return pieces of a comet to Earth, explore Pluto, or probe the hellish atmosphere of Venus. By making careful choices about which of those tantalizing targets are most important, we set ourselves on the path to realizing all our scientific dreams concerning the solar system.

From a scientific perspective, we must consider how future missions will help answer a set of fundamental questions that reach beyond just planetary exploration:

- **Are we alone?**
- **Where did we come from?**
- **What is our destiny?**

Answering these questions requires several simultaneous approaches. On Earth, theoretical models and research with telescopes can improve our understanding. In space, small spacecraft—like those in NASA's ongoing and highly successful Discovery series—can pursue limited objectives. Larger probes, like the U.S.-European Cassini/Huygens mission currently en route to Saturn, have comprehensive goals. With the wide variety of subjects and approaches, the question remains: Which missions are the most scientifically significant, technically ready, and fiscally viable?

In 2001, NASA asked the National Academies to study the current state of solar system exploration in the United States and devise a set of scientific priorities for missions in the upcoming decade (2003-2013). After soliciting input from hundreds of scientists around the nation and abroad, the Solar System Exploration Survey (SSE Survey) produced the discipline's first long-range, community-generated strategy and set of mission priorities: *New Frontiers in the Solar System: An Integrated Exploration Strategy* (National Academies Press, Washington, D.C., 2003). The key mission recommendations made in the report, and the scientific goals from which the recommendations flow, are summarized in this booklet.

After studying input from the scientific community, the SSE Survey developed four themes to guide the prioritization process:

The First Billion Years of Solar System History covers the formative period that features the initial accretion and development of Earth and its sibling planets, including the emergence of life on our globe. This pivotal epoch in the solar system's history is only dimly glimpsed at present.

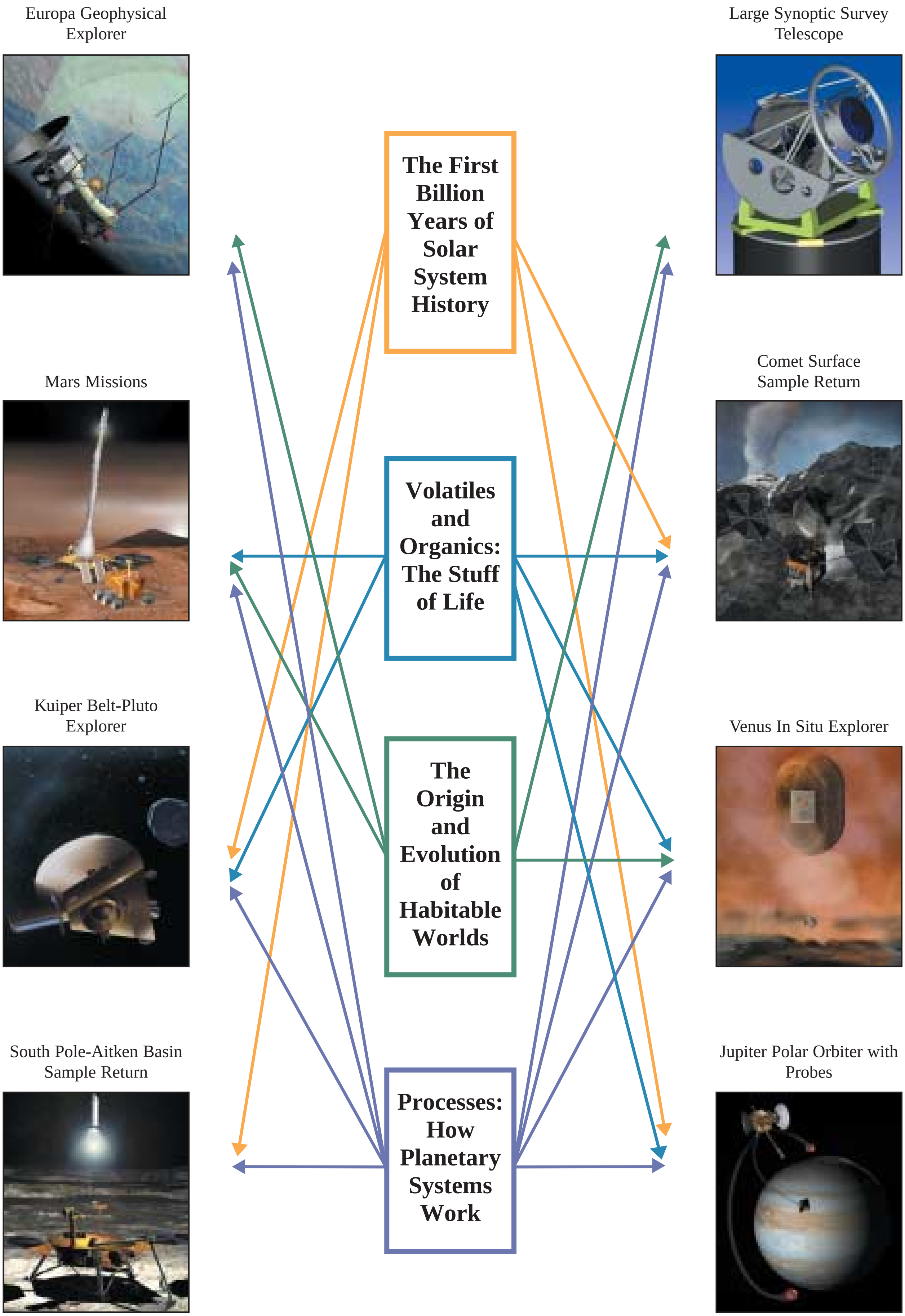
Volatiles and Organics: The Stuff of Life addresses the reality that life requires organic materials and volatiles, notably, liquid water. These materials originally condensed in the outer reaches of the solar nebula and were later delivered to the planets aboard organic-rich comets and asteroids.

The Origin and Evolution of Habitable Worlds recognizes that our concept of the "habitable zone" has been overturned, and greatly broadened, by recent findings on Earth and elsewhere throughout our galaxy. Taking inventory of our planetary neighborhood will help to trace the evolutionary paths of the other planets and the eventual fate of our own.

Processes: How Planetary Systems Work seeks deeper understanding of the fundamental mechanisms operating in the solar system today. Comprehending such processes—and how they apply to planetary bodies—is the keystone of planetary science. It will provide deep insight into the evolution of all the worlds within the solar system and of the multitude of planets being discovered around other stars.

With the assistance of six expert panels, the SSE Survey developed a list of eight recommended activities for the decade 2003-2013 (see adjacent diagram). These activities—including the development of medium- and large-class, flight-mission concepts as well as supporting ground-based facilities—were ranked in priority order according to their relevance to the themes outlined above and their role in answering important scientific questions. A program based on these recommendations will provide a strong backbone for the continuation of solar system exploration through 2013.

Subsequent pages outline a set of scientific topics in which exciting research is being conducted today, matching those topics with mission concepts proposed by the SSE Survey to further our knowledge in these areas. The description of each proposed mission includes a list of important science questions the mission should address, the measurements needed to do so, and the guiding themes in solar system exploration that the mission would help elucidate.


Europa Geophysical Explorer
Large Synoptic Survey Telescope
The First Billion Years of Solar System History
Mars Missions
Comet Surface Sample Return
Volatiles and Organics: The Stuff of Life
Kuiper Belt-Pluto Explorer
Venus In Situ Explorer
The Origin and Evolution of Habitable Worlds
South Pole-Aitken Basin Sample Return
Jupiter Polar Orbiter with Probes
Processes: How Planetary Systems Work

Six Continuing Mysteries About the Solar System

- **The diversity of bodies in the solar system.** There are several distinct classes of objects in the solar system. The terrestrial planets such as Earth are rocky and close to the Sun. The gas giants (Jupiter and Saturn) are tens of times larger than Earth and are made mostly of hydrogen and helium. Beyond the gas giants are the ice giants, Uranus and Neptune, which are composed of frozen methane and ammonia. Farther out are relatively small icy fragments called Kuiper Belt objects. These bodies (Pluto is one) are thought to have undergone relatively little change since their formation some 4.6 billion years ago. Is this diversity of objects a common feature of planetary systems? If so, what is its cause?

- **The sharp contrast between Earth and Venus.** Although similar in size, mass, composition, and distance from the Sun, Venus is hellish while Earth has life. Why are Venus and Earth so different? Did Venus once have an ocean? Is the uniqueness of Earth's Moon a factor in making Earth hospitable to life? What basic factors control a planet's climate?

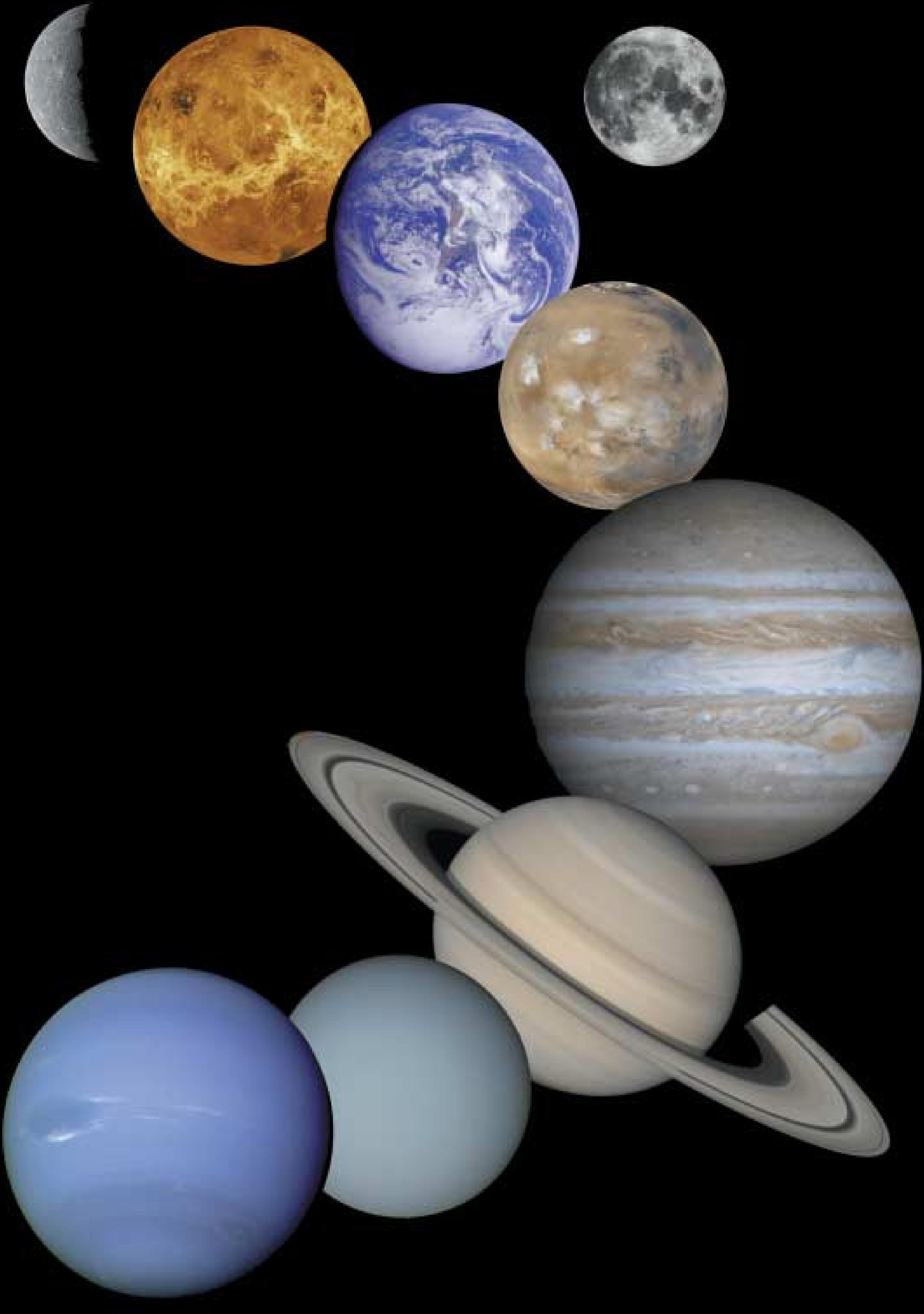
- **The potential habitability of Mars.** Mars, the planet with the most Earth-like environment, is a potential abode of life. Throughout its history, Mars has undergone significant changes, including massive climatic shifts, enormous volcanic eruptions, loss of volatiles like water vapor into space, and the development and subsequent decay of a strong magnetic field. When and how did these changes occur? How did they affect Mars's environment, and what was the impact of such changes on the possible origin, evolution, and survival of life?

- **The effects that asteroids and comets have on Earth.** The small, wandering bodies of the solar system may determine the fate of Earth. What role did asteroids and comets play in the origin of life on Earth by delivering amino acids and water during Earth's formation? What role have small bodies played in shaping the course of evolution through globally devastating impacts? Will these objects determine our ultimate fate?

- **Distant worlds of fire and ice, and possible life.** Activity abounds on the moons of the outer solar system, from Io's fiery volcanoes to Triton's frigid geysers. Much of this activity is due to the fact that these satellites orbit within the strong gravitational pull of the ice and gas giants. What is the role of tidal heating (heating of the satellites' interiors by the pull of gravity)? How many of the large icy moons hide oceans beneath the surface? Are these oceans habitable?

- **Nature of the Kuiper Belt and its myriad objects.** What is the composition of the Kuiper Belt objects found in the outer reaches of the solar system? Is there a great deal of diversity in their makeup? How many Kuiper Belt objects are Pluto-size or larger? What is the relationship of Kuiper Belt objects to other small bodies like comets and asteroids? How far out from the Sun does the Kuiper Belt extend?

The rocky bodies—Mercury **(upper left)***, Venus, Earth and the Moon, and Mars—and the gaseous bodies—Jupiter, Saturn, Uranus, and Neptune* **(lower left)***—of the inner and outer solar system. Not to scale.*



Europa and Large Satellites

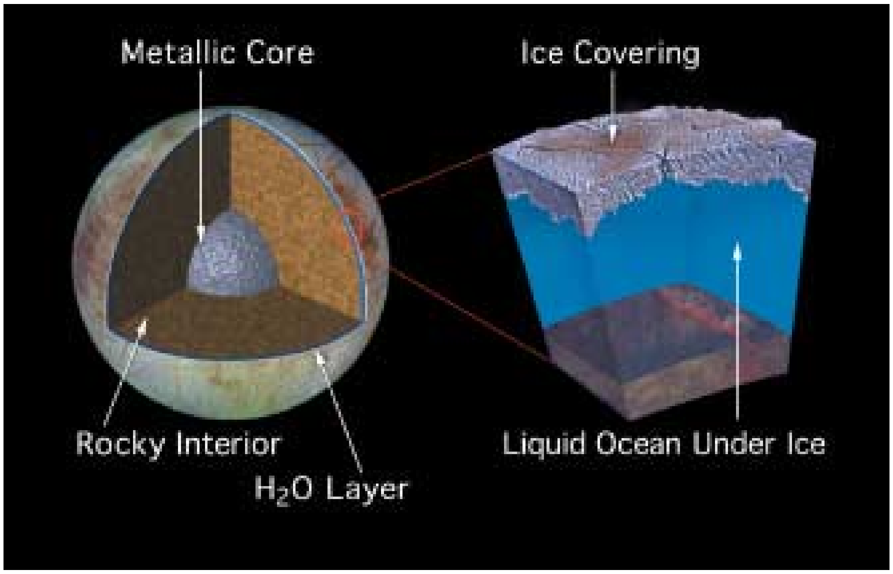
The outer solar system is dominated by the giant ice and gas planets, whose enormous gravitational fields sweep up much of the debris that passes through their orbits. As the solar system evolved, this debris formed a host of satellites around Jupiter, Saturn, Uranus, and Neptune, and very large satellites formed around all but Uranus. These major moons, all larger than Pluto and two larger than Mercury, are interesting worlds in their own right.

Why are these worlds worthy of national and international exploration and research? The most compelling motivation relates to understanding the origin and survival of life and the limits on where life can be found in a planetary system. Water is essential to life as we know it, and the large icy satellites may contain the largest reservoirs of liquid water in the solar system. Jupiter's moon Europa may be the best place in the solar system beyond Earth to search for signs of life. Saturn's moon Titan provides a natural laboratory for the study of organic chemistry over spans of time and distance unattainable in terrestrial laboratories. The origin and evolution of the satellite systems of the giant planets also provide analogs for understanding planetary systems around other stars, some of which may be abodes for life. Perhaps teeming with life or perhaps sterile today, these moons seem certain to contain the basic ingredients for life. Knowing whether or not life exists on them today is equally compelling.

Icy Europa as seen by Voyager 2 **(top)** *and Galileo* **(above)**. *The view from Galileo of Europa's Conamara region shows objects as small as 60 m across. The discontinuities in the linear features create the strong impression that pieces of the surface have fractured and drifted before refreezing into new positions.*

Europa holds the most promise for understanding the biological potential of icy satellites. There is convincing evidence that the incessant pushing and pulling on Europa by Jupiter's gravitational field generates sufficient tidal heating to sustain a global ocean of liquid water just a few tens of kilometers beneath the satellite's icy surface. Moreover, there is geological evidence of recent transfer of material between the surface and the water layer. If a cold europan ocean is in direct contact with Europa's warmer rocky mantle, the result could be an environment in which complex chemical processes can occur. Such an environment could lead to the beginnings of life.

A Europa mission with the goal of confirming the presence of an interior ocean is the first step in understanding icy satellites' potential as abodes for life. Characterizing Europa's ice shell and understanding its geological history are also vital components of such a mission. By exploring the extent to which organic chemistry progresses toward life in extreme planetary environments, a Europa mission would help us to understand how tidal heating can affect the evolution of worlds.



Europa's internal structure may include a water layer some 100 km thick.

Europa Geophysical Explorer

Profile

Europa Geophysical Explorer

Mission Type: Orbiter

Cost Class: Large

Priority Measurements:

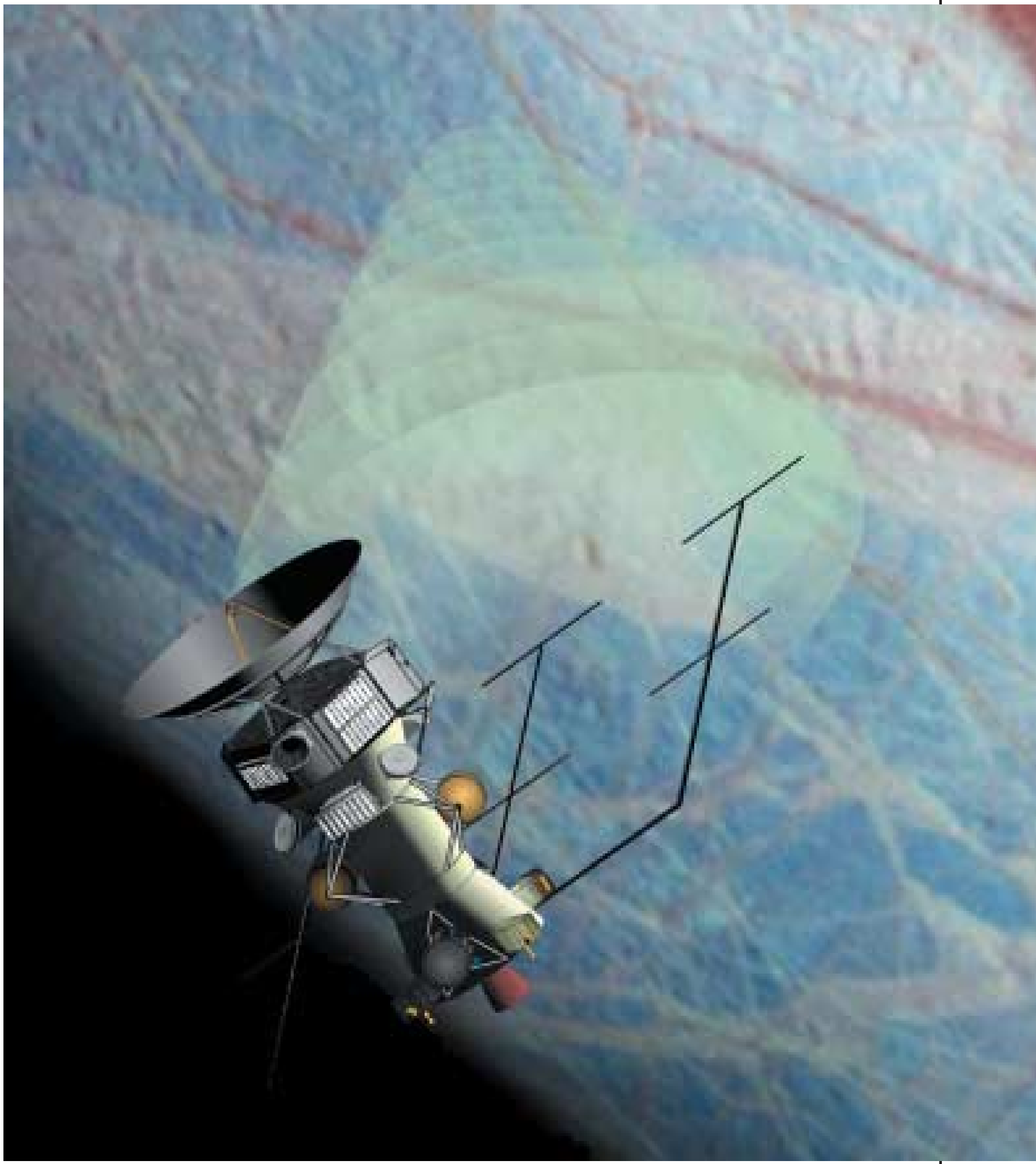
- Obtain high-resolution images of Europa's surface.
- Characterize its internal heat sources.
- Determine its surface composition.
- Sound the ice shell to determine its thickness and structure.
- Search for temporal variations in its magnetic properties.

Guiding Themes Addressed	Important Planetary Science Questions Addressed
The Origin and Evolution of Habitable Worlds	*What planetary processes are responsible for generating and sustaining habitable worlds?* *Where are the habitable zones in the solar system?* *How has the suspected ocean varied throughout Europa's history?* *What is keeping the ocean from freezing?*
Processes How Planetary Systems Work	*How do the processes that shape the contemporary character of planetary bodies operate and interact?* *What is the chemical composition of Europa's suspected ocean?*

These concepts are key to understanding the origin and evolution of water-rich environments in icy satellites.

The Europa Geophysical Explorer mission proposed by the SSE Survey is an extension of orbiter concepts studied by NASA in the 1990s, and would pave the way for more ambitious Europa missions in the future, such as a lander or even a submarine to explore the ocean (if it exists). The Europa Geophysical Explorer would be tasked with confirming the presence of an ocean, identifying areas of recent surface activity, finding areas with possible biotic or prebiotic compounds, and characterizing the europan environment in preparation for further study.

The large cost (in excess of $1 billion) of this mission would place it in the same class as Galileo and Cassini/Huygens. Such large missions have been a traditional focus for international cooperation in which NASA and other national space agencies can leverage their resources to accomplish what might otherwise be too costly to achieve. Galileo and Cassini/Huygens provide perfect examples of partnerships that have proved highly successful. NASA should engage prospective international partners in the planning and implementation of the Europa Geophysical Explorer.



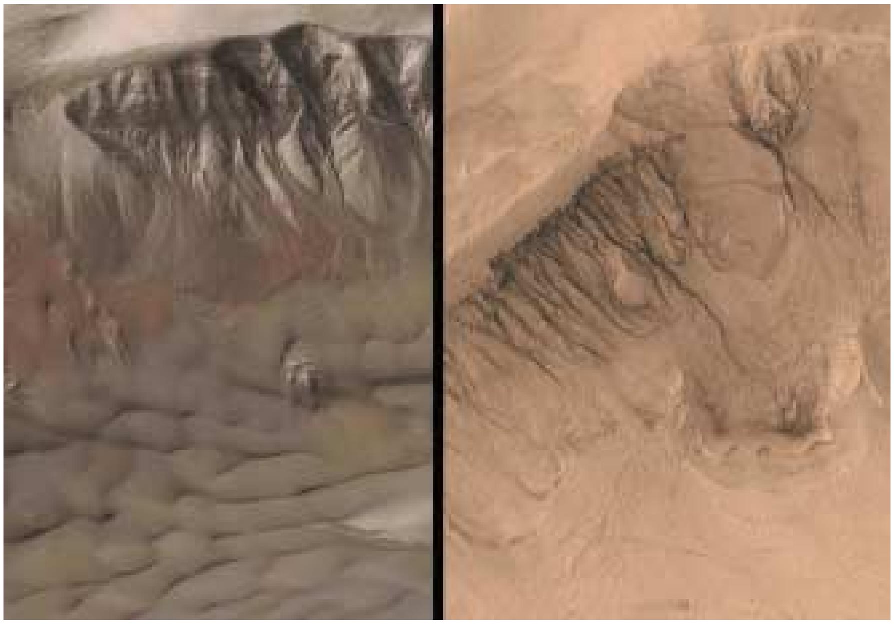
In addition to mapping the satellite's topography, the Europa Geophysical Explorer will use radar to probe the structure of Europa's icy surface layer.

Mars

The first high-resolution martian images acquired by the Mariner 4 spacecraft in 1965 shattered popular notions of Mars. Far from being an oasis, the surface of Mars appeared instead to be as battered and barren as the Moon. With its thin atmosphere and bitterly cold temperatures, Mars seemed more parched than the driest places on Earth. The prospect that life could have evolved there seemed dim.

Each subsequent mission to Mars has changed that impression in surprising ways. Mariner 9 revealed ancient towering volcanoes, extensive polar caps, and immense canyons apparently cut by water. Systematic observations of the surface and atmosphere by Viking led to a dramatic increase in our knowledge of the breadth of martian geological history and the dynamics of the current climate. The recent Mars Global Surveyor (MGS) mission has again revolutionized our understanding of martian evolution. Far from having no magnetic field as previously believed, MGS discovered that large portions of the surface of Mars were strongly magnetized early in martian history. Moreover, MGS has seen indications of recent or ongoing climate change, and has found small gullies with characteristics suggesting that they were recently carved by fluid flow. Additionally, fundamental information has been derived from the study of martian meteorites. Detailed analysis of these samples has invigorated the debate over whether life ever existed on Mars.

Despite studies to date, we still do not know fully where water exists on Mars today. There are direct observations of four exposed martian water reservoirs, which include water vapor in the atmosphere, water ice in the atmosphere, seasonal water ice deposits at the surface, and permanent water ice deposits at the north and south poles. Of the four reservoirs, the martian polar caps are by far the most massive. Recent MGS data sets indicate that the mass of water ice contained within the martian north and south polar caps is equivalent to a global ocean some 22 to 33 meters deep. Recent observations from the Mars Odyssey spacecraft also suggest a patchy reservoir of water ice beneath the martian surface. At increasing depth, where the rock is warmer, liquid water may be present in pore spaces.



The Mars Pathfinder landing site **(above)***, like much if not all of the martian surface, is drier than Earth's driest desert. But this may not always have been the case. Gullies on canyon and crater walls, such as these* **(top)** *in Sirenum Terra seen by Mars Global Surveyor, are possible evidence that water has flowed on or near to the martian surface in the geologically recent past.*

Mars Sample Return and Precursor Missions

On Earth, life is found wherever there is liquid water. On Mars, although the peak daytime surface temperature near the equator can rise above the freezing point of water, the average surface temperature is about –55°C. The surface of Mars today is cold, dry, oxidized, and exposed to an intense amount of solar ultraviolet radiation. These factors are likely to limit or even to prohibit life at or near the surface of the martian soil.

The surface environment of Mars, however, may not always have been as hostile to life as it is today. The geological evidence, especially in the valley networks, indicates that the martian climate could have been appreciably more hospitable to life about 3 billion years ago—the atmosphere appears to have been warmer and more dense, and liquid water existed on the surface. In such a climate, life could have developed, possibly leaving behind fossil evidence in mineral deposits created by surface water.

To date, a single set of robotic studies has searched directly for existing life on Mars: the Viking life-detection experiments, which were designed to test for organisms using carbon dioxide or organic molecules in a manner analogous with terrestrial organisms. The results of the Viking experiments very strongly suggest that the materials tested were devoid of organic compounds or other signs of life, but this conclusion has been debated. The lack of unanimity in the scientific community highlights the difficulties inherent in the detection of microorganisms by robotic means. Indeed, even if it were generally acknowledged that the Viking experiments did not show the presence of life, the experiments could still be criticized as being overly geocentric in showing only a lack of evidence for lifeforms on or near the surface of Mars that were similar to life on Earth.

The pace of Mars exploration is currently breathtaking! NASA currently has two spacecraft—Mars Global Surveyor and Mars Odyssey—operating in orbit about the Red Planet, and two more—the twin Mars Exploration Rovers, Spirit and Opportunity—are en route. The NASA missions are scheduled to be joined by a Japanese orbiter, Nozomi, and Europe's Mars Express orbiter and Beagle 2 lander. Moreover, NASA has well-defined plans to launch additional Mars missions at each launch opportunity for the remainder of this decade (see the diagram on page 10).

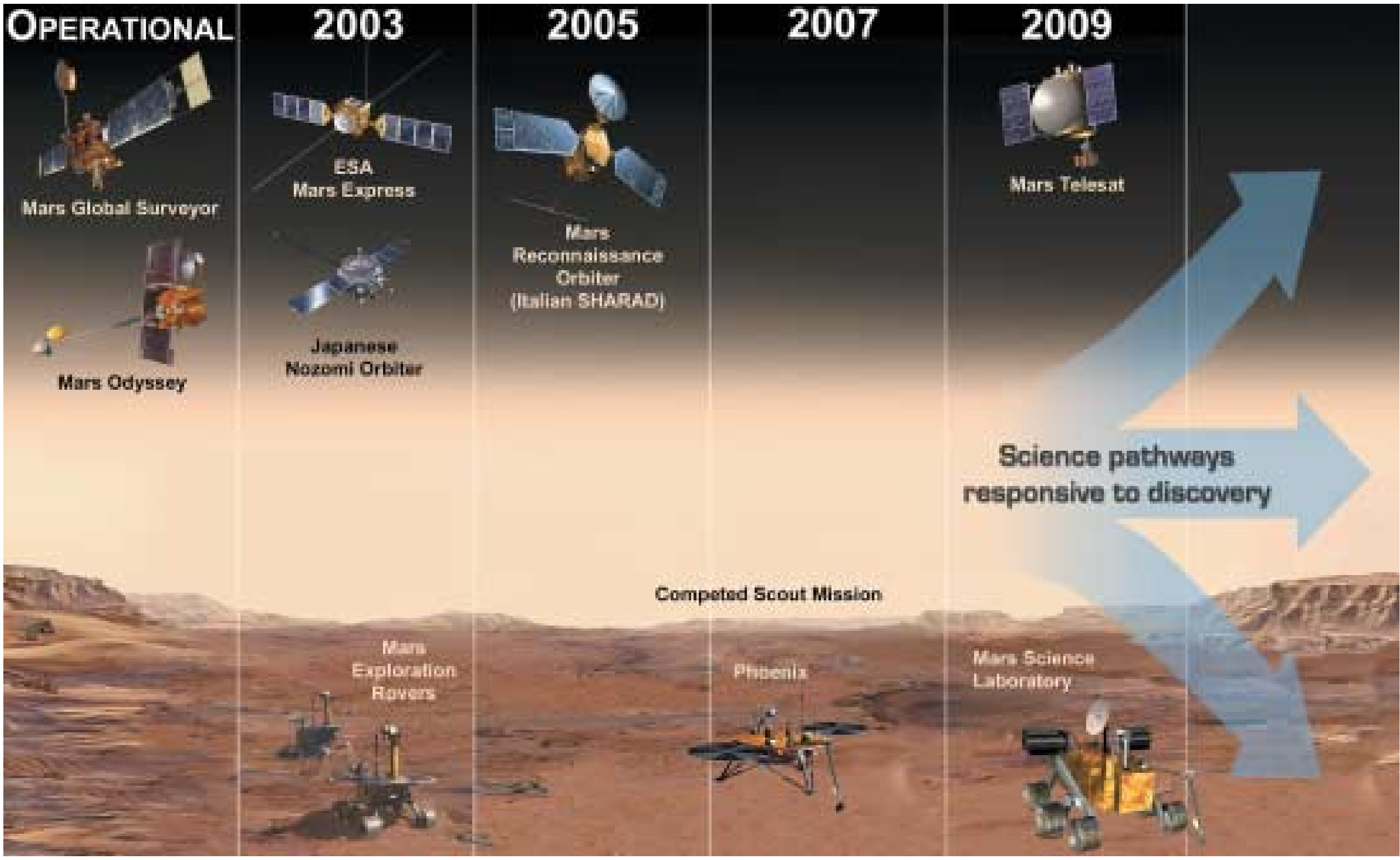
At 3000 km long and up to 8 km deep, Mars's Valles Marineris canyon system dwarfs any such feature on Earth. Mosaic constructed from Viking 1 orbiter images.

Since Mars exploration activities for the rest of this decade are well in hand, the SSE Survey concentrated on identifying gaps in the existing program and laying the groundwork for activities in the decade beyond 2013. The SSE Survey concluded that, with our present state of knowledge and technological expertise, it is unlikely that robotic techniques will be able to conclusively prove whether there is or has been life on Mars. Results obtained from life-detection experiments carried out by robotic means on the martian surface can be challenged as ambiguous for the following reasons:

- Results that show an absence of life may not be accepted because the experiments yielding them were too geocentric or otherwise limited;
- Results consistent with, but not definitive of, the existence of life (e.g., the detection of organic compounds of unknown, either biological or nonbiological, origin) may be regarded as incapable of providing a clear-cut answer; and
- Results interpreted as showing the existence of life will be regarded as necessarily suspect, since they might reflect the presence of terrestrial contaminants instead of true martian life.

Definitive answers about the existence of martian life will require laboratory analysis of Mars samples returned to Earth. Samples provide the ultimate ground truth for the wealth of data returned from telescopes, orbiting sensors, and in situ missions thoughout the solar system.

Mars



NASA, together with other national and international space agencies, has detailed plans for missions **(above)** *to follow on from the current Mars Global Surveyor and Mars Odyssey. These missions include the Mars Exploration Rovers* **(right)**, *Mars Express, and Nozomi currently en route to Mars. Missions beyond 2009 are being planned.*

The SSE Survey recommends that NASA should spend the next 10 years preparing for a Mars Sample Return campaign near 2015. Sample return should be conducted to obtain rocks from a variety of geological settings. Moreover, to best assess Mars's potential for life, robotic techniques should be devised to collect samples from beneath the martian surface where conditions are more hospitable for living organisms. (For more discussion of sample-return missions, see the Technology Development section on page 25.)

Mars Sample Return and Precursor Missions

Profile

Mars Sample Return and Precursor Missions

Mission Type: Continuing program of landers and orbiters leading toward sample-return missions

Cost Class: Small, Medium, and Large

Priority Measurements:

- Collect and return selected samples of martian soil and rock to Earth.
- Measure the chemical and isotopic composition of the atmosphere at ground level over the course of a martian year.
- Map the distribution of water in the crust.
- Assess the rate of escape of gases from the middle and upper atmosphere.
- Conduct a long-lived survey of seismic activity.
- Quantify the heat flow from the martian interior.
- Determine the composition and age of martian rocks.
- Undertake high-resolution magnetic mapping of the southern highlands.

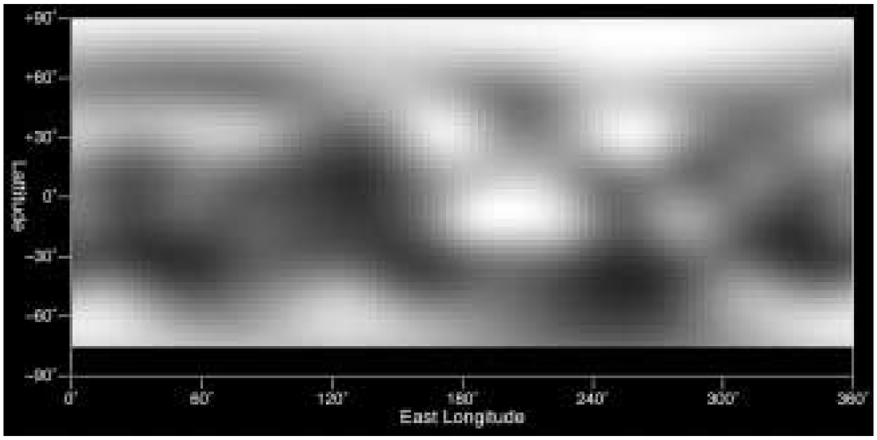
Although technically challenging, collection and return of martian samples to Earth for intensive study in terrestrial laboratories is a key scientific priority for the decade beginning in 2013. Advanced rovers may be used to collect samples.

Guiding Themes Addressed	Important Planetary Science Questions Addressed
Volatiles and Organics The Stuff of Life	*What global mechanisms affect the evolution of volatiles on planetary bodies?* *Where is the water on Mars?*
The Origin and Evolution of Habitable Worlds	*What planetary processes are responsible for generating and sustaining habitable worlds?* *Where are the habitable zones in the solar system?* *Does life currently exist on Mars?* *Did life ever exist on Mars?* *Why have the terrestrial planets differed so dramatically in their evolution?*
Processes How Planetary Systems Work	*How do the processes that shape the contemporary character of planetary bodies operate and interact?* *How did the atmosphere evolve over long periods of time?* *What kinds of rocks are in the martian crust?* *Why does the martian crust show evidence of a strong magnetic field in the distant past?*

Kuiper Belt Objects

In 1977, twin spacecraft lifted off from the same launch pad at the Kennedy Space Center in Florida, only a few months apart. These spacecraft, Voyager 1 and Voyager 2, were Earth's first emissaries to the outer solar system. The information that they returned about the giant planets and their moons revolutionized our understanding of the solar system. Voyager stands as one of the greatest missions of planetary discovery in the space age. For all the Voyager program's success, however, Voyager 1 and 2 left the reconnaissance of the outer solar system incomplete. To date, no missions have explored the ninth planet, Pluto, and its satellite, Charon.

At the time of the Voyager missions, Pluto was thought to be less important than other planetary bodies, such as Neptune and Saturn's moon Titan, which were also easier to reach. In 1992, however, scientists found the first direct evidence for the existence of the Kuiper Belt—a region of icy planetary debris on the edge of the solar system. The discovery of the Kuiper Belt refocused attention on Pluto. Instead of an afterthought, Pluto became the largest and most important member of an entirely unexplored type of body—the Kuiper Belt objects (KBOs).



Even the most detailed map of Pluto's surface, assembled from observations made with the Hubble Space Telescope, reveals little about the most distant planet from the Sun. The nature of the surface features remains unknown.

Another exciting discovery came within a few years of the detection of the first KBO—the identification of planets in orbit around other stars. Many of these extrasolar planets reside in large disks of material orbiting young stars, which scientists believe resemble our solar system in its youth. If current theory holds, objects in these extrasolar disks are similar in composition to objects in the Kuiper Belt. Most KBOs are thought to have undergone relatively little change since their formation in the solar nebula some 4.6 billion years ago. If that is the case, they would be relics of the building blocks from which the planets were formed. Thus, analyzing the structure and composition of these objects will provide new insights into the early history of planetary systems and help scientists understand the processes that formed Earth and other planets.

Studies of the surface compositions of KBOs undertaken with Earth-based telescopes suggest that these objects likely contain organic matter and volatile materials such as water. This is an exciting discovery because researchers believe that the water and carbon-rich materials essential for the development of life on Earth are not indigenous to our planet. In other words, these life-giving materials were delivered to the primordial Earth during impacts with objects originating elsewhere in the solar system. A likely source of the impactors, and thus of the building blocks of life, may have been the Kuiper Belt.

The first exploratory voyage to an unexplored region always turns up new and unexpected findings. As the first spacecraft specifically targeted to study this distant part of the solar system, the Kuiper Belt-Pluto Explorer will undoubtedly lead to a new understanding of the KBOs and, perhaps, inform us about the role played by KBOs in the origin and evolution of other parts of the solar system.

Collisions, for example, are a ubiquitous process in planetary formation and in shaping planetary environments. But next to nothing is known about the 4.6 billion-year-old collisional history of the Kuiper Belt. A comparison of the density of craters on Pluto, its moon Charon, and several KBOs will provide our first hard data on the history of impacts in the extreme outer solar system.

If indeed KBO material is as ancient and relatively unaltered as scientists believe, characterizing the composition will provide an important reference for comparison with the surface materials on other related bodies, including the Centaurs, the nuclei of comets, and certain near-Earth asteroids. Such observations may provide information on whether comets are fragments of large KBOs or are themselves primordial bodies. Kuiper Belt-Pluto Explorer data will also allow researchers to compare the surface compositions of KBOs with Pluto, Charon, and Triton—a satellite of Neptune suspected of being a captured KBO. This may allow us to determine how primitive material in the outer solar system is changed over the course of planetary evolution.

Telescopic observations to date indicate that KBOs have diverse and sometimes unexpected characteristics—most display wide color variations from object to object, some have rapid rotation rates, a few exist in loosely bound double systems, and Pluto even has a tenuous atmosphere. Because of the incredible variety in color, size, composition, and orbit among KBOs, the value of the Kuiper Belt-Pluto Explorer mission increases as it observes more KBOs and, thus, samples more of the

Kuiper Belt-Pluto Explorer

physical and chemical diversity displayed by these objects.

NASA has been working for more than a decade to develop a mission to Pluto, and much of the planning and design has already been done. The compelling scientific investigations outlined above and the body of existing technology and planning led the SSE Survey to conclude that a flyby mission to multiple KBOs, including Pluto and Charon, should be NASA's highest priority for medium-size missions in the decade 2003-2013.

Profile

Kuiper Belt-Pluto Explorer

Mission Type: Multi-object Flyby

Cost Class: Medium

Priority Measurements:

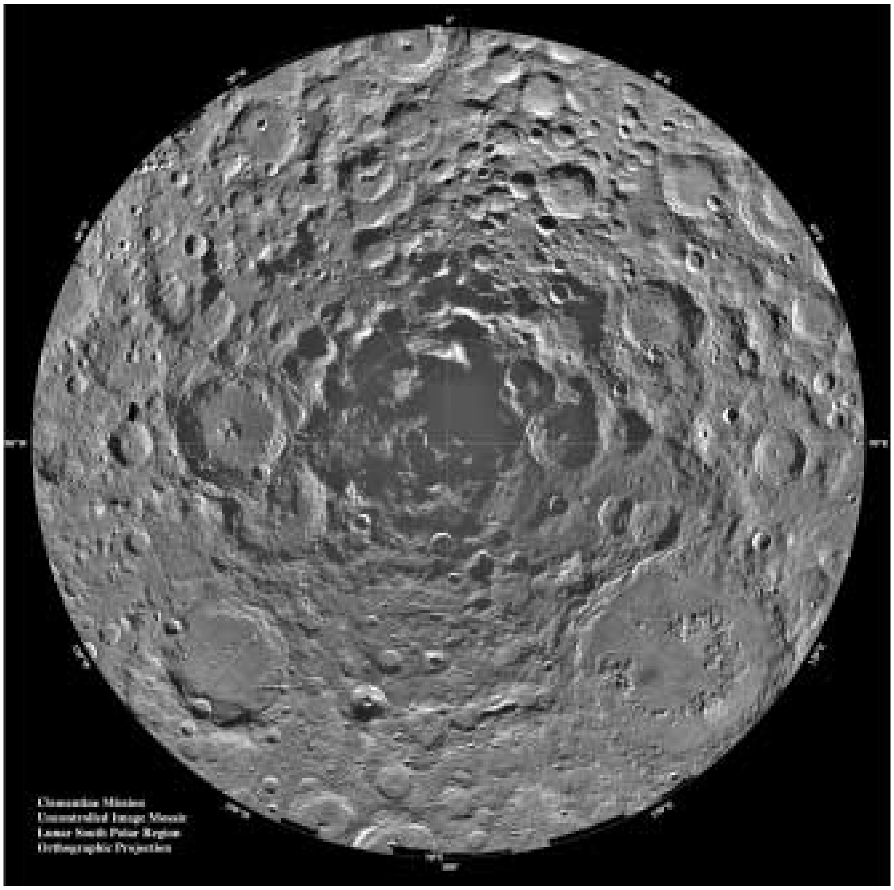
- Determine the dimensions and shapes of the KBOs visited.
- Assess their crater density.
- Measure their surface composition through imaging spectroscopy.
- Detect their atmospheres.
- Search for evidence of ongoing geological activity (e.g., geysers).
- Assess the dust density with increasing distance into the Kuiper Belt.

Artist's impression of New Horizons, the Kuiper Belt-Pluto Explorer.

Guiding Themes Addressed	Important Planetary Science Questions Addressed
The First Billion Years of Solar System History	*What processes marked the initial stages of planet and satellite formation?* *How did the objects beyond Neptune form?* *How did the impactor flux decay during the solar system's youth, and in what way(s) did this decline influence the timing of life's emergence on Earth?*
Volatiles and Organics The Stuff of Life	*What is the history of volatile compounds, especially water, across the solar system?* *What is the nature of the Kuiper Belt objects?* *What kinds of objects are in the outer solar system, and how many are there?*
Processes How Planetary Systems Work	*How do the processes that shape the contemporary character of planetary bodies operate and interact?* *What does the solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?* *Are Pluto, its moon Charon, and other KBOs geologically active today?*

Cratering and Planetary Evolution

The early solar system was a chaotic and violent place. Debris from the formation of the solar system rained down onto the surfaces of the forming planets much more frequently than it does in the solar system today. Indeed, an early, key advance in the understanding of shaping of planetary environments was the realization that these impacts are not merely catastrophic accidents but instead constitute a fundamental process in planetary formation and evolution. For example, a variety of data strongly supports the idea that a Mars-size object struck the primordial Earth, resulting in the formation of the Moon and setting Earth on a distinctive evolutionary path.



The region around the Moon's South Pole as seen by the Clementine orbiter.

The additional heat resulting from impacts likely caused partial, or even global, melting of Earth and other terrestrial planets, leading to the formation of magma oceans and the differentiation of their interiors. The development of planetary atmospheres was also affected by impacts. Impacting objects are believed to have been the source of much of the gases that made up Earth's early atmosphere as well as most of the terrestrial water. Learning when these impacts occurred will offer tremendous insight into planetary evolution. Impact research also has implications for the origin of life because living organisms could not gain a toehold on Earth, and perhaps elsewhere in the solar system, until the era of planet-wide, sterilizing impacts was at an end.

Quebec's 70-km-diameter Manicouagan impact structure is one of Earth's largest.

By studying the patterns of visible craters on such bodies as the Moon and Mercury, researchers have developed some theories on the timing of the impacts. There is considerable uncertainty in this system of interpretation, however, and two differing models have been proposed, though both have considerable uncertainty. In one, the rate of impacts has decreased exponentially since the beginning of the solar system. In the other, the number of impacts peaked around 4 billion years ago, before dropping off to their present level. To test these theories (or develop totally new ones) requires knowing the actual ages of the craters, which can be determined only by dating the surface materials—an objective whose accomplishment depends in turn on obtaining samples from known locations on a number of bodies.

At this time, only lunar samples have been returned to Earth, by the Apollo and Luna missions. As a result, the Moon is the only planetary body whose surface age is known with any confidence, and thus all attempts to date other bodies stem from a comparison with the Moon. While incredibly valuable, the data set from the Apollo missions is very small. Gathering a wider variety of samples from the lunar surface is an important step in more accurately determining ages for objects throughout the solar system and thereby better understanding the evolution of our celestial neighborhood.

After the initial formation of planetary bodies and the conclusion of the period of heavy bombardment, the internal structure of the planets shaped their history. Key issues in understanding a terrestrial body's evolution include the dissipation of internal heat, core formation and the associated magnetic field, distribution of heat-producing radioactive elements, and styles and extent of volcanism. For example, Earth's crust is the product of differentiation and a few billion years of recycling through the movement of continental plates. Based on analysis

South Pole-Aitken Basin Sample Return

Profile

South Pole-Aitken Basin
Sample Return

Mission Type: Sample Return

Cost Class: Medium

Priority Measurements:

- Measure elemental and mineralogical surface compositions.
- Determine interior (mantle) compositions.
- Study compositional variations and the evolution of crusts and mantles.
- Quantify the large-impactor flux in the early solar system and calibrate the lunar impact record.
- Investigate how major impacts early in a planet's history can alter its evolution and orbital dynamics.

Artist's impression of the South Pole-Aitken Basin Sample Return. The largest lunar impact structure, this basin occupies the lower two-thirds of the image of the Moon's southern polar region shown on page 14.

of the Apollo lunar samples, scientists believe that the Moon began hot, with an ocean of magma some 400 kilometers deep, and that its crust rose to the surface as the low-density component during solidification of the magma ocean. Knowledge of the internal structure of the Moon is constrained by the small set of Apollo samples, limited geophysical measurements on the surface, and observations from orbit. Remote sensing data show that the Moon has a strong hemispheric asymmetry—the side facing Earth and the farside differ significantly. Although its cause is not known, the asymmetry likely influenced the amount and location of subsequent volcanic activity on the Moon.

The goal of the South Pole-Aitken Basin Sample Return mission is to understand the nature of the Moon's internal structure and tie down the history of early impacts by returning samples from the Moon's South Pole-Aitken Basin. The largest known basin in the solar system and the oldest and deepest impact structure preserved on the Moon, this giant excavation penetrates the lunar crust and, unlike any other location in the solar system, allows access to materials from the upper mantle. Data from the South Pole-Aitken Basin may have a substantial effect on our understanding of the evolution of planetary interiors. Absolute dating of returned samples, which will include both soil and diverse rock chips, could also change our understanding of the timing and intensity of the bombardment suffered by both early Earth and the Moon.

Another benefit of the South Pole-Aitken Basin Sample Return mission is that it gives scientists and engineers the opportunity to try out sample-return techniques and strategies on a relatively easy target before moving on to more challenging and expensive sample-return missions in the rest of the solar system.

Guiding Themes Addressed	Important Planetary Science Questions Addressed
The First Billion Years of Solar System History	*What processes marked the initial stages of planet and satellite formation?* *How did the impactor flux decay during the solar system's youth, and in what way(s) did this decline influence the timing of life's emergence on Earth?*
Processes How Planetary Systems Work	*How do the processes that shape the contemporary character of planetary bodies operate and interact?* *What kinds of minerals are the inner planets made of, and does this vary depending on a planet's distance from the Sun?* *What is the internal structure of each planet and how did the core, crust, and mantle evolve?*

Formation of the Giant Planets

Three hundred years ago, Isaac Newton used the motions of the Galilean satellites (the four moons of Jupiter discovered by Galileo) to determine Jupiter's mass. A century later, William Herschel deduced that Jupiter's density was anomalously low. In the 20th century it became clear that Jupiter was composed primarily of the lightest elements, hydrogen and helium. Further studies of Jupiter, combined with analyses of the spectrum of light reflecting off the planet, gave rise to the so-called solar composition model of the giant planets. That is, as far as their overall elemental compositions are concerned, Jupiter and also Saturn appear to be pieces of the Sun cooled down to planetary temperatures.

Unfortunately, the solar composition model does not work for Uranus and Neptune, which are twice as dense as Saturn. Their densities indicate that they formed from material that was rich in water, ammonia, and methane ices and more deficient in the light gases than Jupiter, Saturn, or the Sun. Since oxygen and carbon are the third and fourth most abundant elements in the Sun after hydrogen and helium, the modified solar composition model was proposed to explain the creation of all of the planets. This model starts with a young Sun surrounded by a disk of leftover material, a mix of elements similar in overall composition to that of itself. During an early active phase, which many young stars undergo, the Sun ejected a wind of high-speed electrons, protons, and heavier particles that swept the hydrogen, helium, and other gases out of the disk. The mixture that remains has a composition similar to that of the Sun, except for the missing gaseous component. Close to the Sun, where it is hot, the ices too are lost, and only the rocks and metals remain. This interpretation fits our solar system, with small rocky planets in the inner solar system and the gaseous giant planets further out.

A composite image of the four Galilean satellites and Jupiter's Great Red Spot.

In this theory, timing is critical. The giant planets had to have formed before the gases were swept out of the solar system. Timing might explain the compositional difference between the ice giants, Uranus and Neptune, and the gas giants, Jupiter and Saturn. According to theory, giant planets could form faster at the orbits of Jupiter and Saturn where the density of material was higher and collisions more frequent. Perhaps Uranus and Neptune were just starting to accumulate gases when the Sun blew the lighter gases out of the solar system.

The time that it takes to produce a Jupiter-size object depends on the method of formation, and here there are two possibilities. The slow way is to first form a rock-ice core about 10 times the mass of Earth—the resulting dense, solid object is able to attract gas and grow in mass once it reaches this size. The fast way assumes that Jupiter formed much the way the Sun did—the gas in one region of the solar nebula became sufficiently dense that its collective gravity caused it to collapse in a spherically symmetric manner. If created this way, Jupiter would resemble an object known as a brown dwarf—a star with insufficient mass to sustain nuclear fusion reactions in its core. Distinguishing between these hypotheses required determining if the giant planets have rock-ice cores. While the evidence indicates that Saturn, Neptune, and Uranus do indeed have cores, the nature of Jupiter's deep interior remains unknown.

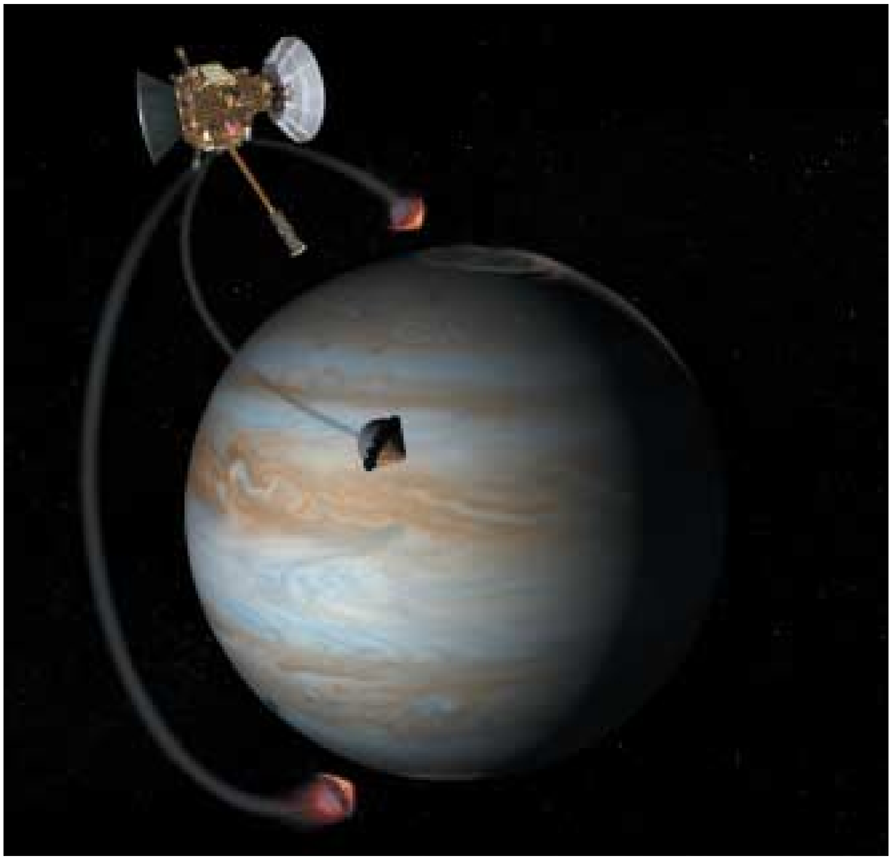
Another mystery about Jupiter concerns the distance from the Sun at which it formed. An analysis of Galileo spacecraft data shows that Jupiter has greater amounts of certain heavy elements than does the Sun. One explanation for this suggests that Jupiter formed far out in the solar system, where such elements were more prevalent, and then migrated inward toward its present orbit. Another possibility is that Jupiter formed approximately where it is today but was more likely to collect heavier elements than lighter ones. The key to resolving which if either of these ideas is correct is to determine the relative amounts of hydrogen and oxygen in Jupiter's atmosphere.

Studies of Jupiter also have the potential to significantly improve our understanding of planetary magnetospheres and their interactions with the solar wind. Jupiter's magnetosphere is sustained in a manner different from Earth's—it derives its energy from the rotation of the planet itself. In addition, Jupiter has the strongest magnetosphere in the solar system. By studying Jupiter's magnetosphere, especially using spacecraft to see regions unobservable from Earth, we could learn answers to questions about a diverse set of objects, ranging from Earth to distant pulsars.

Answering these questions requires measurements both inside and above Juipiter's atmosphere. The Jupiter Polar Orbiter with Probes is, in a sense, two missions in one. A carrier spacecraft equipped with three probes is launched toward Jupiter. As the spacecraft nears the planet the probes are released and penetrate Jupiter's thick atmosphere, taking measurements and reporting back data on Jupiter's interior. Following the completion of the probe mission, the carrier enters a low-altitude polar orbit about Jupiter from which vantage point it conducts additional studies for a year or more.

The Jupiter Polar Orbiter with Probes mission has five primary objectives. The first is to determine if Jupiter has a core. The second is to measure the water abundance below the visible clouds and, hence, determine the

Jupiter Polar Orbiter with Probes



Profile

Jupiter Polar Orbiter with Probes

Mission Type: Orbiter with atmospheric probes

Cost Class: Medium

Priority Measurements:

- Probe Jupiter's interior with gravity and magnetic field measurements from a polar orbit.
- Measure condensable gas abundances, temperature, wind velocity, and cloud opacity down to the 100-bar pressure level.
- Determine how internally produced plasma is ejected from a rotation-dominated magnetosphere.

Artist's concept of the Jupiter Polar Orbiter with Probes spacecraft illustrating how the three probes will enter different parts of the planet's atmosphere.

oxygen/hydrogen ratio. Both of these investigations address outstanding questions about the formation of Jupiter and, thereby, the solar system.

To address the third objective, the spacecraft's probes will measure the deep winds to a depth of 100 bars while another instrument may be able to give some information about the winds to thousands of bars. (Depth on Jupiter is measured by the atmospheric pressure, not by distance; 1 bar is the atmospheric pressure at sea level on Earth.) The deep winds may be key to the extreme stability of the weather systems observed at cloud top.

The fourth objective is addressed by virtue of the spacecraft's cloud-skimming orbit, which will permit more precise measurements of the planet's magnetic field than previously possible. Similarly, the polar nature of the orbit permits the mission's fifth objective—repeated visits to the hitherto unexplored polar magnetosphere—to be addressed. Taken together, these latter two investigations will allow researchers to map Jupiter's magnetosphere much more accurately, learn more about the magnetic field's origins inside Jupiter, study how these fields interact with Jupiter's moons, and teach us much about Jupiter's magnetic activity.

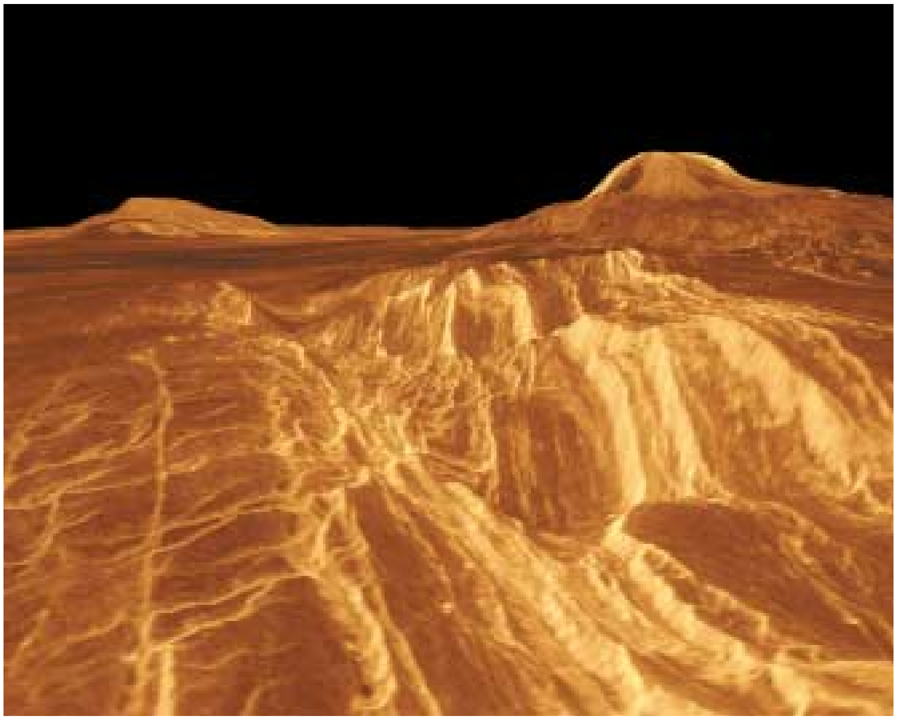
Guiding Themes Addressed	Important Planetary Science Questions Addressed
The First Billion Years of Solar System History	*How long did it take the gas giant Jupiter to form?* *How was the formation of Jupiter and its gas-giant sibling, Saturn, different from that of the ice giants, Uranus and Neptune?* *How have the orbits of the giant planets changed throughout history?*
Volatiles and Organics The Stuff of Life	*What is the history of volatile compounds, especially water, across the solar system?* *What is Jupiter's core made of, and what is the composition of its lower atmosphere?*
Processes How Planetary Systems Work	*How do the processes that shape the contemporary character of planetary bodies operate and interact?* *How does Jupiter's magnetosphere interact with the Galilean satellites?* *What does the solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?*

Comparative Planetology and Climate Change

At the most fundamental level, Earth is unique; it is the only planet in the solar system where the conditions support a thriving biosphere. Through the study of other objects in the inner solar system, it is now understood that habitability is the result of a series of events that occurred over its 4.6 billion-year history. The solar system provides us with two additional laboratories for studying terrestrial planets. The first, Mars, is a small, frozen world, whose surface is hostile to life because of the planet's thin atmosphere and harsh radiation environment. By contrast, Venus has a dense atmosphere that traps radiation so efficiently that its surface is as hot as a kiln.

Given these two extremes, and the awareness that humans are altering Earth's climate, what clues do Mars and Venus hold for the eventual fate of Earth's environment? Can we inadvertently cause Earth to evolve into a state similar to that of either Mars or Venus, or some other inhospitable regime? Part of the key to answering these questions lies in the lower atmosphere and surface of Venus. Determining how its atmosphere evolved to its present state and how the escape of atmospheric gases affects the chemical composition of its atmosphere and surface will provide insight into similar processes on Earth.

Climate change over long periods of time seems to be an inherent feature of the terrestrial planets. Earth's climatic record illustrates that there are wide swings in regionally and globally averaged surface temperatures. Mars may once have had liquid water on its surface, even at a time when the Sun was less bright than it is today. There is evidence that Venus's climate has varied significantly within the last billion years. These environments are produced and sustained by complex interactions among the surface, atmosphere, and interior. Despite the considerable efforts of previous space missions, these processes are poorly understood. Global monitoring of Venus's atmosphere and climate, in situ measurements of the composition of the planet's surface, and detailed data on the types of gases in the atmosphere are necessary to expand our understanding of the climates of the terrestrial planets.



A computer-generated view of a portion of Venus's western Eistla Regio.

Analysis of diverse surface materials of the inner planets, determination of their ages, and assessment of the processes that have affected them are needed to understand how important elements have evolved differently on each of the planets. Data on oxygen, hydrogen, and other atmospheric gases provide clues to planetary compositions and atmospheres, early solar-system processes, and environments relevant to the origin of life. Such data from Earth and Mars suggest that their initial atmospheres were lost and later replaced by gas emitted in volcanic eruptions and added by cometary impacts. By contrast, the (incomplete) measurements of the atmosphere of Venus are consistent with what would be expected of a primordial atmosphere. However, the state of the interactions between the surface and atmosphere is unknown. Measurements of these interactions will enable scientists to answer many questions about Venus's atmosphere and how it relates to Earth.

The Pioneer Venus and Magellan spacecraft mapped and measured the surface of Venus and, although these data reveal extensive geological activity (such as volcanism), the expressions of Earth-like plate tectonics are absent. Instead, the topography and relative youth of Venus's surface indicate that a major, possibly global resurfacing may have occurred—possibly numerous times. Although Venus appears to have an iron core, the absence of a magnetic field suggests that it does not have a magnetic dynamo like that operating in Earth's liquid core. The slow rotation of Venus (whose day is longer than its year) could explain the missing dynamo, but data are needed to test this hypothesis.

Motivated by the scientific questions discussed above, the Venus In Situ Explorer mission is designed to undertake a detailed exploration and study of the composition of Venus's atmosphere and surface materials. Such a mission has been contemplated in the past, but the technical challenges are daunting. Venus's extremely high surface temperatures and pressures (~450°C, and ~100 bars)

Venus In Situ Explorer

Profile

Venus In Situ Explorer

Mission Type: Lander

Cost Class: Medium

Priority Measurements:

- Determine elemental and mineralogical surface compositions.
- Measure the composition of the atmospheres, especially trace gases and their isotopes.
- Undertake high-precision measurements of noble gases and light stable isotopes.
- Assess processes and rates of atmosphere-surface interaction.
- Search for evidence of volcanic gases in inner-planet atmospheres.

Artist's impression of the Venus In Situ Explorer. One of its goals is to provide ground truth for the Magellan radar images used to create the three-dimensional view on page 18.

Guiding Themes Addressed	Important Planetary Science Questions Addressed
Volatiles and Organics The Stuff of Life	*What global mechanisms affect the evolution of volatiles on planetary bodies?* *What is the history of water on the inner planets?* *How did the atmospheres of the inner planets evolve?*
The Origin and Evolution of Habitable Worlds	*Why have the terrestrial planets differed so dramatically in their evolution?* *What kinds of minerals are the inner planets made of, and does this vary depending on a planet's distance from the Sun?*
Processes How Planetary Systems Work	*How do the processes that shape the contemporary character of planetary bodies operate and interact?* *What processes stabilize climate?* *How do planets' varied geological histories enable predictions of volacanic and tectonic activity?*

would render the most rugged spacecraft inoperable in a matter of hours. Venera 7, a Russian mission that landed on Venus in 1970—the first spacecraft to return data from the surface of another planet—survived for approximately 23 minutes (subsequent Russian Venus landers survived for up to 2 hours).

To survive long enough on Venus's hellish surface to make key scientific measurements requires a creative approach. The Venus In Situ Explorer concept envisages a spacecraft that descends through the atmosphere and lands just long enough to collect a sample of the surface material. The Explorer will study the surface for the short time it touches down, but once the sample is acquired, a balloon will inflate and carry the spacecraft up to a cooler region in the atmosphere, where the sample can be studied by onboard instruments for a much longer period of time. In addition, the Explorer will make measurements of winds and atmospheric chemical composition, and other measurements will be obtained during descent and ascent. This set of experiments should provide researchers with enough data to meaningfully compare Venus, Mars, and Earth.

A further benefit of this mission would be the development of technologies required for survival of a spacecraft in Venus's extreme environmental conditions. The development work done for this mission will pave the way for a mission to return a Venus sample to Earth in the following decade, and possibly further missions in the future.

Primitive Bodies and the Origin of Life

In its earliest youth the solar system was inhabited by a huge swarm of small rocky and icy bodies called planetesimals, orbiting the Sun in a giant disk. And, although the full details are still being debated (see the section, Formation of the Giant Planets), it is clear that collisions between planetesimals led to the formation of increasingly larger objects, with the end result being the planets we know today. Many of the diverse small bodies now seen in the solar system are directly related to the primordial population of planetesimals.

Beyond the orbit of Pluto, for example, many small icy objects remain in their archaic forms. For the most part these so-called Kuiper Belt objects and their relatives remain in their orbits far from the Sun. But every so often, one gets flung into a new path taking it into the inner solar system—we call these objects comets.

As comets travel through the solar system, their surfaces undergo a number of changes. The most obvious example is the development of the comet's characteristic tail as the Sun warms the surface ices and causes them to turn from a solid into a vapor. Other physical and chemical changes occur owing to the effects of radiation, micrometeorite impacts, and other processes. By studying these changes in a comet's surface material, scientists glean a significant amount of information about the history of the Sun and the solar system, much as reading the rings of a tree can teach us about the history of climate changes on Earth.

One change of particular interest to researchers results from the discovery that complex carbon compounds are created when a comet's surface ices (water, ammonia, carbon dioxide, methane, and so on) are irradiated by ultraviolet light, high-energy particles from the Sun, or cosmic rays. Laboratory simulations indicate that, when exposed to liquid water, such radiation-processed material produces amino acids and other organic molecules found in living systems. Radiation on the surfaces of planets and their satellites can also create and destroy complex organic molecules, but the details of the required conditions and the balance between destruction and creation are not known. Studying the differences between cometary and planetary organic molecules can help scientists understand this balance by showing which molecules are likely to have come from comets and which have been formed by other processes. This understanding will provide important insights into the origin and evolution of life on Earth.

The Comet Surface Sample Return mission emphasizes the return to Earth of a sample of cometary surface material that will provide the first direct set of data on cometary

Above: *Cometary material bombarding early Earth, as illustrated in this artist's concept, may have carried organic materials from which life arose.* **Right:** *A wide-angle view of the twin tails of Comet Hale-Bopp on the night of March 10, 1997.*

Comet Surface Sample Return

Profile

Comet Surface Sample Return

Mission Type: Sample Return

Cost Class: Medium

Priority Measurements:

- Characterize the target comet.
- Select, document, and return material collected at one or more sites, preferably in or near an active vent.

processes and answer whether the water in comets is very close to the surface. Such a sample will also show if the organic materials we believe to exist there actually do. If they do, then the sample will also give us our first look at ancient organic molecules similar to those first brought to our planet by cometary impacts 4 billion years ago. Knowing the nature of these molecules should provide exciting new insights into the origin of life on Earth.

The Comet Surface Sample Return (CSSR) mission would address other scientific interests as well. It would provide the first direct data on the difference between a comet's nucleus and the relatively well studied material in the cometary tail. In addition, data from this mission would enable scientists to resolve questions about the wealth of large-mass molecules and fragments seen by spacecraft in the cloud of gas and dust around Halley's comet during its last visit to the inner solar system in 1986.

Finally, the CSSR mission concept would give scientists their first look at how a comet is actually put together. Is it really a dirty snowball, as conceived in popular and scientific imagination? Is a comet a homogenous mixture of dust and ices, or are there pockets of differing materials scattered throughout its body? If the latter is true, what holds these different pieces together? Studying the structure of the material returned by CSSR should answer many of these questions.

Artist's impression of the lander portion of the Comet Surface Sample Return spacecraft just after it has deployed its twin solar arrays.

Guiding Themes Addressed	Important Planetary Science Questions Addressed
The First Billion Years of Solar System History	*What processes marked the initial stages of planet and satellite formation?* *Are comets near-pristine relics of the early solar system?*
Volatiles and Organics The Stuff of Life	*What is the history of volatile compounds, especially water, across the solar system?* *What is the nature of organic material in the solar system, and how has this matter evolved?* *What is the chemical composition of materials on a comet's surface?* *What changes the surface of asteroids and comets as they travel through the solar system?*
Processes How Planetary Systems Work	*How do the processes that shape the contemporary character of planetary bodies operate and interact?* *What is below the surface on the nuclues of a comet, and how does it relate to what is on the surface and in the tail?*

Near-Earth Objects

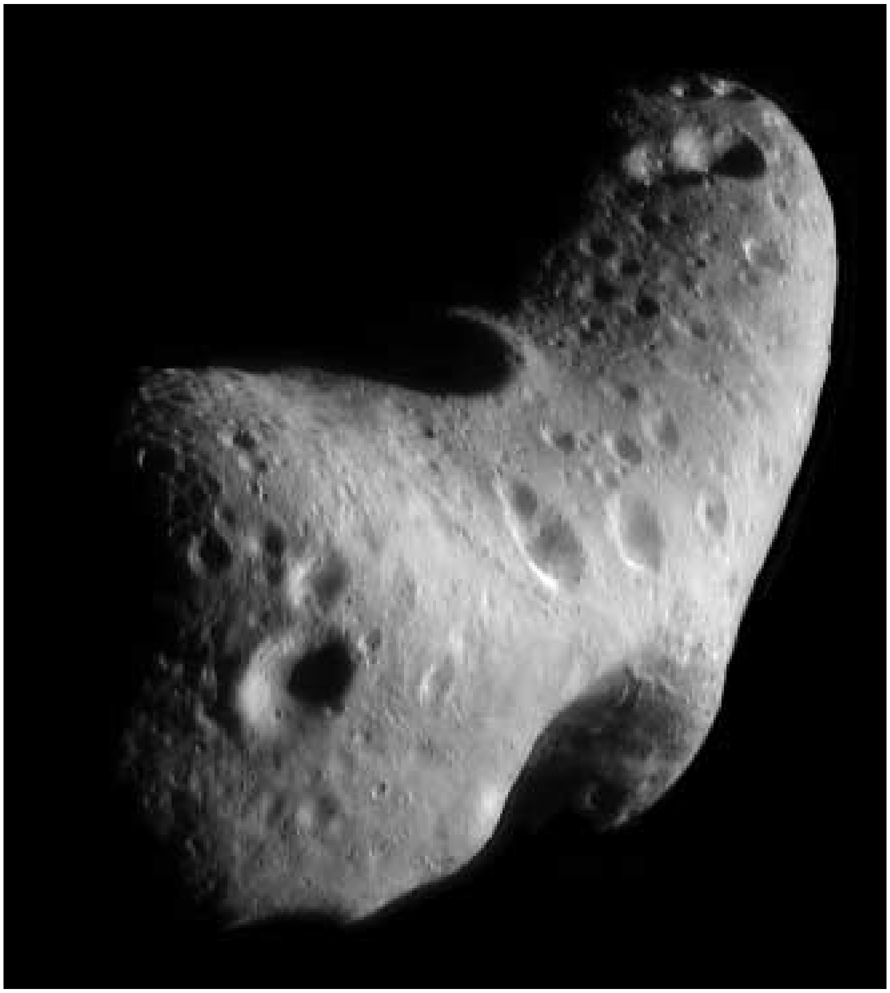
Imagine yourself lying in an open field on a warm summer evening, watching the sky as it darkens. Suddenly, a streak of light traces across the sky. As you continue to watch you see another, and then another. Over the course of the evening, you lose count of the number of streaks. The meteor shower you are watching offers evidence that the solar system is replete with small pieces of cosmic debris. Most of this material is too small to detect—too small, that is, until it collides with Earth's atmosphere and provides the celestial light show you are witnessing.

Meteor showers are only one type of evidence of these bits of wandering rock. While you are counting the meteor trails, the Moon rises into the sky. Studying it with binoculars, you pick out some of the craters that cover the lunar surface—craters caused by meteoroids hitting a surface without a protective atmosphere like Earth's.

It rarely happens, but sometimes these objects do descend through Earth's atmosphere, impact the surface, and form craters like those seen on the Moon. Though not as numerous as lunar craters, the scars of such impacts are still evident on Earth's surface (see page 14). Scientifically, the history of impacts on Earth is vital for understanding how the planet evolved and how life arose. For example, it has been suggested that most of the water on this planet was delivered by comet impacts (see the Kuiper Belt Objects section, pages 12-13). A better-known example of the role of impacts is the Cretaceous-Tertiary event 65 million years ago that led to global mass extinctions, including that of the dinosaurs. Impacts are not now as numerous as they were in the first billion years of the solar system's history, but the potential for a major impact is still there. A close examination of Earth's history shows that there is a 1 percent chance in the next century that Earth will be struck by an object large enough (greater than 300 meters in diameter) to cause significant damage.

Current telescopic surveys have identified an estimated 50 percent of near-Earth objects (NEOs; asteroids and comets whose orbits cross that of Earth) that have a diameter of 1 kilometer or greater, and approximately 10 to 15 percent of objects between 0.5 and 1 km. NASA's current goal is to finish cataloging the objects larger than 1 km by 2008, but the agency has no formal plans to extend the search to smaller objects.

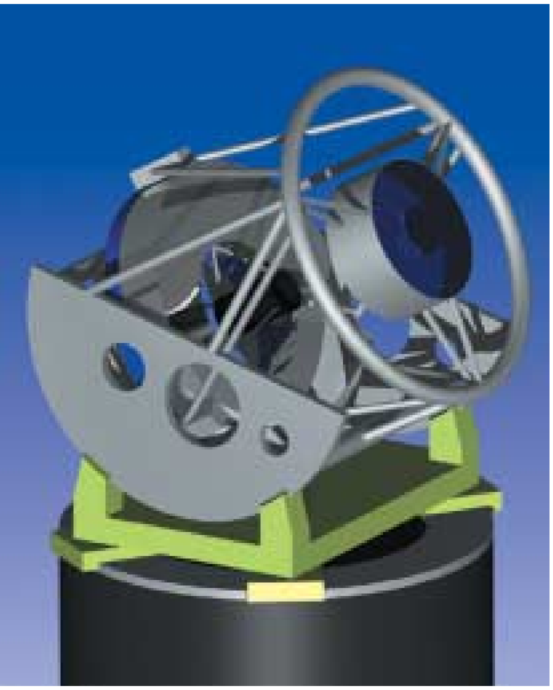
Searching for NEOs demands an exacting observational strategy. To locate NEOs as small as 300 meters requires a survey down to 24th magnitude (sensitive enough to detect objects 16 million times fainter than the feeblest stars that are visible to the



The 19-km-long asteroid 951 Gaspra **(above)** *and the 33-km-long 433 Eros* **(right)** *as seen, respectively, by Galileo from a distance of 5,300 km while en route to Jupiter and by the NEAR Shoemaker orbiter from a distance of about 200 km.*

Large Synoptic Survey Telescope

Guiding Themes Addressed	Important Planetary Science Questions Addressed
The Origin and Evolution of Habitable Worlds	*What hazards do solar system objects present to Earth's biosphere?* *What kinds of objects are in the solar system, and how many are there?*
Processes How Planetary Systems Work	*What does the solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?*



A simulation of a design for the Large Synoptic Survey Telescope. This ground-based telescope will survey the visible sky once each week.

Profile

Large Synoptic Survey Telescope

Mission Type: Ground-based Facility

Cost Class: Small

Priority Measurements:

- Survey the Kuiper Belt.
- Survey the population of near-Earth objects down to 300 km in diameter.

naked eye). Images have to be taken every 10 seconds to allow complete coverage of the sky in a reasonable amount of time, a necessary capability that is almost 100 times greater than that of existing survey telescopes. Furthermore, NEOs spend only a fraction of each orbit in Earth's neighborhood where they are most easily seen. Repeated observations over a decade would be required to explore the full volume of space populated by these objects. Such a survey would identify several hundred NEOs per night and obtain astrometric (positional) measurements on the much larger (and growing) number of NEOs already catalogued. Precise astrometry is needed to determine the orbits of the NEOs and to assign a hazard assessment to each object. Astrometry at monthly intervals would ensure against losing track of these fast-moving objects in the months and years after discovery.

In its most recent decadal survey (*Astronomy and Astrophysics in the New Millennium,* National Academy Press, Washington, D.C., 2001), the astronomy and astrophysics community singled out the proposed Large Synoptic Survey Telescope (LSST) as one of its highest-priority ground-based instruments. The SSE Survey echoed this finding and named the LSST as the solar system exploration community's top-ranked ground-based facility. Instruments like the Hubble Space Telescope and the Keck telescopes in Hawaii are designed to study selected, localized regions of the sky with very high sensitivity. Another type of telescope is needed to survey the entire sky relatively quickly, so that periodic maps can be constructed that display how objects change in position and/or appearance from week to week.

The LSST is a 6.5-m-effective-diameter, very wide field (~3 degrees) telescope that will produce a digital map of the visible sky every week. For this type of survey observation, the LSST will be a hundred times more capable than the Keck telescopes, the world's largest at present. Not only will LSST carry out an optical survey of the sky far deeper than any previous survey, but also—and just as importantly—it will add the dimension of time and thereby open up a new realm of discovery. By surveying the sky each month for over a decade, LSST would revolutionize our understanding of various topics in astronomy concerning objects whose brightnesses vary on time scales of days to years.

NEOs, which drift across a largely unchanging sky, are easily identified. The LSST could locate 90 percent of all near-Earth objects down to 300 m in size, enable computations of their orbits, and permit assessment of their threat to Earth. In addition, this facility could be used to discover and track objects in the Kuiper Belt, the largely unexplored, primordial component of our solar system. Beyond the solar system, it would discover and monitor a wide variety of variable objects, such as the optical afterglows of cosmic gamma-ray bursts. In addition, it would find approximately 100,000 supernovae per year and be useful for many other cosmological observations.

At this time, NASA has no systematic survey capability to discover the population distribution of solar system bodies. The LSST would enable the compilation of a systematic inventory of near-Earth objects that is crucial to an improved understanding of Earth's cosmic environment, especially to the prediction of future hazards posed to our species. Many of the targets are as yet undiscovered, and construction of the LSST provides a necessary first step toward a rational spacecraft exploration program for these bodies.

Technology Development

The exciting set of scientific goals outlined in this booklet will be made possible by a suite of new power, communications, robotics, and instrumentation technologies that are currently being developed.

Electrical power is the most crucial factor in a spacecraft's operations. Today, spacecraft produce electricity with one of two technologies: solar panels or radioisotope power systems (RPSs). Solar panels work well in the inner solar system, but as a spacecraft moves farther from the Sun their utility decreases substantially due to the reduction in the intensity of sunlight. A spacecraft requiring a 1-square-meter solar array to satisfy its power needs in Earth orbit would require 25-, 100-, and 1600-square-meter arrays to supply the same amount of power at Jupiter, Saturn, and Pluto, respectively. An RPS enables a spacecraft to, for example, operate for long periods of time in the region stretching from Jupiter and its moons to the far reaches of the Kuiper Belt. RPS technology was used on the Voyager missions, as well as on Viking, Galileo, and Cassini. Solar panels and RPSs will both continue to be useful power-generating technologies in the next decade.

In the future, a nuclear reactor spacecraft electrical system will enable scientists to craft a new generation of powerful instruments as well as to deploy advanced propulsion systems that will decrease the amount of travel time needed to get to other bodies in the solar system. Furthermore, these systems will enable spacecraft to sequentially orbit numerous solar system objects, thereby improving on the current flyby method of investigation. NASA is currently working on developing these systems, and the SSE Survey endorses these efforts.

Building on research and development done by other federal agencies, NASA is studying the use of optical communications systems, which use laser light rather than radio waves to transmit information. Optical communications will allow spacecraft to return more data than is currently possible, similar to the way broadband Internet connections enable faster communications than those possible with dial-up modem connections.

Our understanding of other places in the solar system will also be greatly enhanced by sample-return missions. In fact, three of the SSE Survey's recommended mission concepts involve the return of samples. As planetary exploration moves forward, returning samples of the basic "ingredients" that compose the solar system will become an integral element, providing a host of new challenges on the ground. For example, Earth-based, state-of-the-art analytical capabilities to study the returned samples must be developed. Instead of instruments for launch into space, extremely capable and sophisticated instruments for use in Earth-based laboratories must be developed to study and extract science information from the returned samples. A review of the analytical capabilities for sample analysis has identified the need for developing new instrumentation and for upgrading U.S. laboratories. In addition, scientists and technicians must be trained to handle samples and to use the new instruments to analyze them. Finally, facilities must be built that will protect Earth's environment from possible contamination by the returned samples, and vice versa.

Artist's conception of an advanced Jupiter mission powered by a nuclear-electric propulsion system.

Conclusion

Missions Recommended by the SSE Survey

In setting priorities for solar system exploration in the next decade, the SSE Survey considered missions to a diverse set of targets, from Mercury to beyond the orbit of Pluto. The missions described in the previous pages are a subset selected from this larger sample on the basis of the importance of the scientific issues they will address, their technical and fiscal feasibility, and, more intangibly, their ability to take best advantage of available opportunities.

Prioritized List of New Solar System Missions for the Decade 2003-2013

Priority in Cost Class	Mission Concept Name
Flight Missions	
Small (<$325 million)	
1	Continuation of the existing series of Discovery missions
2	Extended operation of the ongoing Cassini mission to Saturn
Medium (<$650 million)	
1	Kuiper Belt-Pluto Explorer
2	South Pole-Aitken Basin Sample Return
3	Jupiter Polar Orbiter with Probes
4	Venus In Situ Explorer
5	Comet Surface Sample Return
Large (>$650 million)	
1	Europa Geophysical Explorer
2	Preparation for Mars Sample Return
Ground-based Facility	
Small (<$325 million)	
1	Large Synoptic Survey Telescope

Other Mission Concepts with Future Potential

Other mission concepts thought by the SSE Survey to be extremely valuable either were too expensive or difficult to undertake with current technology, or depended on having certain scientific questions answered before the missions would be ready. These concepts are listed on page 27 in order to give some direction to the solar system exploration program as the current set of mission concepts recommended for 2003-2013 nears completion.

Candidate Missions for Flight After 2013

Medium Class

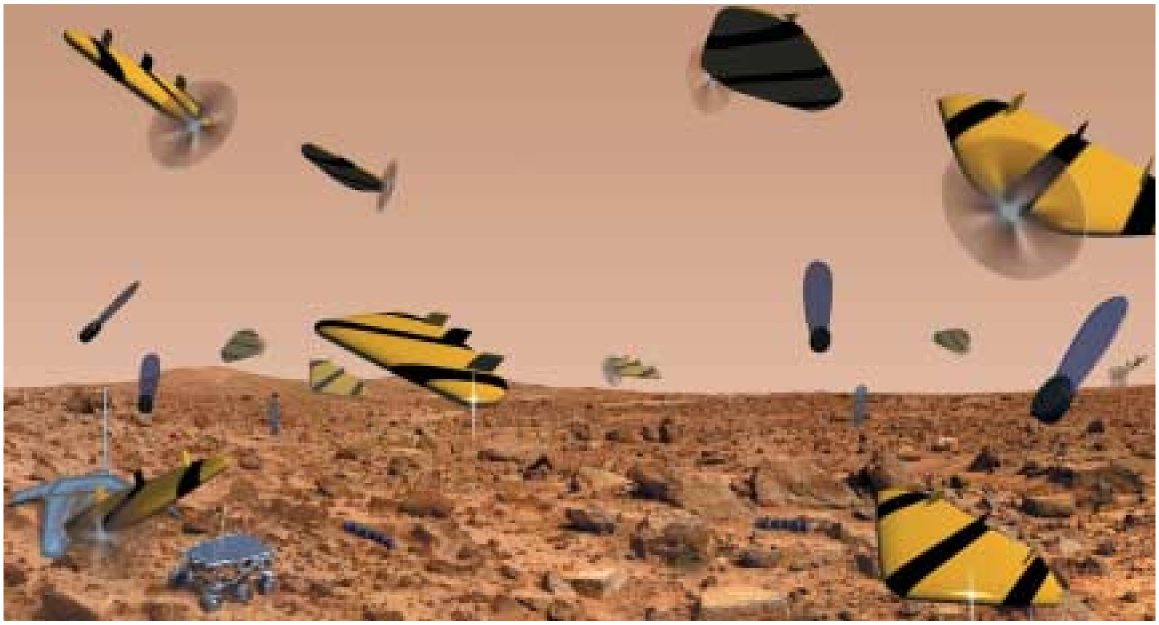
Geophysical Network Science
Asteroid Rover/Sample Return
Io Observer
Ganymede Observer
Trojan/Centaur Reconnaissance Flyby

Large Class

Mercury Sample Return
Venus Sample Return
Mars Sample Return
Europa Lander
Saturn Ring Observer
Titan Explorer
Uranus Orbiter with Probes
Neptune Orbiter with Probes
Neptune Orbiter/Triton Explorer
Comet Cryogenic Sample Return

Future Mars Missions

Prominent by its relative absence in the preceding lists of potential future missions is mention of missions to Mars, whose unique nature as the most promising planetary abode for life in the past, and the most likely target for a future human exploration mission, keep the Red Planet in a special category. NASA has recognized this special status by establishing the Mars Exploration Program Office, an organization parallel to NASA's Solar System Exploration Division that concentrates exclusively on martian research. The Mars Exploration Program already has under development the slate of missions pictured in the diagram on page 10.



Swarms of cooperating microrobots explore the martian surface—the future of solar system exploration?

Final Thoughts

When the SSE Survey began its task of charting the goals and priorities for NASA's solar system exploration activities in the period 2003-2013, it was far from clear where its deliberations would lead. As discussed in the preceding pages, current scientific understanding of the solar system, combined with the aspirations of the planetary-science community and moderated by technological and fiscal realities, points to missions to destinations as diverse as the icy wastes beyond Pluto and Venus's hellish surface. In addition to enhancing our knowledge of the solar system, the suite of missions outlined in this booklet promises the possibility of revolutionizing our understanding of our origins and surroundings. Missions to extraterrestrial environments as familiar as the Moon or as exotic as the surface of a comet and Jupiter's deep interior will not only increase our knowledge concerning our planetary neighbors but also help improve our understanding of our own planet and, perhaps, determine whether life—be it human or otherwise—is sustainable on other solar system bodies. The answers to profound questions are now within our grasp.

Now that the goals are set, the challenge is to stay on track and bring to reality the spacecraft missions the SSE Survey has outlined, and in doing so to write the next chapter in one of humanity's greatest endeavors.

Artist's concept of an ice-penetrating probe deploying an autonomous submersible to explore a hypothetical aquatic environment—possibly an ice-covered lake in Antarctica, or an ice-covered moon of Jupiter.

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