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Priority Questions for Solar System Exploration, 2003-2013: The Basis for an Integrated Exploration Strategy

The 15 themes and more than 100 scientific questions spanning six categories of targets listed in Part One give a clear view of the scope, complexity, and diversity of contemporary solar system studies. They provide evidence for the richness and breadth of the knowledge that has been gained from four decades of solar system exploration. These questions also tell of how much more there is to learn with regard to vital fundamental issues about the solar system. To address these questions, the SSE Survey's panels proposed a broad range of future flight-mission candidates (see Part One), which are summarized in Table 7.1. The purpose of this chapter is to integrate the many scientific questions posed by the individual panels into a small set of key questions of the highest scientific priority, from which it is possible to derive a practical program of exploration for the next decade and a glimpse of the future that it heralds.

SETTING PRIORITIES

Rational judgments as to scientific priorities must take into account contemporary motivations for solar system exploration, which tend to be reflections of the most profound questions and the most significant of recent discoveries. The most basic motivating questions for solar system exploration, which also reflect the interests of the public, must play a role in setting priorities for the future: Are we alone? Where did we come from? What is our destiny? The discussion in the previous chapter documents the intimate associations of these questions with a robust planetary exploration program.

Assessment of priorities for the next decade must take into account the discoveries and successes of the recent past and the potential for resolution of high-level questions. In its analysis of the inputs from its panels and from the solar system exploration community (see Appendix B) the SSE Survey arrived at a list of what it asserts to be the most significant discoveries of the past decade (see Box 6.1). Moreover, the many questions raised in Part One illustrate some of the more profound mysteries that still confront us (see Box 6.2). Lastly, the Survey notes that it is intrinsic to the nature of science that priorities must be continually adjusted to take account of new findings, and that such adjustments are sometimes unexpected and sudden.

TABLE 7.1 Mission Concepts Proposed by the SSE Survey's Panels

Panel	Mission Concept Name	Cost Class
Inner Planets	**Venus In Situ Explorer**	Medium
	South Pole-Aitken Basin Sample Return	Medium
	Geophysical Network Science	Medium
	Venus Sample Return	Large
	Mercury Sample Return	Large
	Discovery missions	Small
Primitive Bodies	**Kuiper Belt-Pluto Explorer**	Medium
	Comet Surface Sample Return	Medium
	Trojan/Centaur Reconnaissance Flyby	Medium
	Asteroid Rover/Sample Return	Medium
	Comet Cryogenic Sample Return	Large
	Discovery missions	Small
Giant Planets	**Cassini Extended**	Small
	Jupiter Polar Orbiter with Probes	Medium
	Neptune Orbiter with Probes	Large
	Saturn Ring Observer	Large
	Uranus Orbiter with Probes	Large
	Discovery missions	Small
Large Satellites	**Europa Geophysical Explorer**	Large
	Europa Lander	Large
	Titan Explorer	Large
	Neptune Orbiter/Triton Explorer	Large
	Io Observer	Medium
	Ganymede Orbiter	Medium
	Discovery missions	Small
Mars	**Mars Sample Return**	Large
	Mars Science Laboratory	Medium
	Mar Long-Lived Lander Network	Medium
	Mars Upper Atmosphere Orbiter	Small
	Mars Scout missions	Small

NOTE: Missions in boldface are a short list developed in this chapter in response to the 12 key scientific questions.

Judging scientific priority requires careful consideration and choice of the criteria that are used to make the judgment. The SSE Survey's criteria are these:

- Scientific merit,
- "Opportunity," and
- Technological readiness.

The scientific merit of a question is measured by asking the following questions (listed in order of importance):

1. Does the question's answer have the possibility of creating or changing a paradigm?
2. Might the new knowledge have a pivotal effect on the direction of future research?
3. Will the knowledge gained substantially strengthen the factual base of our understanding?

"Opportunity" has to do with the practical matter of achieving a resolution to the question under consideration. A positive measure of opportunity could be a favorable budgetary situation, or the favorable orbital configuration of a planet. Other possibilities exist—for example, successes in related research in another scientific field, or the concurrent development of a mission or a technology with related objectives.

Assessment of technological readiness is a powerful tool for making judgments, as is seen more clearly in the following chapter on mission priorities. It can also be of use in judging the relative priorities of fundamental scientific questions. For example, if answering such a question demands deep drilling into the subsurface of some distant solar system body and the subsequent return of a sample to laboratories on Earth, this will surely affect that question's priority with respect to a question that perhaps has equal scientific merit but requires little more than, say, the easier task of collecting remote-sensing data for its resolution.

TWELVE KEY SCIENTIFIC QUESTIONS THAT UNDERPIN THE OVERALL EXPLORATION STRATEGY

The SSE Survey defines four broad, crosscutting themes that integrate the various goals identified by the panels in Part One:

- The First Billion Years of Solar System History;
- Volatiles and Organics: The Stuff of Life;
- The Origin and Evolution of Habitable Worlds; and
- Processes: How Planetary Systems Work.

Next, the SSE Survey identifies 12 top-level questions that represent the distillation of more than 100 individual questions identified by the Survey panels; the 12 questions are categorized within the four crosscutting themes.

- *The First Billion Years of Solar System History.* The processes that occurred during this epoch propelled the evolution of Earth and the other planets. Planetary-scale dramas were played out during those formative years, including the emergence of life on Earth. Yet this epoch in the solar system's history is poorly known. Three top-level questions emerge:

1. What processes marked the initial stages of planet and satellite formation?
2. How long did it take the gas giant Jupiter to form, and how was the formation of the ice giants (Uranus and Neptune) different from that of Jupiter and its gas giant sibling, Saturn?
3. 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.* We are truly made of star-stuff. Life requires organic materials and volatiles, notably liquid water, originally condensed from or acquired by the protoplanetary nebula and later delivered in some degree to the planets by organic-rich cometary and asteroidal debris. The distribution and transport of volatiles and organics are intimately linked to the evolution of our planetary system and the state in which we find it today. These three top-level questions emerge:

4. What is the history of volatile compounds, especially water, across the solar system?
5. What is the nature and history of organic material in the solar system?
6. What global mechanisms affect the evolution of volatiles on planetary bodies?

- *The Origin and Evolution of Habitable Worlds.* Our concept of the "habitable zone" is being expanded by recent discoveries on Earth and elsewhere in the solar system. Whether or not life has taken hold in the solar system beyond Earth, the implications are equally profound. Understanding our planetary neighborhood will help to trace the evolutionary paths of the other planets, and the fate of our own. The four top-level questions that emerge are these:

7. Where are the habitable zones for life in the solar system, and what are the planetary processes responsible for producing and sustaining habitable worlds?
8. Does (or did) life exist beyond Earth?
9. Why did the terrestrial planets differ so dramatically in their evolution?
10. What hazards do solar system objects present to Earth's biosphere?

- *Processes: How Planetary Systems Work.* Understanding the operation of fundamental processes is the firm foundation of planetary science. Studies of planetary interiors, surfaces, atmospheres, rings, and magnetospheres are windows into the evolution of worlds. Studying processes in our planetary system allows extrapolation to extrasolar planets, and of those planetary systems to ours. Two top-level questions emerge:

11. How do the processes that shape the contemporary character of planetary bodies operate and interact?
12. What does the solar system tell us about the development and evolution of extrasolar planetary systems and vice versa?

All of these questions are of high scientific merit. Most have the potential to lead to major paradigm shifts in our general understanding. All have the potential of being pivotal and could lead to new pathways in solar system research. All will lead to an increase in the factual base of our knowledge. All, as indicated below, can be substantially addressed with reasonable levels of technical development, and most can be addressed within the envelope of opportunities that are implied in the proposed New Frontiers program and NASA's ongoing Mars and Discovery flight programs, along with less frequent Flagship-class missions. Many of these questions build directly on recent discoveries. They will also help elucidate the outstanding mysteries about the nature of the solar system and make significant progress toward answering the most basic motivating questions. The missions with the greatest potential for answering these high-priority questions are specified below and listed in Table 7.2.

RECOMMENDED MISSIONS TO ANSWER KEY QUESTIONS

The First Billion Years of Solar System History

What Processes Marked the Initial Stages of Planet and Satellite Formation?

The planetary system accreted from a spinning disk of gas and dust (the solar nebula) surrounding the proto-Sun about 4.6 billion years ago. Beyond Neptune, the solid material never accreted into the major planets but remains as a vast collection of objects known as the Kuiper Belt. These icy bodies hold clues not only to the origin of the outer planets but also to the origin of Earth's inventory of volatiles and possibly to the origin of prebiological organic material on Earth. Because of the cold temperatures at trans-neptunian distances and because smaller objects are less likely to have undergone internal differentiation, the smaller Kuiper Belt objects (KBOs) are thought to be relatively unmodified since their formation. It is therefore expected that studies of the chemical composition of KBOs will provide knowledge of the pathways of volatile and organic molecular materials from their interstellar origins to their disposition in Earth's hydrosphere, atmosphere, and biosphere. The Kuiper Belt-Pluto Explorer (KBP) mission constrains the bulk properties of several KBOs, including the best-studied of these icy objects, Pluto and Charon, by determining their densities. Radii are precisely measured by high-resolution imaging and solar occultations, and masses by measurement of the gravitational deflection of the spacecraft. Moreover, the mission observes the surfaces and atmospheric constituents of Pluto, Charon, and other KBOs at high spatial and spectral resolution in order to determine the composition and distribution of volatiles. These measurements cannot be performed with necessary precision from Earth-based telescopes but can be achieved with KBP. Thus, the KBP mission is central to addressing the nature and composition of the planetesimals that are

TABLE 7.2 Most Relevant Missions to Address Fundamental Scientific Questions

Fundamental Scientific Question	Most Relevant Missions[a]
The First Billion Years of Solar System History	
1. What processes marked the initial stages of planet and satellite formation?	Comet Surface Sample Return Kuiper Belt-Pluto Explorer South Pole-Aitken Basin Sample Return
2. How long did it take the gas giant Jupiter to form, and how was the formation of the ice giants (Uranus and Neptune) different from that of Jupiter and its gas-giant sibling, Saturn?	Jupiter Polar Orbiter with Probes Neptune Orbiter with Probes
3. 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?	Kuiper Belt-Pluto Explorer South Pole-Aitken Basin Sample Return
Volatiles and Organics: The Stuff of Life	
4. What is the history of volatile compounds, especially water, across the solar system?	Comet Surface Sample Return Jupiter Polar Orbiter with Probes Kuiper Belt-Pluto Explorer
5. What is the nature of the organic material in the solar system? Its history?	Cassini Extended Comet Surface Sample Return Titan Explorer
6. What global mechanisms affect the evolution of volatiles on planetary bodies?	Mars Exploration Program Mars Upper Atmosphere Orbiter Venus In Situ Explorer
The Origin and Evolution of Habitable Worlds	
7. Where are the habitable zones for life in the solar system, and what are the planetary processes responsible for producing and sustaining habitable worlds?	Europa Geophysical Explorer Mars Long-Lived Lander Network Mars Sample Return Mars Science Laboratory
8. Does (or did) life exist beyond Earth?	Europa Lander Mars Sample Return
9. Why did the terrestrial planets differ so dramatically in their evolution?	Mars Long-Lived Lander Network Mars Sample Return Mars Science Laboratory Venus In Situ Explorer
10. What hazards do solar system objects present to Earth's biosphere?	Large Synoptic Survey Telescope
Processes: How Planetary Systems Work	
11. How do the processes that shape the contemporary character of planetary bodies operate and interact?	Cassini Extended, Comet Surface Sample Return, Europa Geophysical Explorer, Jupiter Polar Orbiter with Probes, Kuiper Belt-Pluto Explorer, Mars Long-Lived Lander, Mars Sample Return, Mars Science Laboratory, Mars Upper Atmosphere Orbiter, South Pole-Aitken Basin Sample Return, Venus In Situ Explorer
12. What does the solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?	Cassini Extended Jupiter Polar Orbiter with Probes Kuiper Belt-Pluto Explorer Large Synoptic Survey Telescope Neptune Orbiter with Probes

[a]This column lists alphabetically only what the SSE Survey considers to be the *most* relevant mission candidates to address the scientific question. However, the Survey recognizes that some of the mission candidates could address specific aspects of a scientific question even if not listed. Missions within the Discovery program could fall in any of the cells in this column.

best preserved from the initial stages of planet and satellite formation. The value of this mission increases as it observes more KBOs and investigates the diversity of their properties. KBP will make the first survey of this most poorly known but very significant portion of the solar system.

The Kuiper Belt is the birthplace of short-period comets; therefore, sampling one of these comets is a means of examining the material from which the planets were built. The Comet Surface Sample Return (CSSR) mission will gently collect material from one or more sites on the surface or in the near-surface layer of a short-period comet and return it to Earth. This will permit a full suite of sophisticated elemental, isotopic, organic, and mineralogical measurements to be performed in terrestrial laboratories, studies that will yield unprecedented information on the materials and chemical processes that dominated the initial stages of planet and satellite formation. Although it is ultimately desirable to return a nucleus sample at a temperature sufficiently low to preserve the full suite of ices, the highest priority is given to a mission returning the full suite of organic materials and non-ice minerals from the surface of an accessible short-period comet.

The Moon records some of the most ancient history of terrestrial planet evolution. The Apollo and Luna missions investigated a limited region of the Moon's nearside and did not resolve fundamental questions of how the Moon's interior differentiated into layers after its formation. The recently recognized South Pole-Aitken Basin is the largest known impact structure in the solar system and the oldest and deepest well-preserved impact structure on the Moon. This giant basin allows access to materials from the interior of the Moon. The South Pole-Aitken Basin Sample-Return (SPA-SR) mission will obtain samples of materials produced during this enormous impact event and return them to Earth. Analyses of these samples in terrestrial laboratories will permit detailed characterization of the mineralogy, elemental composition, and isotopic makeup of the lower crust and upper mantle of the Moon. This will allow the several models for early lunar evolution to be tested and distinguished, providing insight into processes that are likely to have occurred on Earth and the other terrestrial planets during the initial stages of their formation.

Over What Period Did Jupiter Form, and How Did Its Birth Differ from That of the Ice Giants?

During the formation of the giant planets, timing is critical, with dramatically different consequences for the inner solar system depending on whether giant planet formation was slow or fast. A commonly cited model is that the gas giant Jupiter formed relatively slowly, in about 10 million to 100 million years, by condensation of gas around an accumulated rock-ice core of about 10 Earth masses. If this occurred, then Jupiter's composition should reflect that of an evolving solar nebula while the solar wind was blowing the nebula away, rather than a pristine nebula. Beyond Jupiter, where the density of the solar nebula was very low, the other giant planets formed even more slowly. Consistent with this, the bulk properties of Uranus and Neptune suggest that these ice giant planets formed too late to capture the gas of the solar nebula. Without Jupiter's enormous gravitational effect to disturb them, other solar system bodies would have formed in a relatively benign environment.

On the other hand, observations of gas disks around nearby stars show that the gas is depleted on time scales of just a few million years, suggesting that the formation of the giant planets may have been relatively rapid. If Jupiter formed relatively quickly, in about 100,000 years by the process of hydrodynamic collapse, then the planet should have a negligible core. In this case the planet's composition must represent a relatively pristine sample of the solar nebula. This model is attractive because it might partly explain the apparent abundance of gas giants around other stars, which are commonly in close-in orbits where rock-ice cores seem unlikely to have formed. A quickly formed Jupiter would have prevented objects in what is now the asteroid belt from ever forming into a single planet, and inside the asteroid belt, Earth and other terrestrial planets would have been subjected to a rain of impacting objects scattered by the forming giant planet.

Whether Jupiter formed rapidly or slowly can be deduced by whether the planet has a rock-ice core. Thus, the existence of a core is key to whether Jupiter's composition reflects the pristine or evolved solar nebula and whether the planet's formation dramatically affected the burgeoning inner solar system. The Jupiter Polar Orbiter with Probes (JPOP) mission concept reveals whether Jupiter has a rock-ice core and determines its mass, by carefully measuring the planet's gravity field. Moreover, remote-sensing instruments and three deeply penetrating probes search for water and other volatiles and measure their abundances to provide compositional clues into the nature of the solar system's largest planet and the timing of its formation.

The Neptune Orbiter with Probes (NOP) mission concept samples a distinctly different class of giant planet, an ice giant. Neptune's chemistry will be measured by remote-sensing instruments and in situ with entry probes. This enables direct comparison between an ice giant (Neptune) and a gas giant (Jupiter) in terms of their chemistries, apparent time scales of formation, and effects on the evolution of the inner solar system.

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?

The formation of the massive gas and ice giant planets probably had a profound influence on the early cratering rate throughout the solar system as they cleared their formation zones of unused debris. A sustained, solar system-wide rain of projectiles could have resulted, and this may have delayed life from gaining a foothold on planet Earth.

The lunar impact record, dated by collected rock samples, is used to extrapolate surface ages throughout the solar system. However, there is considerable uncertainty in the early flux of impacts, with two models proposed. In one, the flux decayed exponentially with time. In the other, the flux peaked at about 4 billion years in a period of enhanced bombardment that would have profoundly influenced all of the terrestrial planets. These two scenarios have vastly different implications for the conditions under which life might have emerged on early Earth.

The record of most early events on Earth is long gone, but important information is preserved in the face of our neighboring Moon. To understand the conditions on early Earth, it is important to establish the age of the Moon's oldest surface units. Dating of samples returned from the interior of the recently identified South Pole-Aitken Basin, a major impact structure on the Moon's farside, would establish a benchmark date for this earliest chronology. From this benchmark, the ancient impactor flux would be more firmly established, with important implications for early impact processes reassessed for Earth and the other terrestrial planets. The SPA-SR mission collects samples of the Moon's oldest well-preserved impact basin and returns them to Earth, where precise age-dating techniques can be applied. From the derived age of the South Pole-Aitken Basin impact event, a vital point of reference is established for the cratering rate during the earliest history of the Moon and infant Earth. This is a well-grounded and straightforward experiment that builds on a substantial base of knowledge about our satellite, consolidating its position as a cornerstone for understanding the history of Earth and the other terrestrial planets.

If a solar system-wide rain of projectiles did indeed arise from the formation of the giant planets—notably Uranus and Neptune—then the formation of the latter may also have dynamically excited the Kuiper Belt, leading to its present, collisionally sculpted structure and triggering an influx of KBOs into the inner solar system. An investigation of Pluto, Charon, and Kuiper Belt objects will yield a valuable record of the size distribution and flux of impactors within this yet-unexplored region. The atmospheric escape rate on Pluto and inferred kilometers' worth of volatile sublimation erosion of its surface over the age of the solar system suggest that Pluto's surface may be young and hence may record the present-day impactor rate and impactor size distribution in the Kuiper Belt. In contrast, the record on Charon and other KBOs is expected to be cumulative and to reflect the size distribution and flux of impactors in the ancient Kuiper Belt before clearing occurred. The comparison of Pluto to Charon and other KBOs thus has important implications for whether the late heavy bombardment was a solar system-wide phenomenon, indeed whether or not it occurred at all.

The KBP mission will image the sunlit hemispheres of Pluto and Charon at resolutions sufficient to determine the populations of large craters on their surfaces and to lead to an understanding of the modifying geological processes that have affected each surface. Analysis of these images will constrain the role that the clearing of the Kuiper Belt played in the bombardment of the inner solar system and in the transport of volatiles and organics from the deep outer solar system to early Earth.

Volatiles and Organics: The Stuff of Life

What Is the History of Volatile Material, Especially Water, Across the Solar System?

Earth formed too hot to contain the large proportions of volatile materials now present, giving rise to the idea that its volatiles, including water, were delivered to the terrestrial planets after their accretion. Even Jupiter may have received much of its complement of volatiles from farther out in the solar system. The observed comets are volatile-rich, and many move in orbits that cross those of the planets, resulting in collisions. Comets are leading candidates as deliverers of volatiles to the planets, including an uncertain fraction of the water now found in Earth's oceans. Asteroids from the outer regions of the main belt may also contain volatiles in sufficient abundance to contribute significantly to the terrestrial planets. For these reasons, strong scientific motivation exists for exploring the reservoirs and transport mechanisms of volatiles in the solar system.

The CSSR mission will approach the surface of a short-period comet and gently collect material from one or more sites on the surface or in the near-surface layer, returning organics and non-ice minerals together with water maintained in a frozen state. While this mission does not address the full range of scientific issues that could be accomplished by collection of volatile-rich material from depth and returned at deep cryogenic temperatures, laboratory analyses of the cometary volatile minerals will firmly establish the chemical standard for the elemental and isotopic abundances in short-period comets. Such comets are thought to come from the Kuiper Belt, which contains some of the most primitive, unprocessed material in the solar system. Although repeated trips through the inner solar system will have altered the surface regions of a comet considerably, many important chemical ratios will be preserved, providing important insights into the history and transport mechanisms of water and other volatiles in the solar system.

The Galileo probe returned data within Jupiter where the pressure reached some 22 bars, but it entered the gas giant planet in an unusually dry downdraft region and so did not sample the deep-water abundance that is believed to be characteristic of the planet as a whole. As a consequence, the water abundance in Jupiter remains uncertain by at least an order of magnitude. The JPOP mission sends three probes deep into Jupiter's clouds at different latitudes to measure the abundances of jovian water and other elements. In addition to determining composition with depth, the probes also measure winds, temperatures, clouds, and sunlight to a depth where the pressure reaches 100 bars. Understanding the abundance of jovian water is very important to understanding the volatile history of Earth and other planets, because ice is the medium by which other, less-abundant volatiles would have been incorporated into Jupiter by planetesimals, and, similarly, could have been transported to the inner solar system, including Earth.

What Is the Nature of the Organic Material in the Solar System, and What Is Its History?

Stardust, a Discovery mission to return minute samples of cometary dust, is under way and will provide information about the chemical composition of dust grains captured during flight through the coma of an active comet at high velocity. More comprehensive investigations demand access to a larger sample of cometary matter, preferably one collected directly and gently from the nucleus in order to preserve the composition and structure of the sample. The CSSR mission will collect a full suite of cometary organic materials and non-ice minerals, and return them to Earth, where detailed elemental, isotopic, organic, and mineralogical measurements can be performed. The mission provides a vital stepping-stone by sampling the organic and nonvolatile mineralogy of a comet. It would provide fundamental new data about the chemical and structural properties of prebiotic organic matter, addressing vital questions such as these:

- What is the handedness of cometary molecules, and what bearing does this have on the handedness of life on Earth?
- What is the ratio of carbon chain molecules to carbon rings in the comets, and how does this compare with the corresponding quantities in the interstellar dust?

- Were the materials in comets incorporated at low temperatures with little modification, as suggested by the abundance of the volatiles carbon monoxide and carbon dioxide? Or was the constituent material first cycled through a wide range of solar distances and temperatures by turbulent motions in a heavily mixed solar nebula, as suggested by the presence of high-temperature silicates in comets?

The atmosphere and surface of Titan are inferred to be rich in organic materials, providing a natural arena for the study of organic chemistry over temporal and spatial scales unattainable in terrestrial laboratories. Understanding the pathways of organic synthesis on Titan may hold answers to the evolution of prebiotic chemistry on ancient Earth. Cassini will enter orbit around Saturn in July 2004 and will release the Huygens probe into Titan's atmosphere in 2005. Huygens will sample Titan's atmosphere in situ, identifying and quantifying its constituents. Huygens descent data and mapping by several orbiter instruments will provide a first close look at Titan's haze-shrouded surface and identify possible regions of liquid hydrocarbon lakes or seas. Results from Cassini and Huygens will elucidate the satellite's surface state, atmospheric composition, and complex chemical processes. However, after the nominal Cassini mission ends, coverage of Titan's surface will be incomplete. Cassini Extended (CasX) provides an opportunity to follow up on major discoveries of the nominal Cassini-Huygens mission with focused orbiter remote-sensing observations and scientific analyses.

Because the pathways and products of long-term organic evolution on Titan may have implications for the origin of life on Earth, it is important to thoroughly investigate the natural organic chemistry in the atmosphere and on the surface of Titan. A future Titan Explorer (TEX) mission might consist of an orbiter and an "aerobot" that is able to move within the atmosphere to obtain samples and conduct experiments at multiple locations. The craft would include aerosol collectors, mass spectrometers, and other atmospheric-structure and -composition instrumentation. In addition, the system would make high-resolution remote observations of the surface from various altitudes and would descend to the surface multiple times to make close-range and possibly in situ measurements of surface composition and properties. Through analyses of the products of organic synthesis on Titan, we will better understand the prebiotic processes that led to the origin of life on Earth.

What Global Mechanisms Affect the Evolution of Volatiles on Planetary Bodies?

Once delivered to the planets, volatiles may be sequestered in surface and interior reservoirs, partitioned into the atmosphere, or lost to space. For example, on Earth, CO_2 dissolves in ocean water, precipitates as carbonate rock, and reemerges in subduction zone volcanic eruptions. On Venus, the lack of liquid water and plate tectonics precludes this mechanism, and CO_2 remains in a gaseous state and contributes to the atmospheric greenhouse. Both the CO_2 and the nitrogen abundance are similar on Earth and Venus, so a real mystery is what happened to the water that should once have been present on Venus?

The atmosphere and surface of Venus preserves records of that planet's evolutionary history, including the interaction of the atmosphere and surface rocks. Therefore, compositional and isotopic measurements of the atmosphere and of the surface rocks would reveal the planet's internal and atmospheric evolution. The proposed Venus In Situ Explorer (VISE) mission would measure the composition and isotope ratios of the atmosphere on descent and of surface rocks on landing. Moreover, the mission would retrieve a core sample and then undertake sophisticated geochemical and mineralogical measurements from a more benign environment at high altitude. These VISE results would constrain the original complement of water and other volatiles on Venus, mechanisms of volatile origin and loss, and the internal evolution of the planet. The mission is central to understanding terrestrial planet volatile evolution, which can proceed toward either supporting life or preventing its inception.

At the other extreme, Mars volatiles are largely trapped in the polar caps and in vast buried reservoirs of frozen permafrost probably overlying liquid groundwater. Mars missions currently under way, including Mars Odyssey, are revealing the past and present reservoirs of water on Mars, as well as the processes that control the distribution. Mars Exploration Program (MEP) missions offer important potential to continue the theme "Follow the water." Specifically, the Mars Long-Lived Lander Network (ML^3N) includes mass spectrometers that permit precise long-lived chemical and isotopic analysis to track the dynamics of Mars's ground-level atmosphere. Time variability of isotopic compositions will indicate sources, sinks, and reservoirs of volatiles, and the planet's atmospheric evolution.

The Mars Upper Atmosphere Orbiter (MAO) mission will study the upper atmosphere of the planet to determine its dynamics, hot-atom abundances and escape fluxes, ion escape, minimagnetospheres and magnetic reconnections, and the energetics of the ionosphere. These results will for the first time reveal the coupling between the lower and upper atmosphere of Mars and thus are key to understanding the evolution of atmospheric volatiles.

The Mars Science Laboratory (MSL)—an approved mission, currently scheduled for launch in 2009—will conduct detailed in situ investigations of a site that orbital data identify as a water-modified environment, providing critical ground-truth for orbital remote-sensing data and testing hypotheses for the formation and composition of water-modified environments. The types of in situ measurements possible on the MSL are directly relevant to martian volatile evolution, including atmospheric sampling, surface mineralogy, and chemical composition. The Mars Scout program also provides opportunities for missions that investigate the evolution of the planet's volatiles.

Thus the stage will be set for Mars Sample Return (MSR), in which samples from carefully chosen sites will be returned to Earth and subjected to a full array of analytical techniques, merging new understanding of the geological evolution of Mars with detailed knowledge of the chemistry, mineralogy, and chronology of the crust, the role of volatiles, and elucidation of the conditions that could potentially have led to the emergence of life on Mars.

The Origin and Evolution of Habitable Worlds

Where Are the Habitable Zones for Life in the Solar System, and What Are the Planetary Processes Responsible for Producing and Sustaining Habitable Worlds?

The boundary conditions for habitable zones in the solar system are principally constrained by the occurrence of liquid water and a source of energy for biological activity. On Earth, life exists wherever water occurs. Microbes thrive in both extremely hot and subfreezing temperatures, under acidic or alkaline conditions, and in the presence of high concentrations of salts or heavy metals. Life forms capable of surviving similar conditions may have existed, and might persist today, in the subsurface of Mars and within large icy satellites, notably Europa. Study and comparison of planets and satellites that have a water history allow an understanding of how habitable worlds evolve.

Mars is at the outer edge of the traditionally defined habitability zone, and today its near-surface water resides largely as ice. MEP missions will improve our understanding of the Red Planet's potential current and past habitability by investigating the distribution and history of its volatiles (see above), and through remote-sensing and in situ investigations of the geological and geochemical processes that have operated there. Debate will continue as to whether Mars supports or ever supported life—at least until samples are returned from carefully chosen sites on the planet.

The MSR missions will collect samples from carefully selected locations and return them to Earth, where they can be subjected to detailed mineralogical, chemical, and isotopic analyses. When correlated with remote-sensing and in situ data and inferred geological processes, the results of sample analyses will clarify whether the planet's environmental conditions have ever been conducive to life. Thus, MSR missions are ultimately critical to understanding the limits of habitability in the solar system.

The putative sub-ice ocean of Europa might provide a different type of habitable world, one that does not rely upon solar energy. Tidal heating provides a source of energy to maintain liquid water beneath Europa's icy carapace. Morphological features there suggest surface motions broadly analogous to the jostling of floating ice plates in Earth's polar oceans. Geological processes would allow for communication between the ocean and surface, and therefore the transport of nutrients and perhaps organisms between the surface and the subsurface ocean. Inferences about oceans within Europa and the other icy Galilean satellites have received dramatic support from induced magnetic-field measurements from Galileo, and the existence of subsurface liquid water is now widely accepted. However, many uncertainties remain regarding the level of current activity, the nature of the satellite's geological processes, the thickness of the ice shell, the chemistry of the surface and ocean, and potential energy sources for life.

The Europa Geophysical Explorer (EGE) mission will address the potential habitability of Europa. This mission orbits Europa and employs geophysical methods—specifically, gravity and altimetry measurements of Europa's tidal fluctuations—to confirm the presence of an interior ocean and characterize the satellite's ice shell. Additional remote-sensing observations will examine the three-dimensional distribution of subsurface liquid water; elucidate the formation of surface features, including sites of current or recent activity; and identify and map surface composition, including compounds of astrobiological interest. EGE is the vital next step in understanding the potential habitability of Europa and the processes that might produce and sustain habitable environments within icy satellites.

Does (or Did) Life Exist Beyond Earth?

Whether life exists in the solar system beyond Earth is among the most profound questions we can ask. Even more profound is the fact that we can make substantial progress toward answering it during the next decade and the decade beyond.

Today, Mars appears hostile to life because of its thin atmosphere and harsh radiation environment; yet life may have existed in the planet's distant past or may still exist in subsurface reservoirs. The SNC meteorites are of martian origin but, because of their origin by random impact ejection, have unknown provenance and are unlikely to be typical of the surface rocks on Mars. Already it has been suggested that the SNC meteorites contain evidence for extraterrestrial life. The ambiguous and controversial nature of the evidence, however, suggests that a definitive answer to the question of whether or not Mars fossils exist must await the return of carefully retrieved samples, as proposed for the MSR missions. The MSR missions will carefully collect and return martian samples for comprehensive examination on Earth, employing sophisticated analyses that could not be done in situ at Mars. Only close analysis using the full range of analytical facilities available in a terrestrial laboratory can provide the detail and experimental confidence to address the substantial issue of past and current life on Mars.

The popular and scientific interest in Europa lies with the possibility that its subsurface ocean might constitute a habitable zone for past or present life. Following the EGE mission, if an ocean is indeed confirmed, a subsequent Europa Lander (ELAN) mission should be aimed at in situ investigation of the surface and its chemistry. Such a mission can search for and characterize near-surface organic materials and perform detailed geophysical investigations pertinent to the potential for Europa to harbor life. The potential for life in protected environments beneath the surfaces of otherwise inhospitable worlds is a fascinating possibility, undreamed of just a few decades ago.

Why Did the Terrestrial Planets Differ So Dramatically in Their Evolution?

The terrestrial planetary bodies share many similarities, but solar system exploration has revealed that they are also fundamentally different in many other ways. The Moon, Mercury, and Mars stabilized their crusts and lithospheres early in planetary evolution and became "one-plate" planets. In contrast, Earth evolved into a dynamic, multiplated planet that is constantly renewing itself through atmospheric erosion and recycling of the crust into the interior. Venus shows no sign of active plate tectonics and may have been catastrophically resurfaced within the last billion years. Terrestrial planet atmospheres also show major differences, with Venus and Mars being CO_2-dominated, but with orders-of-magnitude different surface pressures. On Earth, liquid water provides a substantial thermal buffer to sudden changes in the climate; nevertheless, ample evidence indicates that the climate has varied considerably with time.

Climate can be altered by changes in global volcanism, solar output, celestial mechanics, and the effects of pollutants made by humans. The interactions between these influences are so complicated that they are not fully understood. Adjacent planets Venus and Mars provide compelling examples of planets whose atmospheres have evolved along very different paths from that of Earth. The thin CO_2 atmosphere of Mars represents an extreme in which temperatures are low and a significant fraction of the "atmosphere" lies buried as ice within the regolith and upper crust. It is critical to understand whether climate change has truly occurred at Mars, and, if so, what its causes and effects are.

The MEP missions will explicitly address Mars's climate change and atmospheric evolution. To understand the planet's current sources, sinks, and reservoirs of volatiles, the ML^3N mission will determine the ground-level chemical and isotopic composition of the atmosphere, including humidity, at a network of surface stations for at least 1 martian year. To better understand the longer-term evolution of the atmosphere, the MAO determines the composition and dynamics of the middle and upper atmosphere and measures the escape rate of atmospheric molecules. The MSL is scheduled to conduct detailed in situ investigations of a site that orbital data identify as a water-modified environment, testing hypotheses for the formation and composition of water-modified regions, and providing critical ground-truth for orbital remote-sensing data sets that are used to infer past water. Mars Scout missions provide the potential for focused studies of Mars climate change and atmospheric evolution not otherwise addressed in the MEP. MSR missions will establish the role of liquid water and weathering processes by enabling detailed laboratory study of the chemical and isotopic signatures of mineral samples and weathered materials. Corresponding measurements on volatiles within returned samples may provide definitive evidence of past atmospheric and chemical conditions, allowing past climate conditions to be understood.

Understanding the causes and effects of climate change also requires in situ investigations of Venus, where surface temperatures hotter than an oven are produced by a CO_2 greenhouse. Global monitoring of Venus's atmosphere and climate, in situ elemental, mineralogical, and geochemical measurements of the surface, and detailed data on the noble gas isotopes and trace gas abundances of the atmosphere are necessary to understand Venus's climate, and potentially the fate of Earth's climate. These are goals of the VISE mission, which will also prepare the groundwork for a future Venus sample-return mission.

What Hazards Do Solar System Objects Present to Earth's Biosphere?

Cosmic impact has the potential to eliminate humankind as we know it. Therefore, it is critical for us to systematically assess the magnitude of these threats. The atmospheric, geological, and biological effects of cosmic impact have become apparent only since the early 1980s, when the likely cause of the Cretaceous-Tertiary extinction was first linked to the impact of a 10-km asteroid. Even much smaller impactors still possess enormous energies and may cause local to regional devastation. At Congress's direction, NASA has supported a ground-based program to identify the NEOs larger than 1 km in diameter. This task is about 50 percent complete, with estimates for the date of completion ranging from 2010 to 2020 and beyond. The kilometer-sized impactors would be globally devastating, but much smaller projectiles would wreak unimaginable local havoc and are much more frequent. The high-altitude explosion of an 80-m-diameter body above Tunguska, Siberia, in 1908 flattened trees over a broad area. A differently aimed impact of this scale could flatten a modern city, with deaths in the millions. Bodies larger than about 300 m in size cause ground-level explosions in the gigaton range. Such impacts would devastate whole countries. There is about a 1 percent chance that such an impact will occur in the next century.[1]

Assessment of the NEO population down to 300-m scales, as part of an organized inventory of the small bodies of the solar system, is recognized as a high priority for NASA's Solar System Exploration program. Extrapolations from existing surveys suggest that the number of NEOs larger than 300 m is on the order of 10,000 to 20,000. These bodies are too faint to have been detected by the current surveys, and almost all remain undetected. For each object, we need to determine the orbital elements with accuracy sufficient to predict the probability of terrestrial impact within the next 100 years. This time scale gives sufficiently early warning for the development of mitigation strategies, as needed, and is compatible with the intrinsic time scale for dynamical chaos among the NEOs. For those objects with a non-negligible impact probability, we also need physical observations to determine the size, which, when combined with a "typical" density yields an estimate of the kinetic energy of the projectile. These goals can be achieved with the Large Synoptic Survey Telescope (LSST). Determining the physical properties of comets and asteroids is also an important goal; it can be addressed by aspects of the Discovery program.

Processes: How Planetary Systems Work

How Do the Processes That Shape the Contemporary Character of Planetary Bodies Operate and Interact?

An understanding of planetary formation, evolution, and potential habitability is possible only with a detailed knowledge of the individual processes that shape planetary interiors, surfaces, atmospheres, rings, and magnetospheres. Physical processes define the mechanisms by which planetary interiors, surfaces, atmospheres, and magnetospheres evolve and interact. Relevant interior processes include chemical differentiation and core formation and the mechanisms of heat transfer throughout planetary history. Impact cratering, tectonism, and volcanism represent geological processes that have shaped planetary surfaces throughout history. Planetary atmospheres hold the record of the volatile evolution of the planet and interactions with surface materials, weather, and climate. The nature of the processes that are responsible for the remarkable diversity of planetary ring systems must be better understood. The nature and evolution of the magnetosphere are critical to a wide range of phenomena, from planetary interior processes (e.g., core dynamos) to loss of surface and atmospheric species with time. Together, an improved and integrated understanding of planetary processes is necessary to determine fully how planets work.

Virtually all of the missions suggested in Part One contribute to a better understanding of planetary processes, ranging from our deepening knowledge of the Saturn system (CasX), to the interior structures and gaseous and magnetospheric environments of the giant planets (JPOP and NOP), the surfaces and interiors of icy satellites (EGE, ELAN, and TEX), the surface and atmosphere of Venus (VISE), impact basin formation and the interior of the Moon (SPA-SR), the history and environment of Mars (MEP), and the host of more specific aspects addressed by Discovery missions. Collectively these results will substantially enhance our understanding of planetary processes.

What Does the Solar System Tell Us About the Development and Evolution of Extrasolar Planetary Systems and Vice Versa?

Extrasolar planets are increasingly becoming a focus of both scientific and popular attention. Many more extrasolar planets will be detected in the next decade. Some will be imaged, and their spectra will be partially resolved. To provide critical ground-truth for these exciting discoveries, NASA should pursue a parallel program of close-up exploration and analysis of our own giant planets, their ring systems, and the Kuiper Belt. The solar system provides ground-truth to the study of giant planets around other stars.

The answer to the question of whether or not Jupiter has a rock-ice core is critical to understanding how the planet formed and, by extension, how extrasolar planets form. Two formation mechanisms are believed to be possible. The first, or slow process, invokes the initial aggregation of a rock-ice core of approximately 10 Earth masses. This embryo then attracts gas, but the rate at which it does so is limited by how fast the growing object can radiate energy. The second, or fast process, invokes hydrodynamic instabilities that cause a subcondensation of the solar nebula to collapse as a result of its own self gravity. Stars form this way when the density of matter in giant molecular clouds reaches a critical value. Brown stars—failed stars, that is, substellar objects insufficiently massive to sustain nuclear reactions in their cores—also form in this manner.

The rate and means of formation of Jupiter can be understood by determining whether it has a rock-ice core. Measuring the mass of Jupiter's core is a major objective of the JPOP mission. The NOP mission samples the chemistry of ice giant Neptune, enabling direct comparison to Jupiter in terms of chemistry and inferred time scale of formation. Observations of extrasolar planets—mass, radius, temperature, and composition—will be difficult to interpret unless we draw on our knowledge of giant planets in our own solar system. We need to understand how differences in bulk density translate into differences in composition and origin. The ice giants and gas giants of our solar system will help provide that knowledge.

We also need to know how atmospheric circulation and other meteorological phenomena affect the temperatures and compositions of extrasolar giant planets. These objects have clouds in their atmospheres. Clouds lead to precipitation and release of latent heat. The giant planets found close to their parent stars have large day-night temperature gradients. The temperature gradients lead to winds, which affect both temperature and composition. Clouds, precipitation, temperature gradients, and winds are meteorological phenomena. We know about these things from studying the atmospheres in our own solar system.

Determining the atmospheric composition, properties, and dynamics of Jupiter is a major objective of the JPOP mission. Three probes are deployed deep into the gas giant planet at three different latitudes, measuring composition, winds, temperatures, clouds, and sunlight, as functions of pressure to a depth of 100 bars. The NOP mission samples the chemistry and atmospheric dynamics of ice giant Neptune, enabling direct comparisons to Jupiter.

The study of protoplanetary disks can be influenced by studies of planetary rings in our own solar system. The concept of migration of bodies due to angular momentum exchange with surrounding material was first advanced in the ring context and is now a mainstay of planetary formation models. Moreover, detailed understanding of ring processes would yield significant scientific benefit to a broad range of astrophysical investigations, including studies of accretion disks, spiral disk galaxies, and the disks surrounding interacting binary stars, and investigations of active galactic nuclei. Here the Cassini mission to Saturn and the proposed NOP mission are fundamental to an understanding of ring processes and to a better understanding of the accretion of planets in the solar system and other planetary systems.

We have only just discovered the vast, unexplored region of the solar system known as the Kuiper Belt. At the same time, we have now begun to image the dust and planetesimal debris disks around other stars in our search for planets around other stars. We have discovered close analogues to our own Kuiper Belt around some of these stars—for example, around the star Epsilon Eridani. These observations show arcs and local voids that may be due to the gravitational effects of embedded large planets. If we were to look at the solar system from afar, as we look out at other planetary disks today, we would see a similar void carved by the gravitational scattering of Neptune. In order to understand and interpret imaging and spectroscopy of planetary bodies around other stars, we need to understand the structure and composition of our own Kuiper Belt. In the coming decade, studies of extrasolar planetary systems will continue from new large telescopes on the ground and in Earth orbit. At the same time, the LSST will be able to determine the distribution of objects in the Kuiper Belt in great detail, which will enable comparison with the structure of extrasolar planetary disks. Moreover, the KBP mission will explore Kuiper Belt objects, including Pluto and Charon, firsthand in order to understand their nature, composition, and evolution. These missions will provide local truth for understanding data from other stellar equivalents.

REFERENCE

1. C.R. Chapman and D. Morrison, "Impacts on the Earth by Asteroids and Comets: Assessing the Hazard," *Nature* 367: 33-40, 1994.