Part One

Current Knowledge of the Solar System and Its Implications for Future Solar System Exploration

The five chapters that make up Part One of this report are the work of the Solar System Exploration Survey's (SSE Survey's) panels. These chapters provide a broad survey of the state of knowledge in each of the panels' particular scientific areas, identify key scientific questions, and make recommendations to the Survey's Steering Group on a wide variety of mission concepts to address these questions. This large body of work, together with the ad hoc community input received in various forms, is the basis for the integrated strategy for solar system exploration described in Part Two. Readers interested primarily in the final overall strategy may safely focus on Part Two and, as appropriate, use the material in Part One as a basic reference.

Although the SSE Survey encouraged use of a common format for each of the panel reports, the specific topics discussed by each panel led to some variations in presentation. Nevertheless, each panel chapter discusses the current understanding of, important questions for, and likely future avenues of progress in a small number of unifying scientific themes, and each panel identifies the most relevant ground- and space-based activities needed to advance understanding in its subject area. Each panel chapter prioritizes needed initiatives and makes final recommendations to the Steering Group.

The SSE Survey's Steering Group also requested that each panel identify the relative priorities among the important scientific questions by sorting them into one of three categories, in order of descending priority. This approach was implemented by asking whether the new knowledge gained from answering a particular question posed the possibility of—

1. Creating or changing a paradigm,
2. Having a pivotal effect on the direction of future research, or
3. Substantially strengthening the factual basis of current understanding.

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Primitive Bodies: Building Blocks of the Solar System

The solar system's primitive bodies are those objects that have undergone a low degree of chemical and physical alteration since their condensation and aggregation from the solid and gaseous materials in the solar nebula some 4.6 billion years ago. These bodies are primarily small (less than a few hundred kilometers in size) and are found mostly in the vast region beyond the orbit of Mars. The primitive bodies (and materials) include asteroids, comets, small planetary satellites, the objects in the Kuiper Belt and the Oort cloud, Triton, Pluto, and Charon, and interplanetary dust (Figure 1.1).

While in the strictest sense "primitive" means *entirely* unchanged, the definition is flexible in planetary science and is used in a relative sense both in the research community and particularly in this report. All of these objects and materials have experienced some heating in the form of energy from the Sun and the decay of incorporated radioactive elements. Moreover, heat from collisions and tidal dissipation has caused some degree of change on the surface and in the interiors of many primitive bodies. Other factors affecting the surfaces and near subsurfaces of bodies without atmospheres include ultraviolet solar radiation, the solar wind, cosmic rays, and trapped particles in planetary environments.

Billions of years of bombardment by high-velocity meteoroids of every size (micrometers to kilometers) have affected every known surface in the solar system, causing physical and chemical changes at the exposed surface and creating soils and pulverized subsurface regions (regolith) by severe mechanical fracture.[1] Heat generated inside larger bodies has caused them to segregate the heavier materials (metals) from the lighter materials (rock and ice) in a process of differentiation. The easily evaporated materials (volatiles) have been partly lost from some small bodies by either internal or external heating and escape into space.

From the planetary science perspective, therefore, "primitive" means "substantially unaltered," primarily from a chemical point of view, even though some internal melting and differentiation may have occurred. Asteroids and comets are primitive, but the terrestrial and giant planets are not. The distinction is gray when highly differentiated asteroids, large planetary satellites, and Pluto are considered (although Pluto's bulk composition is

FIGURE 1.1 *(facing page)* A montage of spacecraft images of a small subset of the solar system's primitive bodies. *Clockwise from lower right:* 253 Mathilde, the nucleus of Comet 19P/Borrelly, the martian moons Deimos and Phobos, 433 Eros, 243 Ida, and 951 Gaspra. Courtesy of Peter Thomas, Cornell University.

almost certainly primitive). Objects excluded from this view of primitive bodies are all the major planets, the Moon, and the large satellites of Jupiter, Saturn, and Uranus.

UNIFYING THEMES FOR STUDIES OF PRIMITIVE BODIES

The planets originated from the accretion of solid and gaseous material in the solar nebula.[2] The first bodies to form in the nebula were millimeter- to kilometer-sized planetesimals.[a] Many were subsumed into the planets and their large satellites, but others remained behind and are known today as primitive bodies. Most of the objects considered primitive have not been substantially heated or otherwise changed in a chemical or physical sense since they formed, but others (e.g., certain asteroids and comets, Triton, Pluto, and Charon) have been heated to varying degrees.[3-5] Several populations of these primitive bodies remain in different regions of the solar system, notably the asteroid belt, the Kuiper Belt, and the Oort cloud.[6] Some members of these groupings have left their native regions through gravitational mixing; indeed, objects that originally formed in the outer planetary region and that were then expelled toward their current region by the gravitational action of the giant planets probably populated the entire Oort cloud.

Life on Earth is thought to be a product of the confluence of the necessary materials and an event of origin. The necessary materials include liquid water, carbon-bearing molecules, and energy, all of which were present on early Earth. Life arose early in our planet's history. One widely held view is that life arose at least 3.5 billion years ago, and perhaps as much as 3.8 billion years, but the origin event or events remain unknown and the exact timing is uncertain.[7] Organic molecular material carrying complex assemblages of carbon, hydrogen, oxygen, and nitrogen was delivered to the sterile early Earth by comets and asteroids, and some may also have been formed by impact events in the early ocean and atmosphere.[8]

Complex organic material exists in interstellar dust in our galaxy and others and thus predates the Sun and planets.[9,10] However, as researchers survey the primitive bodies and planets of the solar system, they find compelling evidence not only of the preservation of ancient organic matter but also of the formation and destruction of organic molecules in modern environments. Water, too, is common both in interstellar space and throughout the solar system, though its presence in the liquid phase depends on special circumstances of temperature and pressure. In several cases, however, even where water is not now a liquid, there is evidence that the liquid phase once existed. Thus, a search for organic matter in the solar system is an exploration of the range of environments in which life may have originated and a search for an understanding of our own origins as well.

Two clear themes therefore emerge as basic to study of the primitive bodies of the solar system:

- Primitive bodies as building blocks of the solar system, and
- The origins of organic matter that led to life on at least one planet.

The next two major sections expand upon these themes.

PRIMITIVE BODIES AS BUILDING BLOCKS OF THE SOLAR SYSTEM

Fundamental Issues

The fundamental questions concerning primitive bodies as building blocks of the solar system can be summarized as follows:

- Where in the solar system are the primitive bodies found, and what range of sizes, compositions, and other physical characteristics do they represent?
- What processes led to the formation of these objects?

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[a] Definitions of technical terms and acronyms not explained in the text can be found in the glossary in Appendix E.

- Since their formation, what processes have altered the primitive bodies?
- How did primitive bodies make planets?
- How have they affected the planets since the epoch of formation?

Primitive bodies are highly varied in size, surface properties, composition, and probably origin. Apart from interplanetary dust, these bodies range in size from a few tens of meters to 2,500 km (Pluto and Triton). Some are snowy white, while others are charcoal black. Some have igneous and other minerals on their surfaces, while others have ices, and still others have combinations of ice and rock. Simple and complex organic chemicals are plentiful. The asteroids have highly varied compositions, with combinations of rock, metal, and organic compounds, while comets contain the same materials in a matrix of ices of various compositions.[11] Some asteroids have been thoroughly melted, while others have not. Some comets have been externally heated, with consequent changes in internal structure, but others appear to have been entirely unchanged since they formed.

Interplanetary dust near Earth appears to come from both comets and asteroids, and it contains minerals and organic solid matter.[12]

Triton, Pluto, Charon, and probably several large Kuiper Belt objects have icy surfaces and have probably been heated sufficiently for their interiors to differentiate.[13] Pluto and Triton have significant atmospheres. Triton is geologically active; Pluto and other bodies in this region of the solar system may also be active, and volatile transport clearly takes places on bodies such as Triton and Pluto. Their surfaces record their bombardment histories, hence the collisional history of the Kuiper Belt population.[14]

Important Questions

Questions that emerge from consideration of primitive bodies as building blocks of the solar system include the following:

- Are there Pluto-size and larger bodies beyond Neptune?
- How do the compositions of Pluto-Charon and Triton relate to those of Kuiper Belt objects?
- What are the basic physical properties (mass, density, size) of Kuiper Belt objects, Centaurs, and comets?
- What are the interior properties of all these bodies, and how do they differ from the surface compositions and properties? Are they differentiated?
- What are the surface properties and compositions of these bodies, and how do endogenous and exogenous processes affect them?
- Do Pluto and/or large Kuiper Belt objects show internal activity, as Triton does?
- What are the compositions of comet nuclei, and how do they relate to Kuiper Belt objects?
- What is the origin of the organic matter in carbonaceous meteorite parent bodies, and what are the parent bodies of the many different types?
- What organic materials occur in primitive bodies at various heliocentric distances?
- What is the origin of hydrated minerals in the meteorite parent bodies, and what do fluid inclusions in meteorites tell us about conditions in the solar nebula and parent bodies?
- What is the origin of micrometeorites?
- What are the albedo and color statistics of Centaurs, Kuiper Belt objects, and comets?

These questions are addressed and spelled out in more detailed questions in the remainder of this chapter.

Future Directions

A mission to Pluto-Charon and the Kuiper Belt can give critical, entirely new information on the physical properties of Pluto-Charon and members of the trans-Neptunian population. Despite their limitations relative to flight missions, additional Earth-based remote-sensing observations will give crucial new information on the compositions and other physical properties of primitive bodies in various populations. Such work requires the availability of the largest telescopes and most modern instrumentation. Radar observations of objects near Earth are critical to studying certain classes of asteroids and comets. The improvement of laboratory techniques for the analysis of planetary materials (meteorites and returned samples) offers the promise of new information and new perspectives on materials returned from primitive bodies. Spacecraft encounters with comets and asteroids will continue to expand our perspectives on the overall nature and variety of these objects, but there is an urgent need for samples collected from known sites on well-characterized objects to be returned to Earth for analysis. Curation and analysis of these materials are essential.

The Variety and Distribution of Primitive Bodies in the Solar System

More than 40,000 numbered asteroids are known, mostly orbiting the Sun between Mars and Jupiter but with a significant population in elliptical orbits that cross the paths of the inner planets, Mercury through Mars. Most of the asteroids accreted in the zone between Mars and Jupiter and occupy stable orbits, but some objects that are called asteroids (perhaps 5 percent) are former comets that originated elsewhere and are no longer active.[15] An unknown fraction of the asteroids are binaries, consisting of two separated objects orbiting a common center of gravity. Most of the meteorites that fall to Earth are fragments from collisions among the asteroids. The variety of meteorite types shows that there are many different kinds of asteroids.[16]

All four giant planets (Jupiter through Neptune) have families of distant, small satellites that have the appearance and other characteristics of asteroids; these are presumed to have originated elsewhere in the solar system and to have been captured subsequently by the gravity fields of the planets. The inner, small satellites of the giant planets are also considered primitive bodies, although they may have originated in the vicinity of their parent planet as part of the planet-forming process.

Two vast populations of primitive bodies exist beyond Neptune, both predicted from the orbital characteristics of comets; one of these is now the subject of vigorous exploration. Comets with periods greater than 200 years and with random orbital inclinations, of which 1,200 have been observed in the last two millennia, originate in the Oort cloud, a collection of more than a trillion icy bodies that orbit the Sun and extend almost halfway to the next nearest star.

Shorter-period comets, of which more than 200 are known, fall into two groups, the Halley-class comets that are probably captured from the Oort cloud comets, and the Jupiter-family comets that usually have orbits near the same planes as those of the planets and that originate in the Kuiper Belt, a donut-shaped distribution extending from the orbit of Neptune to at least 55 astronomical units (AU).[17] More than 500 individual objects in the Kuiper Belt have already been detected, and about 100,000 with sizes greater than 100 km are predicted to exist.[18] An unknown fraction of the bodies in the Kuiper Belt are binaries, mirroring the Pluto-Charon binary system.

Dust permeates the solar system. Some of it results from the activity of comets, some comes from the collisional disintegration of asteroids, and some is interstellar dust passing through the planetary region as the Sun and planets move among the stars. Some of the smallest dust grains condensed directly from gas in the solar nebula. Other interplanetary dust may have origins yet undiscovered and unexplored.[19]

Important Questions

Questions that emerge from the study of the variety and distribution of primitive bodies in the solar system include the following:

- Are there undiscovered populations, such as asteroids interior to Earth's orbit?
- What is the radial distribution of dust in the solar system?
- What is the frequency of binary systems among asteroids and trans-Neptunian objects?
- What is the orbital distribution of long-period and new comets?
- What are the orbital and size distributions of Centaurs and Kuiper Belt objects?

Future Directions

Surveys are in progress and planned for the detection of additional bodies in the known populations and for the exploration of their distributions and physical characteristics, but severe limitations are imposed by available facilities. Special search strategies must be developed for exploring each known population and for discovering other populations; proposed new ground-based facilities are well suited to the variety of searches required. The exploration of the dust distribution can be directly addressed by spacecraft carrying the appropriate instrumentation on many different trajectories through the solar system, as well as by missions designed specifically for dust studies.

Processes Leading to the Formation of Primitive Bodies

Planetesimals formed and grew in the solar nebula as interstellar dust, ice, and gas condensed into solid objects of tangible size. The planets formed by the accumulation of planetesimals at various distances from the Sun, but some planetesimals were captured after the planets formed, and became satellites.[20] Between Mars and Jupiter, heated and degassed planetesimals accumulated to become asteroids, some of which subsequently melted, either wholly or partially. At greater distances from the Sun, ices of several kinds from the primitive solar nebula were preserved as major constituents of most solid bodies. While some primitive bodies appear to have formed at their present heliocentric distances, other were gravitationally scattered by the planets. Some primitive asteroids, comets, and planetary satellites are fragments of larger objects produced by collisions among the bodies that originally accreted in the solar nebula.[21]

Important Questions

Questions that emerge with respect to processes leading to the formation of primitive bodies include the following:

- What was the chronology of formation of small bodies, and how and when did Pluto-Charon and some Kuiper Belt objects become binaries?
- Where in the solar nebula did the classes of primitive bodies form? Which were subsequently transported, and which remain in place?
- How did the Kuiper disk and the Oort cloud form, and what degree of compositional mixing is preserved? What forces caused the orbits of the Kuiper Belt objects to display such a wide range of inclinations and eccentricities?
- What was the balance between accretion and collisional destruction at various heliocentric distances during the formation of the solar system?
- Are there Trojan populations for Saturn, Uranus, and Neptune?
- When and how were the irregular satellites of the giant planets captured?

Future Directions

Dynamical studies with improved computational tools will continue to shed new light on problems of the formation and interactions of the primitive bodies of the solar system through time. Remote-sensing observations—particularly spectroscopy, radiometry, and photometry—of the physical properties of primitive bodies will help clarify their surface compositions, leading to improved taxonomy and a better understanding of their conditions of origin. Analysis of the surface structures seen in spacecraft images of key objects will improve our understanding of their fragmentation and cratering histories; such information bears directly on the dynamical history of primitive bodies in various regions of the solar system.

Physical Processes Affecting the Evolution of Primitive Bodies Since Their Formation

Primitive body surfaces, meteorites, and interplanetary dust particles carry information about some of the processes of space weathering and surface modification endured by these materials since the origin of the solar system.[22] These processes include solar heating and bombardment by cosmic rays and micrometeoroids, but other processes may have occurred. Some meteorites contain unaltered interstellar material that condensed before the formation of the Sun and planets, while other meteorites come from parent bodies that have been melted and differentiated, and still others show evidence of interaction with liquid water (some even contain inclusions of water).[23] Meteorites from primitive parent bodies are replete with complex organic molecular material and with water bound in the minerals. Collisions have played a commanding role in the evolution of primitive bodies, as evidenced by fragmented surface layers, irregular shapes, and fragmented soils preserved in some meteorites. Collisions also produce dust that is mixed in unknown proportions with the dust from evaporating comets; the combination of these materials forms the zodiacal cloud and the source of interplanetary dust particles (IDPs) collected in Earth's stratosphere for laboratory study.[24]

Important Questions

Questions that emerge from this discussion of the physical processes affecting the evolution of primitive bodies include the following:

- What processes in the solar nebula acted to alter presolar material?
- Are comets differentiated, and do they contain presolar material?
- What caused the differentiation of some asteroids?
- What are all of the space weathering processes that operate on the surfaces of bodies without atmospheres, and how have these processes varied over time?
- What is the time-history of collisional events and their consequences at various distances from the Sun?
- What are the thermal histories of all classes of comets; do they become extinct or dormant?
- Do Kuiper Belt objects exhibit evidence of transient atmospheres or epochs of internal activity?
- What roles did tidal activity, atmospheric escape, and internal activity play in generating the strongly dichotomous appearance of Pluto-Charon?
- Are Jupiter-family comets fragments of much larger Kuiper Belt objects, or are they still near their original size?

Future Directions

Missions to small bodies throughout the solar system, particularly missions that return samples, will illuminate the details of the evolution of primitive objects. Detailed analysis of IDPs and meteorites, using established techniques and those yet to be developed, will continue to elucidate some processes that occur in space, insofar as the record is preserved. Dust collected in space in the vicinity of known comets and from other locations in the solar system will significantly aid this study, while samples returned from the surfaces and subsurface layers of comets and asteroids will be critical for major advances. Proper curation and the development of new analytical techniques are critical to the understanding of returned samples. Theoretical studies of thermal histories of primitive bodies offer additional insights on several classes of these objects. Experiments with hypervelocity collisions will help clarify some physical processes, subject to the limitations of velocities that can be achieved in the laboratory.

Planets Formed by the Accumulation of Primitive Bodies

In terms of their sizes and compositions, the planets fall into four broad categories: the terrestrial planets (Mercury, Venus, Earth, Mars), the gas giants (Jupiter and Saturn), the ice giants (Uranus and Neptune), and the ice dwarfs (Pluto, plus the Kuiper Belt objects). All of the planets were formed by the accretion of smaller planetesimals that in turn condensed from the solar nebula at various distances from the forming Sun, but some of the planets may now occupy positions (heliocentric distances) different from the sites of formation.[25] The atmospheres of the terrestrial planets originated in whole or in part from the impact of volatile-rich primitive bodies.[26,27]

Important Questions

Questions that emerge with respect to the formation of planets by the accumulation of primitive bodies include the following:

- How did primitive bodies contribute to the volatile inventories of the terrestrial planets?
- Did organic matter delivered to early Earth (and other planets) by primitive bodies trigger the formation of life or provide the materials?
- When did Pluto and the Kuiper Belt objects form?
- How does accretion work, where do the materials come from, and what is the time scale?
- How much radial mixing of primitive material took place?
- What was the role of giant impacts in the formation of the planets and Earth's Moon?
- Why is there no planet between Jupiter and Mars?
- How large are the accreted bodies in the outermost solar system?
- What was the role of gas drag in the early solar system?

Future Directions

Dynamical studies with improved computational tools will continue to shed new light on problems of the formation and interactions of the primitive bodies of the solar system through time. Determinations of the densities and compositions of primitive bodies through spacecraft remote sensing techniques, and later by study of returned samples, will provide critical information on the materials from which the planets formed. Laboratory analysis to determine the isotopic signatures of samples returned from primitive bodies are essential to understanding the development of volatile inventories of the terrestrial planets.

Effects of Primitive Bodies on the Terrestrial Planets Since Their Formation

The cratering records on the Moon, the terrestrial planets, asteroids, and outer planet satellites reveal a history of bombardment throughout the solar system, from the time of formation to the present.[28] Meteorites, the tangible fragments of bombarding bodies, give information on the collisional fragmentation of primitive bodies and on the times of disruption and impact on Earth, all for relatively recent events. Interplanetary dust collected in the stratosphere and in space gives us a window on the generic composition of comets and some asteroids, but the exact source(s) of this material remain elusive.

Important Questions

Questions that emerge with respect to the effects of primitive bodies on the terrestrial planets since the planets' formation include the following:

- Do impacts lead to discrete and long-lasting changes in the surface-atmosphere regime?
- What volatiles and organics were delivered to the terrestrial planets?
- What fraction of impactors are comets vs. asteroids?

Future Directions

Computational studies of the interactions of impactors and their targets can further elucidate the nature of these processes in the early and modern solar system. Surveys of comets and asteroids will help clarify the flux of these objects in the planetary region. The physical properties of near-Earth objects must be measured to distinguish between comets and asteroids; this can be done with missions to these bodies and can be accomplished partly by radar and other remote-sensing techniques. Cometary dust must be distinguished from asteroidal or other (e.g., interstellar) dust. Expanded studies of the volatiles and organics in primitive meteorites and their parent bodies will bear on the questions of the materials delivered to the terrestrial planets.

PRIMITIVE BODIES AS RESERVOIRS OF ORGANIC MATTER: RAW MATERIALS FOR THE ORIGIN OF LIFE

The fundamental questions concerning the role of primitive bodies as reservoirs of organic matter (OM) in the solar system and in extrasolar planetary systems can be summarized as follows:

- What is the composition, origin, and primordial distribution of solid organic matter in the solar system?
- What is its present-day distribution?
- What processes can be identified that create, destroy, and modify solid organic matter in the solar nebula, in the epoch of the faint early Sun, and in the current solar system?
- How did organic matter influence the origin of life on Earth and other planets?
- Is organic matter similarly distributed among primitive bodies in other planetary systems?

Origin and Primordial Distribution of Solid Organic Matter in the Solar System

Carbon-rich molecular material condenses in the outflows from evolved stars and is injected into the interstellar medium. Modified by ultraviolet radiation and other processes, this material becomes enriched in complex organic molecules that coat silicate dust grains, but it also exists as submicron-size particles consisting entirely of interlocked ring structures.[29] High-resolution spectra with the Infrared Space Observatory (ISO) spacecraft recently showed that polycyclic aromatic molecules exist as a gas in the interstellar medium, together with condensed species on interstellar grains. The Sun and planets formed in a fragment of a giant molecular cloud enriched in this organic dust and gas. While some organic matter was destroyed in the solar nebula, new molecular material was created as chemical processes in the nebula occurred.[30] Later, additional organic molecular material may have formed on the parent bodies of the meteorites.[31]

Important Questions

Questions that emerge with respect to the origin and primordial distribution of solid organic matter in the solar system include the following:

- What is the composition and structure of primitive organic matter in the solar system?
- Where and under what conditions did organic matter originate?
- What are the relative fractions of organic matter in meteorites and comets that are interstellar and solar nebula in origin?
- Was primitive organic matter racemic?

Future Directions

Answers to the key questions listed above will come from the study of samples returned from well-characterized comets and asteroids and from continued astronomical observations of these objects as well as interstellar matter. The application of newly developed analytical techniques to existing and future collections of meteorites, micrometeorites, and stratospheric interplanetary dust particles will move this subject area forward. The analysis of dust collected in space is critical to these issues.

Present-Day Distribution of Organic Matter

Individual grains rich in organic matter are found in carbonaceous meteorites and interplanetary dust particles and are presumed to be a fundamental component of comets. The deuterium abundance in meteoritic and IDP organic matter is the same as is measured in the interstellar medium, providing a link to presolar matter in space.[32] There is spectroscopic evidence for the presence of complex organic material on several planetary satellites, Centaurs, and Kuiper Belt objects, and possibly certain asteroid classes. On icy satellites and in the rings of Saturn, the organic material may exist in very small quantities incorporated in water ice. On Pluto and Triton, photo processing of the methane ice may produce colored materials consisting of more complex organic chemicals.[33]

Important Questions

Questions that emerge regarding the present-day distribution of organic matter include the following:

- Which asteroids (or comets or Kuiper Belt objects) are the sources of the carbonaceous meteorites of various types, including the micrometeorites?
- What is the composition of organic matter in non-icy bodies?
- What are the compositions of organic matter that color some icy bodies, including Pluto and the Kuiper Belt objects?
- What are the sources of IDPs?

Future Directions

Answers to the key questions listed above will come from the in situ study of well-characterized regions on comet and asteroid surfaces, as well as the study of samples returned from comets and asteroids. Remote-sensing observations (spectroscopy) from missions to small bodies will contribute significantly to the understanding of their compositions. Continued studies of meteorites and interplanetary dust particles are critically needed. Astronomical observations of comets, asteroids, and planetary satellites from Earth and from space will expand our understanding of the relationships between meteorites and asteroids and will contribute to understanding the extent of organic material on primitive bodies, but they are unlikely to determine the organic material’s composition.

Processes That Create, Destroy, and Modify Solid Organic Matter in the Solar Nebula

When simple gases or ices (water, ammonia, methane, hydrogen, and so on) are irradiated with ultraviolet light or a stream of atomic particles (electrons or protons), chemical changes occur that produce complex polymers and other solid residues that are strongly colored. When exposed to liquid water, such material produces amino acids and other complex molecules that occur in living systems.[34,35] The energy associated with impacts on planetary bodies can destroy some of this organic material, but it can create new species as well. In addition, radiation environments on the surfaces of planets and their satellites can both create and destroy complex organic molecules, but the detailed conditions and the balance between destruction and creation are unknown. Processes in space may affect the balance between the left-handed and right-handed mix of those organic molecules that have the property of chirality, and thus may have played a role in the origin of life on Earth, which is based on left-handed molecules.

Important Questions

Questions emerging from consideration of the processes that create, destroy, and modify solid organic matter in the solar nebula include the following:

- Are there unidentified processes that create and destroy organic matter?
- Do natural processes result in racemic mixtures of complex OM?
- What are the chemical details of the formation of macromolecular organic solids under different conditions and with different starting mixtures?
- What is the temporal history of organic formation in various environments in the solar system?
- What is the balance in the creation and destruction of OM in impacts and radiation environments?

Future Directions

Laboratory analysis of organic material in meteorites, IDPs, and returned samples from comets and asteroids is critical to making progress on the key questions listed above. Laboratory synthesis of complex organic with simulated planetary materials and environments will play a key role in understanding the genesis and evolution of this material in primitive bodies. Remote-sensing observations from missions to small bodies will contribute to understanding the processes that modify materials in the space environment.

How Did Organic Matter Influence the Origin of Life on Earth and Other Planets?

Organic molecular material, both simple and complex, existed in the solar nebula and was included in accreting planetesimals as ices and other solids of low volatility. Comets and Kuiper Belt objects are presumed to contain such material in their ices, while several classes of meteorites originating in the asteroid belt also contain large inventories of amino acids, carboxylic acids, and so on.[36] Asteroids and comets impacting Earth and other terrestrial planets during the late heavy bombardment delivered vast quantities of these materials, perhaps providing the raw materials for the origin of life.[37]

Important Questions

Questions that emerge from studies of how organic matter from primitive bodies influenced the origin of Life on Earth and other planets include the following:

- How does refractory OM vary among the comets, asteroids, planetary satellites, and other solar system bodies, and what does this tell us about the chemical environments in which it formed?
- What kind and quantities of OM delivered to early Earth and other terrestrial planets survived the impact and the planetary environments at that time?
- Did extraterrestrial organic matter trigger or provide the feedstock for early life on Earth?
- Where else in the solar system does life exist or has it existed?
- Could the terrestrial L-enantiomer preference result from the chirality of extraterrestrial OM?

Future Directions

While key questions can be formulated in the context of planetary science, the future directions in this area of how OM from primitive bodies influenced the origin of life on Earth and other planets are probably in the field of biology. In terms of the existence of fossil or contemporary life elsewhere in the solar system, exploration is the only tool available. Samples returned from primitive bodies will shed light on these questions in ways that no other source of information can.

Is Organic Material Similarly Distributed Among Primitive Bodies in Other Planetary Systems?

Many stars are surrounded by disks of dust showing structure suggestive of the presence of planets.[38] This dust is presumed to contain a mix of silicates and macromolecular carbon molecules preserved from the interstellar clouds in which the stars originated. One such star with a dust disk, β Pictoris, exhibits spectral flashes thought to result from the impact of comets into it. In addition, the recent detection of water in the outflow of a carbon-rich red giant star by the Submillimeter Wave Astronomy Satellite (SWAS) spacecraft suggests that a large number of comets are being vaporized in its extended atmosphere. Discoveries of Saturn- and Jupiter-size planets surrounding about 5 percent of solar-type stars in the Milky Way galaxy[39] further suggest that primitive comets and asteroids are relatively common in many star systems; they may be repositories of organic material preserved from the molecular clouds in which those stars and planets originated.

Important Questions

Questions that emerge from studies relating to the distribution of organic material among primitive bodies in other planetary systems include the following:

- Are there planets in the habitable zones around other stars?[b]
- What are the characteristic signatures of primitive body reservoirs around other stars?
- Is our assemblage of primitive bodies typical?

Future Directions

Numerical modeling and astrophysical observations of other star systems with indicators of the presence of planets will address the key questions listed above.

SPACE MISSIONS FOR THE EXPLORATION OF PRIMITIVE BODIES

While certain missions are expected to fall within the cost framework of the Discovery program, the Primitive Bodies Panel focused on missions that appear to exceed the $325 million Discovery-class limit but that are expected (when competed) to cost less than $650 million. These are termed "medium class." Missions that are expected to cost in excess of $650 million are called large-class missions.

Medium-Class Missions

Kuiper Belt-Pluto Explorer

A reconnaissance mission to two or more Kuiper Belt objects and Pluto-Charon is at the top of the Primitive Bodies Panel rankings because of its compelling importance to the scientific objectives identified by the panel. The core payload of the Kuiper Belt-Pluto (KBP) Explorer should include imaging and spectroscopy in the ultraviolet, visible, and infrared, uplink radio science, a suite of measurements of particles and plasmas, dust detectors, and a high-resolution imager.

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[b] Throughout this report, the word "habitable" is used in a general sense meaning compatible with any kind of life. When "habitable" is used to mean compatible with human life, the text specifies that.

This mission will mark the beginning of the exploration of the third great geographic zone of the solar system, the region beyond the giant planets. The science objectives for a suite of Kuiper Belt objects that could be visited sequentially by relatively small changes in course as a first spacecraft flies deeper into the trans-neptunian region include (but are not limited to) the following:

1. Determination of the dimensions and shapes,
2. Determination of crater density,
3. Measurement of surface composition through imaging spectroscopy,
4. Detection of atmospheres,
5. Detection of evidence of any current geological activity (e.g., geysers), and
6. Measurement of dust density with increasing heliocentric distance in the Kuiper Belt.

For Pluto and Charon, the scientific objectives identified and prioritized by the Pluto Express Science Definition Team (SDT) should be met or exceeded.[40]

The science at Pluto and Charon is time-critical because of long-term seasonal changes in the surfaces and atmospheres of both bodies.

Surface Science Goals. The mandatory objectives of surface mapping and surface composition mapping of Pluto and Charon established by the SDT would be significantly compromised without an early mission.[41] This is due to Pluto-Charon's ongoing approach to a steep solstice geometry that increasingly hides in shadow large expanses of polar terrain on each object (~200,000 km^2 of terrain will be lost to imaging and spectroscopic mapping on Pluto alone for each year of arrival delay between 2015 and 2025). Beyond the proportional damage that this does to the global geology and composition mapping objectives that the SDT set for the mission, this loss of terrains will also severely affect the ability to answer key questions about the extent and nature of the polar volatile reservoirs on Pluto, the origin of the polar cap dichotomy on Pluto, and the possibility that volatiles capable of generating an atmosphere on Charon are sequestered in polar regions.

Atmospheric Science Goals. Concerning atmospheric science, Pluto's withdrawal from perihelion is widely anticipated to result in a substantial decline,[42] if not a complete collapse,[43] of its vapor-pressure-supported atmosphere.[44] Searches for an atmosphere around Charon, an extremely desirable mission objective called out in the SDT report, will also be adversely affected, or wholly lost, as will be the opportunity to study atmospheric transfer between Pluto and Charon—something unique in the solar system as far as we know. Other atmospheric science that will be lost at Pluto if the atmosphere collapses or significantly declines before mission arrival will be the ability to do the following, among other things:

- Test for hydrodynamic escape (a mandatory objective),
- Determine the base pressure and vertical haze/temperature structure of the atmosphere that has been under study since the 1980s (another mandatory objective),
- Pin down volatile transport rates (an extremely desirable objective), and
- Sample the atmospheric chemistry and the production of organics and nitriles during its maximum pressure (i.e., perihelion) state (another mandatory objective).

Comet Surface Sample Return—Samples from a Selected Surface Site

The Primitive Bodies Panel's second-ranked medium-class mission is the return of samples from a selected surface site on the nucleus of a comet. The science from this mission was considered more important than that from the Kuiper Belt-Pluto Explorer, but two fundamental differences arise related to readiness. First, there are several well-developed designs for KBP missions already available, whereas well-developed designs for a Comet Surface Sample Return (CSSR) mission are not available. Furthermore, there are engineering concerns about the viability of a surface sample-return mission related to the unknown nature of the cometary surface. While most cometary scientists think that the material is relatively weak and therefore easily sampled in a "grab-and-go" mode, only the Deep Impact mission is likely to resolve those engineering concerns as being either justified or not. This implies that the CSSR is most effectively begun after July 2005, when the results from Deep Impact will be known.

No other class of objects can tell us as much as samples from a selected surface site on the nucleus of a comet can about the origin of the solar system and the early history of water and biogenic elements and compounds. Only a returned sample will permit the necessary elemental, isotopic, organic, and mineralogical measurements to be performed. Although it is 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 organics and non-ice minerals together with water maintained as ice—a mission that is technically achievable in the next decade, and which the panel believes might be achieved in the medium-class category. High priority should be given to returning a sample from a comet that has been previously visited by spacecraft, or is characterized by the sample-collecting spacecraft itself, in order to permit the maximum interpretability of information to be obtained from the comet.

In the first sample-return mission from a comet, the material could be collected at one or more sites on the surface or in the near-surface layer, preferably in or near an active vent. It is recognized that this kind of mission does not address the full range of scientific issues that could be accomplished by a mission in which samples were collected from several regions on the nucleus, including the subsurface (by drilling), with the specimens returned at deep cryogenic temperatures. However, this more complete mission is thought to be outside the cost framework of the medium-class envelope. In any case, if a nucleus sample-return mission cannot be accomplished within the medium-class category, it should receive the highest ranking in the category of large missions. The panel strongly recommends that the entire Comet Surface Sample Return mission be competed through an Announcement of Opportunity, as was done for the KBP mission.

Trojan Asteroid/Centaur Reconnaissance

The Trojan Asteroid/Centaur Reconnaissance mission would send a KBP-like flyby reconnaissance spacecraft equipped with imaging, imaging spectroscopy, radio science, and, potentially, other instruments to make the first explorations of both a jovian Trojan asteroid and a Centaur. Beyond simply opening up these two new classes of primitive bodies to exploration, this mission has deep ties to understanding the origins of primitive bodies.

In particular, the Trojan flyby would sample primitive material from the jovian accretion region of the nebula; it would also allow an important recalibration of the bombardment flux on objects in the jovian system and would offer new insights into space weathering and other processes affecting asteroids, particularly in the main belt. The Centaur flyby would provide insights into the nature of the Kuiper Belt, the nature and origin of short-period comets and their parent bodies, and activity in distant comets.

Such a mission can be conducted with current technology, using a heavy-lift expendable launch vehicle (ELV) such as the Delta IV 4050H; if a Centaur inside ~6.5 AU is selected, it is possible to carry out this mission using large photovoltaic arrays, thereby avoiding the need for a radioisotope power supply. Such a mission would very likely also be capable of a main-belt asteroid flyby during its trip from the inner planets region en route to the Trojan zones.

Asteroid Lander/Rover/Sample Return

The Near-Earth Asteroid Rendevous (NEAR) mission to 433 Eros demonstrated that even small asteroids are covered with complex and substantial regoliths, which are heterogeneous in texture and detailed in composition (Figure 1.2). To understand the geologic evolution of asteroids, regoliths must be studied in detail, and their variability must be characterized both vertically and horizontally. NEAR has shown that the surfaces of asteroids can be so heterogeneous that it is difficult to identify a single "representative" locale. What is needed is the ability to land remote-sensing and analytical instruments and to provide the landed package with mobility in order to access a variety of geologic sites. The ability to return samples for detailed analysis on Earth is also essential. Such a mission would address the nature and time scales of geologic processes on asteroids and elucidate how

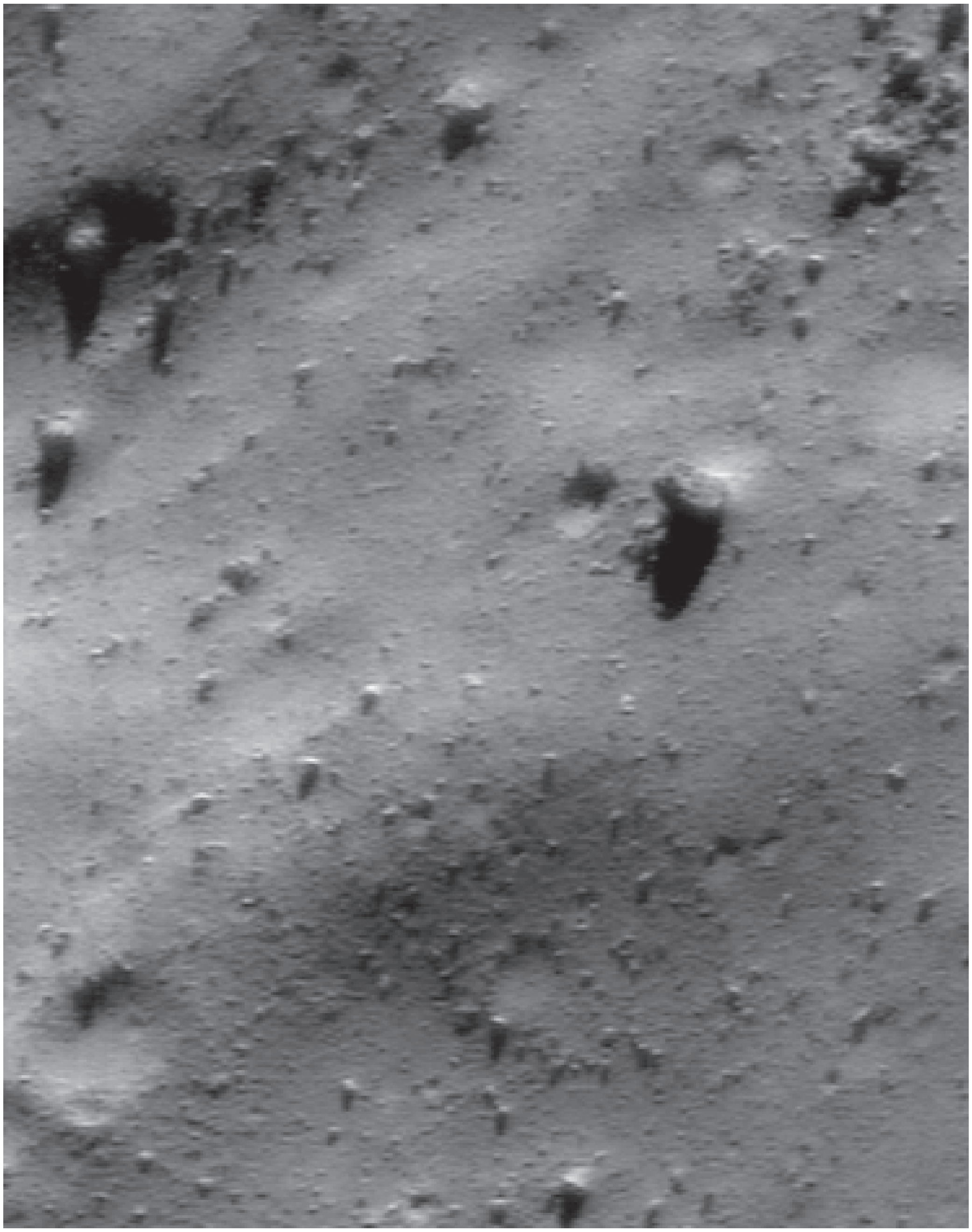
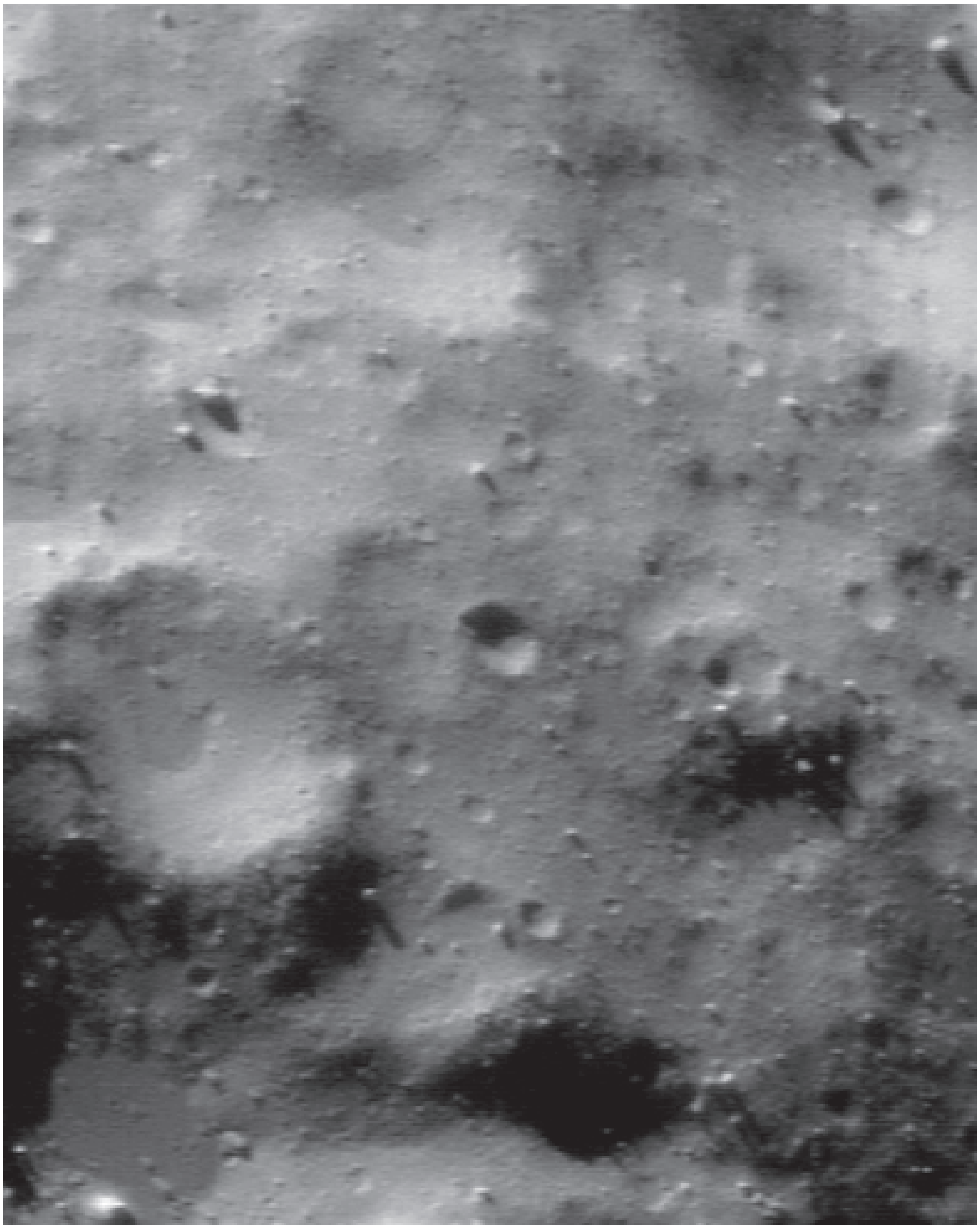


FIGURE 1.2 Though covered with rocks and boulders, the surface of asteroid 433 Eros appears to lack small craters. Those that are seen are muted, suggesting that the surface is covered with a blanket of regolith. These two images were taken by the NEAR Shoemaker spacecraft from an altitude of 38 km *(Right)* and 7 km *(Left)* and show features as small as 6 and 1.4 m, respectively. Courtesy of Applied Physics Laboratory.



these work to modify the texture and composition of the regolith. It would also provide a detailed compositional characterization of the asteroid.

To maximize the science return from such a mission, it is essential to select the most interesting locales on the asteroid, a goal that implies a global reconnaissance of the target body. In this context, a follow-up mission to asteroid 433 Eros should be given high priority. Eros represents a well-characterized, important target on which potentially interesting sites can be selected from existing data. Eros also represents a target that is relatively easy to reach dynamically and on which a successful landing has already been demonstrated.

Triton/Neptune Flyby

The Triton/Neptune Flyby mission would send a KBP-like flyby reconnaissance spacecraft, equipped with imaging, imaging spectroscopy, radio science, and potentially other instruments, to make a detailed second reconnaissance of the Neptune system. Using a Jupiter-gravity assist, such a mission could be launched in 2007, reaching Neptune in 2015. A Centaur flyby en route to Neptune is possible; a post-Neptune flyby of a KBO is also possible in an extended mission.

The primary target, the Neptune-Triton system, is scientifically rich (see Chapters 4 and 5 in this report) and would greatly benefit from a follow-up to Voyager. Such a flyby would bring to bear new technology instruments (e.g., infrared mapping spectroscopy) and would allow time-variability studies. This mission can be conducted with current technology, but it does require a radioisotope power supply. In addition to being deeply attractive to the primitive bodies community, such a mission would be appealing to those researchers interested in studies of the large satellites, planetary rings, and the giant planets—the latter, in particular, if it were feasible to include a Neptune atmospheric probe. Another feature of this mission commending it for additional study is that it would provide a means of sidestepping the return-to-Neptune cost and technology dilemmas imposed by current thinking about Neptune orbiter missions.

Large Missions

The panel identified a single high-priority mission in a cost category that, even with competition, is expected to exceed the cost of medium-class missions.

Comet Cryogenic Sample Return—Cold Samples from Depth

Because of the great importance of sample-return missions from comets to future progress in understanding the origin and development of the solar system and because of the limitations imposed by cost on a medium-class mission, the panel suggests that a larger-scale mission to one or more comets be undertaken. Such a mission would collect samples of a well-characterized comet nucleus from two or more selectable sites, both from the surface and from a depth on the order of 1 m. In order to preserve the full suite of volatile materials, the samples would be maintained at a temperature below 150 K through the return to Earth for analysis. A mission of this complexity requires further technological developments, particularly for drilling and sample collection and for cryogenic preservation and return to Earth.

KEY ENABLING TECHNOLOGIES FOR PRIMITIVE BODY EXPLORATION

The panel considered areas of technological development that are required to enable certain highly desirable missions. Those areas (in no particular order) are as follows:

- *Drilling on small bodies.* Techniques must be developed in order to collect samples of comets and asteroids below the exposed surface and deep into the region where volatiles may be retained. These samples will then be returned to Earth for analysis.

- *Cryogenic sample preservation and handling.* Techniques must be developed for the return of samples of comets to Earth for analysis. In order to retain the critical volatile components of a comet nucleus in samples collected below the exposed surface, the temperature of the sample must be maintained at less than 150 K during the collection, encapsulation, lift-off from the nucleus, and return and capture at Earth. Techniques for handling and analysis of cryogenic samples in the laboratory must also be developed.
- *Remote age determination and compositional analysis.* Techniques must be developed to be performed robotically at selected sites on primitive bodies (asteroids, comets, planetary satellites, and planetary surfaces) in order to provide cost-effective ways to explore the cosmochemical properties of critical bodies in the solar system.
- *Nuclear-electric propulsion.* This technology requires development so that it can be implemented late in this decade or as soon thereafter as possible.

KEY SUPPORTING RESEARCH AND FACILITIES

Near-Earth Objects

Near-Earth objects (NEOs) are asteroids, spent comets, and active comets that approach the Earth-Moon system and that in some cases may constitute an impact hazard of global proportions. Indeed, governmental studies in the United States, the United Kingdom, and elsewhere have requested surveys for near-Earth asteroids in search of objects that may constitute an impact hazard. More than a statistical study, governments desire a catalog of potential impactors that would produce global catastrophes or widespread damage on smaller scales in the next century. Surveys in progress have identified an estimated 50 percent of the near-Earth asteroids and extinct comets 1 km and greater in size, and very roughly 10 to 15 percent of such bodies 0.5 km in size. Approximately 340 (as of November 2001) of these come especially close to Earth and are cataloged as Potentially Hazardous Asteroids. The number of new comets with impact potential is large and unknown.

Important scientific goals are associated with the NEO populations, including their origin, fragmentation and dynamical histories, and compositions and differentiation. These and other scientific issues are also vital to the mitigation of the impact hazard, as methods of deflection of objects potentially on course for an impact with Earth are explored. Information especially relevant to hazard mitigation includes knowledge of the internal structures of near-Earth asteroids and comets, their degree of fracture and the presence of large core pieces, the fractal dimensions of their structures, and their degree of cohesion or friction.

The scientific goals of near-Earth object studies for the objectives of both pure science and science for the public good should be addressed in an aggressive, multidimensional program of detection and physical studies with Earth-based telescopes, including radar, and perhaps telescopes in space. In addition, high priority is given by the panel to missions to representative objects (e.g., 433 Eros) to establish their physical properties, as noted above. Samples returned from near-Earth objects are a critical component of these objectives. Accordingly, the Primitive Bodies Panel recommends a medium-class mission to land on an asteroid, possibly 433 Eros, collect samples from several well-characterized locations, and return them to Earth for analysis. Discovery-class missions for the reconnaissance of additional near-Earth asteroids and extinct comets are also recommended. The panel further recommends that dedicated and powerful ground-based facilities for the detection and physical study of near-Earth objects be implemented, together with the data-handling and data-analysis capabilities that large-scale surveys will require. Additionally, adequate support is critically needed for the analysis of data from missions to near-Earth objects, as well as theoretical studies of the cosmochemical, geophysical, geological, and dynamical evolution of such objects and their precursor bodies.

Earth-Based Telescopes

In the decade under consideration, ground-based telescopes will continue to play key roles in the detection and physical study of primitive solar system bodies. Asteroids near Earth and in the main belt are found and studied with ground-based telescopes, as are Kuiper Belt objects, Centaurs, distant comets, and most planetary satellites. It is essential that ground-based telescopes suited to all-sky surveys and other detection strategies be included as an integral component of the next decade of solar system exploration. Equally important are telescope facilities capable of spectroscopic, photometric, radiometric, and radar investigations of known and newly discovered small bodies in the solar system. With some existing and proposed facilities, the objectives of detection and physical studies can be met with the same telescope equipped with a variety of supporting instrumentation.

Earth-based facilities—a broader term encompassing not only ground-based telescopes but also airborne telescopes (notably, the Stratospheric Observatory for Infrared Astronomy [SOFIA]) and near-Earth spaceborne telescopes (e.g., the Space Infrared Telescope Facility [SIRTF], the Hubble Space Telescope [HST], and the James Webb Space Telescope [JWST])—will play critical roles in the study of solar system bodies in wavelength regions inaccessible from the ground, and these must be supported. Many solar system observations impose special requirements on telescopes (for example, because of moving targets, faint objects near bright planets, and the need for high definition), and it is important that newly defined projects for telescopes on all platforms include the technological options that will enable observations of solar system bodies.

Telescopes on the ground, in the air, and in space afford observations of vastly more objects than can ever be visited by spacecraft. They not only enable us to select appropriate targets for spacecraft visits, but also let us put into context the information gained from expensive and infrequent space missions to asteroids, comets, and other primitive solar system bodies. Numerous examples could be given of the critical value of mission support afforded by observations with telescopes of various kinds; a few are mentioned here to help underscore the breadth of the concept of “mission support”:

- The Galileo probe entered Jupiter’s atmosphere in an anomalously cloud-free region whose strong infrared emissions were detected by NASA’s Infrared Telescope Facility (IRTF) on Mauna Kea. Without this information, the context of the information relayed by the probe would have been lost.
- The Kuiper Belt-Pluto Explorer mission currently under development is intended to visit Kuiper Belt objects that probably have not yet been discovered. The eventual targets will be detected by ground-based surveys of the appropriate volume of space.
- A mission to a presumed organic-rich asteroid will have to be targeted at an object that has been observed and classified from Earth-based observations.
- A mission to a dynamically new, inbound comet would require either dramatically improved discovery capability for comets at large heliocentric distance or a mission “ready to go,” either on the ground or already in heliocentric orbit.

This broad definition of mission support challenges NASA to be forward-thinking and inclusive, so that ground-based telescopes can find targets, define basic parameters, and motivate key science questions that can only be addressed by spacecraft.

Many of the observational requirements for solar system objects are fully as challenging as the faintest and most difficult objects in modern astrophysics and thus require very large apertures, highly sensitive detectors, versatile spectrographs, and other supporting instrumentation, often with special features to enable observations of moving targets and faint targets that are nearby bright planets.

The SSE Survey’s Primitive Bodies Panel endorses the concept of a large telescope capable of an all-sky search strategy that would reveal large numbers of near-Earth objects as well as trans-Neptunian objects, thus completing the surveys of these objects to a brightness level much beyond the current capabilities.

The Primitive Bodies Panel also endorses a telescope that would enable the physical study of such objects by spectroscopic and photometric techniques. The panel heard recommendations for the Large Synoptic Survey Telescope (LSST) and the Next Generation Lowell Telescope (NGLT), both of which enable surveys and physical observations at some level that exceeds current capabilities. Other options, including the Panoramic Optical Imager concept, should be explored and a choice made that NASA can support in the next decade.

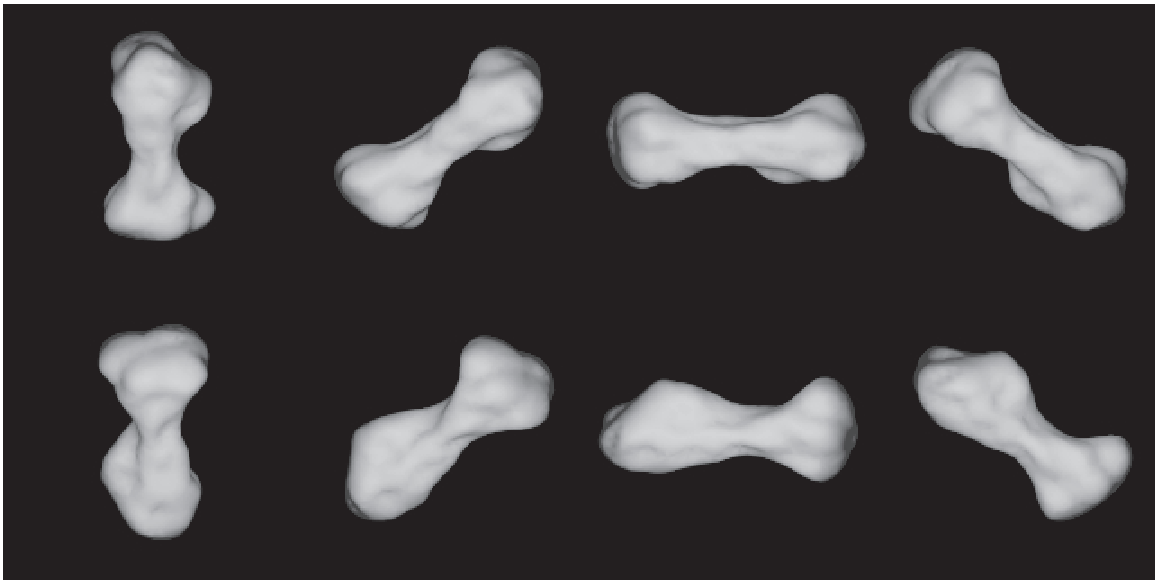


FIGURE 1.3 Multiple radar observations of the main belt asteroid 216 Kleopatra revealed the rotation of this unusual object. At the time that these observations were made with the planetary radar facility at the Arecibo Observatory in Puerto Rico, Kleopatra was some 171 million kilometers from Earth. Spectroscopic studies indicate that this 217-km-long object has a metallic composition. Courtesy of National Aeronautics and Space Administration/Jet Propulsion Laboratory.

Support for Existing Facilities

Planetary Radar Facilities. The panel heard a presentation on the status and future of the planetary radar facilities at Arecibo, Puerto Rico, and Goldstone, California, as they are used for studies of small solar system bodies (Figure 1.3). These highly productive facilities provide unique information on the shapes and sizes, regolith properties, and occurrence of binaries among near-Earth objects, and provide critical astrometry for orbit predictions. Both facilities are working at their limits in terms of equipment and personnel. The data-acquisition systems at both facilities urgently need upgrading, and the staffing is insufficient to handle the observing workload imposed by the increasing numbers of near-Earth objects being discovered and requiring follow-up observations. Replacements for near-term retirement of critical technical staff are urgently needed. The panel recommends that both of these important facilities be supported and upgraded as needed, for the unique information that radar observations of small solar system bodies provide.

The NASA Infrared Telescope Facility. The IRTF, mentioned above, contributes to a wide spectrum of solar system and astrophysics investigations by U.S. and foreign astronomers and makes a special contribution to the study and characterization of near-Earth objects. In particular, in a focused effort on small bodies and with dedicated observing programs, instrumentation, and rapid response time, the IRTF will contribute critical information for planning space missions to comets and asteroids. Even in an epoch of 6- to 10-m telescopes, the contributions of the 3-m-aperture IRTF are very important to the next decade of solar system studies, and the panel recommends that requested upgrades to the facility be made to ensure operations at a state-of-the-art level.

The Keck Telescopes. Some 15 percent of the observing time on the twin 10-m telescopes at the Keck Observatory on Mauna Kea is available for studies in areas selected by NASA. These studies are defined in a priority order with interferometry first, detection of extrasolar planets second, and general solar system astronomy third. The result is that very little time is available for general studies, for example, of KBOs. The Primitive Bodies Panel recommends that NASA's commitment be sustained at a high enough level that scientifically important problems in solar system astronomy, such as physical characterization of KBOs, can be carried out with this facility.

Laboratory Facilities for Returned Samples. It is critically important to prepare for the sample returns from the Stardust, Genesis, and Muses-C and the anticipated returns from Mars and a comet nucleus by the establishment of a realistic laboratory instrument-development program. Existing programs of this nature are dramatically underfunded. Initial funding should be aimed primarily at the development of new analytical technologies, with the most urgent need being for the development of organic chemistry microanalysis. As new techniques are established, the program priorities should shift to upgrading U.S. laboratories with the new analytical equipment.

Laboratory Facilities for the Study of Planetary Materials

Laboratory studies in support of observational studies, and particularly NASA planetary missions to planets, comets, and asteroids, are critical to the correct and complete interpretation of the data acquired at great expense. Such work is inadequately supported either in existing laboratory facilities or through the creation of new laboratories. The Primitive Bodies Panel recommends that as long as sample-return missions are in the mission plan, there is a continuing need for upgrades to the equipment used for analyzing the samples at levels currently in NASA's Sample Return Laboratory Instruments and Data Analysis program.

Curation

A critical necessity in preparation for the sample returns from the Stardust, Genesis, and Muses-C and the anticipated returns from Mars and a comet nucleus is support for sample curation and handling at a significantly increased level over what exists today. The proper preservation of each returned sample for future investigations is of paramount importance. The samples returned from each object will have particular handling and storage demands, which must be addressed by separate, specialized facilities. The funding for these facilities, including long-term operating costs, cannot realistically come from each mission's budget. In particular, development is required in the areas of cryocuration, robotic sample handling, and biological quarantine. The panel recommends that the facilities required for the proper analysis and curation of returned samples be developed and supported.

KEY QUESTIONS AND MEASUREMENT OBJECTIVES

The important questions identified in each of the thematic sections above are merged here into key scientific questions that are amenable to solution in the decade under consideration by a series of space missions and surveys of the solar system from Earth-based observatories, as well as expanded laboratory facilities. These questions are presented here, condensed and reframed, in three categories of expected impact. The panel measures the impact of a question by asking whether its answer has the possibility of creating or changing a paradigm, whether the new knowledge might have a pivotal effect on the direction of future research, and to what degree the knowledge that might be gained would substantially strengthen the factual basis of our understanding. These measures of merit are listed in the order of the priority that the panel associates with them.

Primitive Bodies As Building Blocks of the Solar System

Potentially paradigm-altering questions about primitive bodies as building blocks of the solar system include the following:

- What is the population structure of the solar system?
- What is the nature of Kuiper Belt objects?
- What is the formation history of the trans-Neptunian region?
- Where in the solar system did building blocks form; which were transported and which were not?

Questions of pivotal importance include the following:

- How do compositional differences between the Oort cloud and the Kuiper Belt bodies relate to their sites of origin?
- Are small, distant bodies such as Kuiper Belt objects, Pluto, and Charon geologically active today?
- What is the nature of binary objects in the solar system, and what do they tell us about formation history?
- What processes modify the surfaces of all categories of building blocks?

Foundation-building questions are as follows:

- How do colors and albedos of small bodies relate to their compositions and histories of alteration by various processes since their origin?
- What roles did various dynamical processes play in the origin and evolution of the primitive bodies in the solar system, and what were the time scales?
- What are the orbital distributions of long-period and new comets, and how have these distributions evolved over the age of the solar system?

Primitive Bodies As Reservoirs of Organic Matter

Potentially paradigm-altering questions about primitive bodies as reservoirs of organic matter include the following:

- What are the compositions and origins of the organic and volatile materials in primitive bodies?
- How is organic matter distributed throughout the solar system?
- What is the chemical and isotopic composition of cometary surface materials?
- What are the physical and chemical/isotopic properties of comet nuclei, and do they vary with depth?

Questions of pivotal importance include the following:

- Did organic matter from comets and meteorites provide the feedstock for the origin of life on Earth?
- What are the parent bodies of the carbonaceous meteorites, interplanetary dust particles, and micrometeorites?

Foundation-building questions are as follows:

- What are the processes by which organic material forms on the surfaces of icy and other primitive bodies in the current epoch?
- What is the thermal and aqueous alteration history of the parent bodies of the organic-rich primitive meteorites?

Table 1.1 shows the themes and questions identified by the Primitive Bodies Panel and the impact of specific missions and surveys toward their resolution.

The two themes around which this chapter is organized—primitive bodies as building blocks of the solar system, and organic matter in the solar system as materials for the origin of life—are equally important and urgent. The key questions for each theme are listed in the order of importance in the sense of representing the steps needed to address the themes. Table 1.1 represents the Primitive Bodies Panel's best judgment of the extent to which each

TABLE 1.1 Primitive Bodies: Relationship of Themes, Key Scientific Questions, and Mission Possibilities

Class of Question	Theme and Key Questions	Current Missions	KBP^a	First CNSR^b	Trojan/ Centaur Flyby	Primitive NEO^c Return	Survey and Follow-up Telescopes
	Theme 1. BUILDING BLOCKS OF THE SOLAR SYSTEM						
Paradigm altering	1. What is the population structure of the solar system?		xxx		x		xxx
	2. What is the nature of the KBOs?		xxx	x	xx		xx
	3. What is the formation history of the trans-Neptunian region?	x	xxx	xx	x		xx
	4. Where in the solar system did building blocks form; which were transported and which were not?	xx	xx	xx	xx	x(?)	xx
Pivotal	1. How do compositional differences between the Oort cloud and the Kuiper Belt bodies relate to their sites of origin?	x	x	x	x		x
	2. Are small, distant bodies such as KBOs, Pluto, and Charon geologically active today?		xxx		x		x
	3. What is the nature of binary objects in the solar system, and what do they tell us about formation history?		xx				xx
	4. What processes modify the surfaces of all categories of building blocks?	xx	xx	xxx	xx	xxx	
Foundation building	1. How do colors and albedos of small bodies relate to their compositions and histories of alteration by various processes since their origin?	x	xx	xx	xx	xx	xx
	2. What roles did various dynamical processes play in the origin and evolution of the primitive bodies in the solar system, and what were the time scales?		xx		xx	x	xx
	3. What are the orbital distributions of long-period and new comets, and how have these distributions evolved over the age of the solar system?		x				x
	Theme 2. ORGANIC MATTER IN THE SOLAR SYSTEM: MATERIALS FOR THE ORIGIN OF LIFE						
Paradigm altering	1. What are the compositions and origins of the organic and volatile materials in primitive bodies?	xx	x	xxx	x	xxx	x
	2. How is organic matter distributed throughout the solar system?	xx	xx	xx	xx	xx	xx
	3. What is the chemical and isotopic composition of cometary surface materials?	xx		xxx	x		x
	4. What are the physical and chemical/isotopic properties of comet nuclei, and do they vary with depth?	xx		xxx		x (?)	
Pivotal	1. Did organic matter from comets and meteorites provide the feedstock for the origin of life on Earth?	xx		xx	x	xx	x
	2. What are the parent bodies of the carbonaceous meteorites, IDPs, and micrometeorites?	x		x	x	x	
Foundation building	1. What are the processes by which organic material forms on the surfaces of icy and other primitive bodies in the current epoch?	x	xx	x	x	xx	x
	2. What is the thermal and aqueous alteration history of the parent bodies of the organic-rich primitive meteorites?			x	x	xxx	x

NOTE: xxx = breakthrough level of advance, xx = significant advance in understanding, x = some advance in understanding, and x(?) = requires that target turns out to be an extinct comet.

[a] Kuiper Belt-Pluto Explorer. [b] Comet Nucleus Sample Return. [c] Near-Earth object.

mission or set of missions will advance current knowledge regarding the key (paradigm-altering) questions. The magnitude of the advance is indicated by the number of "x's" in a nonlinear fashion (i.e., xxx > (xx + x)). Similar rankings for different missions on a particular question do not imply scientific redundancy because the questions are multidimensional.

RECOMMENDATIONS OF THE PRIMITIVE BODIES PANEL TO THE STEERING GROUP

In establishing a ranked list of missions for the continued exploration of primitive bodies, the panel took into account various factors related to missions that are technically feasible in the decade 2003-2013. The following factors were included:

- The paucity of radioisotope power systems currently available,
- The fact that no major new technology developments were required, and
- The need for focused scientific objectives.

The ranked mission set that the Primitive Bodies Panel recommends is as follows:

1. *Kuiper Belt-Pluto Explorer.* Such a mission can be accommodated within the cost range of a medium-class program.
2. *Comet Nucleus Sample Return.* A mission of limited scope (e.g., Comet Surface Sample Return) could be included in the medium-class cost category. A larger-scale mission with greater capability (e.g., Comet Cryogenic Sample Return) would fall into the category of a large mission. Depending on phasing, both are desirable.
3. *Trojan Asteroid/Centaur Reconnaissance.*
4. *Asteroid Lander/Rover/Sample Return.*
5. *Triton/Neptune Flyby.*

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