Exploring the Trans-Neptunian Solar System

Committee on Planetary and Lunar Exploration
Space Studies Board
Commission on Physical Sciences, Mathematics, and Applications
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Foreword

At the distance of Neptune, the Sun is 900 times fainter than at Earth and only 400 times brighter than our full Moon. Beyond Neptune lies Pluto with its moon, Charon, and a vast frozen region that recent observations show is teeming with icy remnants of the nebula that formed the solar system, the Kuiper Belt. Although the intrepid Voyager 2 spacecraft zoomed past Neptune in 1989 and continues to send signals from several times that distance, its orbital dynamics did not allow a detailed inspection of Pluto or the Kuiper Belt.

This report considers the scientific imperatives and priorities for further study of the trans-neptunian system, including Neptune's own moon Triton. It considers both ground-based observations and space missions. The report recognizes that technology is the key to cost-effective, in situ exploration of Pluto, Charon, and the Kuiper Belt. Studying these remote objects requires small spacecraft, lightweight enough to be boosted to the outer solar system with modest-sized rockets yet suitably instrumented to perform meaningful science when they arrive.

The trans-neptunian system contains the most primitive and undisturbed remnant of the material from which our planet formed. A major reward for studying and exploring these distant regions is the understanding it can give about the origin and evolution of our home in the solar system.

Claude R. Canizares, *Chair*
Space Studies Board

Preface

In the last decade, our knowledge of the outer solar system has been transformed as a result of the Voyager 2 encounter with Neptune and its satellite Triton and from Earth-based observations of the Pluto-Charon system. However, the planetary system does not simply end at the distance of Pluto and Neptune. In the past few years, dozens of bodies have been discovered in near-circular, low inclination orbits near or beyond the orbit of Neptune. These bodies are now believed to be directly related to each other and to Pluto, Charon, and Triton. As a class they define and occupy the inner boundary of a hitherto unexplored component of the solar system, the trans-neptunian region.

We have just begun to characterize the nearest and larger members of the population of bodies beyond Neptune to at least 100 AU, known as the Kuiper Belt. These bodies have low albedos, are about a hundred to a few hundred kilometers in diameter, and number in the tens of thousands. Smaller Kuiper Belt objects are presumably vastly more numerous. Because the inner part of the Kuiper Belt is unstable with respect to gravitational perturbations by Neptune, the smaller objects are suspected to be the major source for short-period comets that enter regions closer to the Sun and that can collide with the planets. The largest known comet, Chiron, orbits between Saturn and Uranus. It is about 170 km across, has low albedo, and exhibits a complex coma and jet structure. Its orbit strongly suggests that it is a former Kuiper Belt object, and its size indicates that it is similar to those objects recently discovered beyond Neptune. The sizes of the largest Kuiper Belt objects are unknown, but it is likely that the Pluto-Charon system, stabilized in a gravitational orbital resonance with Neptune at the inner edge of the Kuiper Belt, is a large surviving member of the primordial Kuiper Belt population.

Exploration of the Pluto-Charon system by spacecraft is a prime objective of NASA's planetary and lunar exploration program in the 21st century. NASA's present plan is to study and design an integrated instrument suite and spacecraft to explore Pluto-Charon under extreme cost constraints. Mission development is closely connected to the New Millennium advanced spacecraft technology development program and will aim for a new start in FY 2000.

Neptune's Triton is very similar to Pluto in size, density, and surface and atmospheric composition. Although Triton is a planetary satellite, it was probably captured and thus may be related in origin to Pluto and Kuiper Belt objects. The Voyager flyby of Triton revealed it to be a geologically and meteorologically remarkable body. It exhibits a wide array of geological terrains, present-day geological activity, and a variety of atmospheric and seasonal processes that imply dramatic climatic variations on longer time scales. Although NASA has no planned missions to return to the Neptune system, Pluto-Charon and Triton could be studied synergistically to great effect.

As a result of these developments, the Space Studies Board charged COMPLEX to review the state of scientific knowledge of the trans-neptunian region of the solar system and address the following questions:

- What is the present understanding of the origin, composition, and physical characteristics of these bodies and the interrelationships among Kuiper Belt objects, Chiron, the Pluto-Charon system, and Triton?
- What ground-based and Earth-orbiting telescopic observations are needed to characterize the Kuiper Belt and the complex worlds, Pluto-Charon and Triton?
- What observations would clarify the highest-priority scientific questions concerning Pluto-Charon and Triton, and would identify new targets of high scientific interest?
- What are the likely opportunities for relatively inexpensive flyby or rendezvous missions to Pluto-Charon, Triton, Chiron, or Kuiper Belt bodies?
- What are the priority scientific questions for such missions, and what instruments are necessary to answer them?
- What enabling technologies are needed to make these missions affordable?

This project was formally initiated in October 1995, and the bulk of the material was written in the latter part of 1996. This material was extensively revised, updated, and reviewed in the summer of 1997. Although many COMPLEX members past and present worked on this report, the bulk of the task of assembling and editing their many individual contributions was performed by Fran Bagenal with the assistance of Heidi Hammel, Ted Roush, Gerald Schubert, Darrell Strobel, and Roger Yelle. The work of this writing team was made easier thanks to the invaluable assistance rendered by Dale Cruikshank (NASA Ames Research Center), Harold Levison (Southwest Research Institute), William McKinnon (Washington University), Robert Staehle (NASA Jet Propulsion Laboratory), and Paul Weissman (NASA Jet Propulsion Laboratory). COMPLEX also wishes to acknowledge additional assistance given by Donald Brownlee (University of Washington), Karen Meech (University of Hawaii), Robert Pepin (University of Minnesota), Marcia Rieke (University of Arizona), and Peter Stockman (Space Telescope Science Institute).

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The contents of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. COMPLEX thanks reviewers Reta Beebe (New Mexico State University), Robert H. Brown (University of Arizona), Marc Buie (Lowell Observatory), A.G.W. Cameron (Harvard-Smithsonian Center for Astrophysics), William Kaula (University of California, Los Angeles), Margaret Kivelson (University of California, Los Angeles), and Jane Luu (Harvard-Smithsonian Center for Astrophysics) for many constructive comments and suggestions. Responsibility for the final content of this report rests solely with the authoring committee and the NRC.

Contents

Executive Summary

A profound question for scientists, philosophers and, indeed, all humans concerns how the solar system originated and subsequently evolved. To understand the solar system's formation, it is necessary to document fully the chemical and physical makeup of its components today, particularly those parts thought to retain clues about primordial conditions and processes.[1]

In the past decade, our knowledge of the outermost, or trans-neptunian, region of the solar system has been transformed as a result of Earth-based observations of the Pluto-Charon system, Voyager 2's encounter with Neptune and its satellite Triton, and recent discoveries of dozens of bodies near to or beyond the orbit of Neptune. As a class, these newly detected objects, along with Pluto, Charon, and Triton, occupy the inner region of a hitherto unexplored component of the solar system, the Kuiper Belt. The Kuiper Belt is believed to be a reservoir of primordial objects of the type that formed in the solar nebula and eventually accreted to form the major planets. The Kuiper Belt is also thought to be the source of short-period comets and a population of icy bodies, the Centaurs, with orbits among the giant planets. Additional components of the distant outer solar system, such as dust and the Oort comet cloud, as well as the planet Neptune itself, are not discussed in this report.

Our increasing knowledge of the trans-neptunian solar system has been matched by a corresponding increase in our capabilities for remote and in situ observation of these distant regions. Over the next 10 to 15 years, a new generation of ground- and space-based instruments, including the Keck and Gemini telescopes and the Space Infrared Telescope Facility, will greatly expand our ability to search for and conduct physical and chemical studies on these distant bodies. Over the same time span, a new generation of lightweight spacecraft should become available and enable the first missions designed specifically to explore the icy bodies that orbit 30 astronomical units (AU) or more from the Sun. The combination of new knowledge, plus the technological capability to greatly expand this knowledge over the next decade or so, makes this a particularly opportune time to review current understanding of the trans-neptunian solar system and to begin planning for the future exploration of this distant realm.

Based on current knowledge, studies of trans-neptunian objects are important for a variety of reasons that can be summarized under five themes:

1. **Exploration of new territory.** Telescopic discoveries of new Kuiper Belt objects (KBOs) are being made monthly. With continued access to suitable telescopes, this rate of discovery will likely be maintained for many years since very little of the sky (<0.1% of the ecliptic for objects brighter than 17th magnitude[2,3]) has been

surveyed to date. While telescopes are showing us that trans-neptunian objects are relatively common and are providing information about their disk-averaged surface composition, spacecraft missions are necessary to explore the detailed nature of these icy bodies.

2. **Reservoirs of primitive materials.** While KBOs may not be pristine relics of the original solar nebula, it is in the outer solar system that we might expect to find the least-modified materials as well as samples that have suffered a range of degrees of modification. These bodies can provide the links for understanding the relationships among the interstellar medium, the solar nebula, and current materials in the solar system.

3. **Processes that reveal the solar system's origin and evolution.** The observable characteristics of objects tell us about the processes they have experienced. The distribution of a population of objects in orbital phase space provides clues about their origins and the dynamical processes that control them over long periods. The distribution of sizes within a population reveals the relative importance of accretion versus collisional erosion. The wide range of sizes and different collisional histories among objects in the trans-neptunian region implies varying degrees of internal differentiation. Surface geology provides important constraints on an object's thermal history. Surface chemistry and atmospheric properties reveal processes of outgassing, photochemistry, transport, and redeposition of volatiles.

4. **Links to extrasolar planets.** Studies of early stars similar to the Sun have shown that some are surrounded by disks of dust that are thought to be derived from collisions between comets. It is natural, therefore, to relate such dust disks to the Kuiper Belt. Applying knowledge of the Kuiper Belt to stellar dust disks suggests that the inner boundary exhibited by some disks may be an indication of the existence of planets. Comparisons of the Kuiper Belt with these dust disks is an important component of the new field of comparative studies of solar systems.

5. **Prebiotic chemistry.** As remnants of the early solar system, trans-neptunian objects can provide critical clues about processes of prebiotic chemistry and about the materials that would have been delivered to the early Earth and may have formed the source of volatile materials from which life arose here and possibly on other planets of this and other solar systems.

These five themes are not on an equal footing. The first three are well-established areas of scientific investigation and are backed up by a substantial body of observational and theoretical understanding. The last two, however, are more speculative. They are included here because they raise a number of interesting possibilities that seem particularly suited to an interdisciplinary approach uniting planetary scientists with their colleagues in the astrophysical and life science communities.

Although not considered in any detail in this report, the distant outer solar system also has direct relevance to Earth and the other terrestrial planets because it is the source of comets that bring volatiles into the inner solar system. The resulting inevitable impacts between comets and other planetary bodies can play a major role in the evolution of planetary surfaces and atmospheres. Indeed, comets can also play major roles in the evolution of life as suggested by, for example, the Cretaceous-Tertiary boundary bolide and the extinction of the dinosaurs.

TRANS-NEPTUNIAN OBJECTS

The five major themes described above involve general scientific issues that apply to the trans-neptunian region as a whole. Below COMPLEX summarizes the current knowledge and outstanding issues of the separate major types of objects in the trans-neptunian region.

Triton

Triton is by far the best-explored icy body in the distant outer solar system,[4] and, as such, sets the context for the discussion of the other bodies. Triton is thought to be a planetary body that was captured by Neptune in the distant past. Voyager 2's flyby of Triton demonstrated the wealth of information available only from a spacecraft mission. Triton's density suggests that it has a rock core (70% by mass) surrounded by ice. Tidal heating due to orbital evolution and/or collision(s) with other satellites probably caused differentiation of the interior. Geological mapping indicates a youthful surface with few impact craters and with active volcanic eruptions. Its surface is uniformly cold (<38 Kelvin) and is covered with patches of volatile ices that appear to be strongly coupled to Triton's seasonally varying nitrogen atmosphere.

The outstanding issues at Triton are as follows:

- When and by what process was Triton captured by Neptune?
- What is the degree of differentiation of the interior?
- Does Triton have an iron core and/or magnetic field?
- What drives the volcanism?
- How are the volatile ices brought to the surface and distributed?
- What is the distribution of surface materials, and how are they related to geological units?
- What are the structure and dynamics of Triton's atmosphere, and how do they vary with Triton's complex seasonal pattern?

Pluto and Charon

Pluto is both the smallest planet and the largest body in the outer solar system that is not in orbit around a giant planet. Our knowledge of Pluto and its satellite, Charon, is limited to telescopic observations. Other than the identification of certain ices on Pluto and Charon and the observation of strong variations in albedo on Pluto, little can be said about their surfaces or geology, beyond speculation based on knowledge of other icy satellites. As with Triton, Pluto's atmosphere is strongly coupled to the surface volatiles so that differences in their atmospheres result from the different nature of their surfaces. Pluto's warmer atmosphere and enhanced methane abundance are consistent with the ice on Pluto's surface containing 30 times more methane than Triton's ices and with large dark regions where the surface must be warmer. Charon's capture by Pluto probably involved a disruptive collision of the two bodies.

The outstanding issues at Pluto and Charon are as follows:

- What are the bulk densities of Pluto and Charon?
- What are the interior composition and the state of differentiation of Pluto and Charon?
- What were the effects of the initial collision and subsequent tidal stresses produced in each body as a result of Charon's capture by Pluto?
- Is there activity on the surfaces of Pluto or Charon (e.g., plumes as on Triton)?
- Are the large-scale variations in albedo on Pluto due to variations in crustal structure or frost deposits?
- What is the structure of Pluto's atmosphere, and how does it change with time?
- Why is Pluto's atmosphere so different from Triton's?

Kuiper Belt Objects

Very little is known about the approximately 60 KBOs detected to date. Measurements of their orbits suggest that many of them are in resonance with Neptune. Variations in brightness are attributed to variations in size but cannot be quantified accurately without information on albedos. Measurement of brightness at different wavelengths gives an indication of surface color and suggests that surface compositions may vary among KBOs.

Outstanding issues for Kuiper Belt objects are the following:

- What fraction of KBOs are in dynamically evolved orbits?
- What is the rate at which their orbits are perturbed sufficiently to send KBOs inward where they might interact with the giant planets?
- What does the size distribution of KBOs tell us about their accretion and erosion?
- If the range in observed colors is a true indication of diversity in surface composition, what causes this diversity?

- What is the degree of differentiation of these small bodies?

Centaurs

Other than spectroscopic observations that indicate diverse surface compositions, very little information is available about the half-dozen objects with eccentric orbits among the giant planets.

Outstanding issues for the Centaurs are these:

- How many Centaurs are there?
- What are their orbits and how did these objects get where they are?
- How did their orbits evolve from the Kuiper Belt?
- What causes their color diversity?
- Does Chiron have a bound dust atmosphere, and, if so, what are the dynamical processes?

KEY MEASUREMENTS

The key measurements that will answer the outstanding issues for these different classes of objects can be obtained by similar methods. For example, to answer questions about dynamics researchers need to determine the objects' orbits by tracking their motions precisely over months to years. To answer questions about the processes of accretion and erosion it is necessary to determine each object's size by making separate measurements of brightness and albedo. The degree of internal differentiation is indicated by studying the surface geology and measuring gravitational and magnetic fields of larger objects. The distribution of surface volatile ices is derived by combining spectroscopic measurements and multispectral imaging. Stellar occultations of major bodies such as Pluto and Triton have provided rare opportunities to detect and study the vertical structure of their tenuous atmospheres. Characterization of the distribution of atmospheric hazes, clouds, and winds requires imaging from a spacecraft that passes close to the object.

CONCLUSIONS AND RECOMMENDATIONS

Three of the thematic rationales for the exploration of the trans-neptunian region (exploration of new territory, reservoirs of primitive materials, processes that reveal the solar system's origin and evolution) involve using methods that have proven successful in the past—telescopic observations, spacecraft missions, and harnessing new technologies and human ingenuity—to push the boundaries of our knowledge beyond 30 AU. Making links to extrasolar planet detection and studies of prebiotic chemistry will require planetary scientists to take interdisciplinary approaches and to venture with astronomers, chemists, and biologists into new fields of research. *The main tasks for the next 10 to 15 years on the path to exploring the new frontier of planetary science in the distant outer solar system are to search for new objects and, more importantly, to document fully the chemical and physical makeup of the known bodies that constitute the trans-neptunian region.* Spacecraft missions, telescopic observations, and research and analysis are the categories in which COMPLEX makes its highest-priority recommendations, as well as recommendations for augmenting this baseline effort.

Spacecraft Missions

To explore the makeup of objects in the trans-neptunian region, COMPLEX recommends an approach that combines telescopic observations of the bulk properties of a large sample of Kuiper Belt objects with close-up, spacecraft studies of the detailed properties of a few specific objects. The highest scientific priority for the exploration of the trans-neptunian solar system is extensive and detailed measurement of the fundamental physical and chemical properties of the Pluto-Charon system, end members of the KBO population. Since Pluto and Charon are barely spatially resolvable from Earth, many of the relevant properties can be measured only by robotic spacecraft.

NASA's planning for a Pluto mission has undergone significant revision over the last few years. What was conceived of in the early 1990s as a Cassini-class mission requiring launch on a Titan-IV has been reformulated as a highly integrated spacecraft-payload combination capable of being launched on a Delta-II. The associated reduction in cost and the inclusion of a new start for a line of outer solar system missions in the administration's FY 1998 budget suggest that a Pluto mission is closer to realization than it has ever been since one was first conceived. Given Pluto's long rotation period (6.4 days) and the need for redundancy, COMPLEX recommends a dual spacecraft mission to Pluto. A single spacecraft would be able to observe only one hemisphere during its flyby. A second spacecraft would enable coverage of both hemispheres. Staggering the arrival times by, say, 6 months would also enable some retargeting of the second spacecraft based on results obtained during the first spacecraft's flyby.

Augmentations

Following a Pluto-Charon mission there are a number of future spacecraft projects that could be considered as part of a long-term program to explore the trans-neptunian solar system. These augmentations include:

- *Adding a flyby of a Kuiper Belt object to a Pluto-Charon mission.* The scientific potential of any Pluto-Charon mission would be greatly enhanced by the spacecraft continuing on to visit another Kuiper Belt object and thus providing measurements of the size and surface characteristics of two different KBOs that have different histories. Locating a suitable KBO along the trajectory of a Pluto mission should be a priority goal for search programs. This augmentation should be considered only if it has no serious cost or schedule impact on a Pluto-Charon mission.
- *Conducting additional missions to Kuiper Belt objects.* Objects in the trans-neptunian solar system are highly diverse, and the underlying causes for this diversity can be fully explored only by space missions. Scientific priorities for spacecraft missions to the trans-neptunian region in the more distant future, after the successful conduct of a Pluto-Charon mission and a KBO flyby, are, in rank order, as follows:

1. Returning to Triton,
2. Visiting a Centaur, and
3. Encountering a suite of Kuiper Belt objects and/or Centaurs with different spectral and/or orbital characteristics.

Spacecraft Technology

Exploration of the outermost regions of the solar system is a demanding task, especially in an era of tight financial limitations. Although considerable progress has been made in the development of new-style missions to the outer solar system, particularly Pluto flyby missions, the technological obstacles of returning substantial scientific data from >30 AU remain formidable. Although considerable cost savings can be realized by reducing the size of the spacecraft and the complexity of its instruments, missions to the outer solar system still will demand a high launch energy, have a long mission duration (>10 years), be in low sunlight, and have a long telecommunications link. Advanced missions, such as those to put a spacecraft into orbit around a trans-neptunian object or to conduct multiple flybys of different objects, will almost certainly require the use of advanced propulsion techniques. Thus, the development of mission-enabling technologies (e.g., propulsion, compact power sources, autonomous operations, active fault management, radiation-hardened electronics, and long-distance communications) is an important adjunct to any program for the exploration of the trans-neptunian solar system. In addition, compact scientific instruments capable of characterizing the physical and chemical properties of cold (<40 Kelvin), icy objects in the distant outer solar system are needed.

Telescopic Observations

Continued support for both ground- and space-based telescopic studies is an essential aspect of a program for the exploration of the trans-neptunian solar system. The highest priority for both ground- and space-based studies is significant access to existing and future moderate- to large-aperture telescopes equipped with modern instrumentation designed to meet the needs of planetary observers. Telescopes in the 2- to 4-meter class are ideally suited to searching for new KBOs. But larger telescopes (8 to 10 m) are required for spectroscopic studies of known KBOs.

Augmentations

Although access to suitable telescopes can provide much new data, with augmentations in a few critical areas ground- and space-based observations could provide even more information about the trans-neptunian solar system. These augmentations include:

- *Equipping future large space telescopes to study trans-neptunian objects.* To be capable of making the critical measurements of trans-neptunian objects, future large space telescopes should be designed from the outset to incorporate the ability to track moving targets and to measure the thermal emission from small, cold (<40 Kelvin) objects.
- *Developing instrumentation for ground- and space-based telescopes.* Studies of the statistical properties of Kuiper Belt objects would benefit greatly from the availability of large array detectors. In addition, studies of the physical and chemical properties of all trans-neptunian objects would be enhanced by the availability of high-quantum-efficiency array detectors (~1 to 10 microns for studies of reflected light and ~10 to 100 microns for studies of thermal emission), and cooled telescopes.

Research and Analysis

Continued support for research and analysis programs and for relevant theoretical and laboratory studies is an essential component of a program of spacecraft and telescopic observations of the trans-neptunian solar system. Theoretical and laboratory studies of the physical and chemical processes that influence the structure and evolution of cold (<40 Kelvin), icy bodies located in the trans-neptunian region should be fully supported to enhance the scientific return from spacecraft missions and telescopic observations.

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The New Worlds Beyond 30 AU

COMPLEX's 1994 report, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, explains that studies of the objects in the solar system are directed toward two broad goals: explaining how planets work as complex interacting physical and chemical systems, and understanding how the planetary bodies and life originated.[1] To make progress on the latter topic, it is necessary to document the chemical and physical makeup of the planetary bodies, particularly those thought to retain clues about primordial conditions and processes. These primitive materials are most likely found to be on relatively unaltered bodies such as comets, asteroids, meteoroids, and interplanetary dust grains.[2] Since the *Integrated Strategy* was written, new information has been gathered that has enhanced the scientific significance of studies of the trans-neptunian region with respect to questions related to the solar system's origins.

Several recent discoveries have opened up a new frontier for planetary science in the region beyond 30 astronomical units (AU). The Voyager 2 encounter with Neptune and its satellite Triton[3] (Plate 1) and Earth-based observations of Pluto[4] (Plate 2) have transformed our knowledge of the outer solar system. Moreover, recent observations have led to the identification of two new classes of objects, Kuiper Belt objects (KBOs) and Centaurs.[5,6] The Kuiper Belt is thought to be a disk of icy objects that are confined to within ~10° of the ecliptic plane at distances between 30 AU and hundreds of astronomical units. Centaurs are relatively small bodies (with diameters less than ~200 km) whose eccentric orbits cross the paths of Saturn, Uranus, and Neptune. Some numerical studies and new observations suggest that an additional class of bodies may also exist.[7,8] These objects, members of the so-called scattered disk, are characterized by eccentricities and/or inclinations greater than those of typical KBOs. Additional components of the distant outer solar system (e.g., dust and the Oort Cloud), as well as the planet Neptune itself, are not considered in this report.

Observations of the distant outer solar system conducted over the last few years have established a new framework in which to view the relationships among the ensemble of trans-neptunian objects: KBOs, Centaurs, Pluto, Charon, and Triton (Figure 1.1). As a class, the trans-neptunian objects are primitive compared with inner solar system objects, but they do show evidence for diversity[9] and for evolutionary processes having occurred.[10] These newly discovered objects and their relationships represent a fertile, relatively unexplored region for investigation of fundamental questions on the origin and evolution of the solar system.

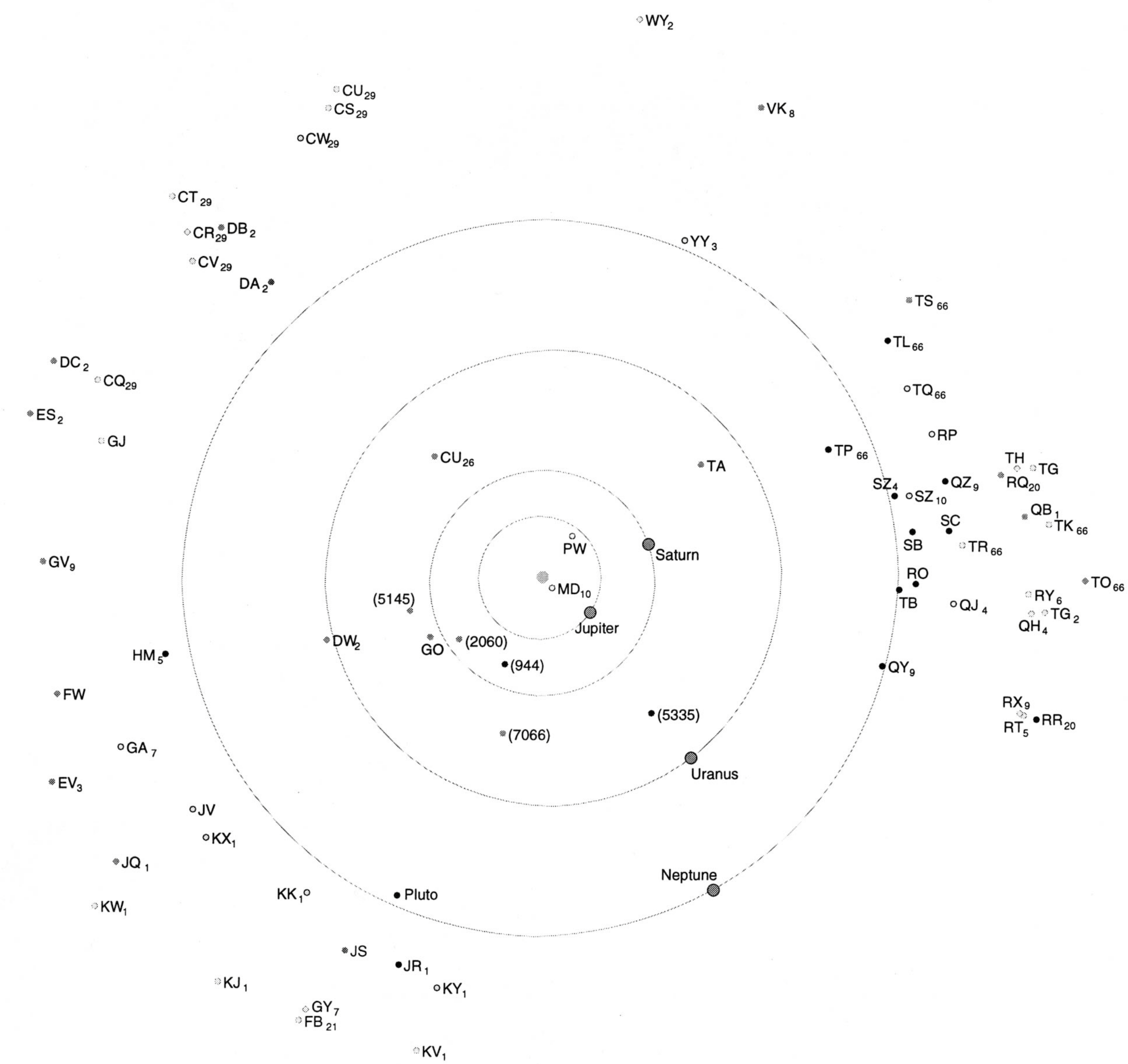

FIGURE 1.1 Map of the trans-neptunian region, October 1997. The circles indicate the orbits of the giant planets. The Kuiper Belt objects are shown in their current location with their designations (e.g., QB_1, TG_2, and so on). Note that on the scale of this map, the inner part of the Oort Cloud would be about 3 meters away from the figure. Map courtesy of Gareth V. Williams, Harvard-Smithsonian Astrophysical Observatory.

TRANS-NEPTUNIAN OBJECTS

The first KBO was discovered in 1992.[11] As of April 1998, there are some 64 known KBOs,[12] but the rate at which they are currently being discovered (10 to 15 per year) suggests that many more will be identified over the next few years. If the known KBOs have low albedos, they are typically a few tens to a few hundred of kilometers in diameter. In total there are probably tens of thousands of ~100-km bodies and many more much smaller objects yet to be discovered. Spectroscopy of a small subset of known KBOs suggests that they have diverse colors and, presumably, surface compositions.[13]

The Centaurs are an eclectic group: some members appear bluish and display cometary activity (e.g., Chiron), whereas others are very red (e.g., Pholus).[14] All Centaurs have orbits that are unstable on short time scales (millions of years). Thus, they have only recently arrived at the locations at which they are found.

Observations and theoretical calculations suggest certain relationships among trans-neptunian objects.[15,16] Roughly half of the KBOs are in stable orbits resonant with Neptune. This situation is similar to that of Pluto, whose dynamical relationship to Neptune is well established. It is therefore prudent to view Pluto and its satellite Charon as large members of the KBO population. It is also reasonable to view Triton as a KBO, considering its likely solar nebula origin, its similarity to Pluto, and the fact that it is also in a stable orbit with regard to perturbations by Neptune.

Because the inner part of the Kuiper Belt is unstable with respect to gravitational perturbations by Neptune, KBOs are suspected to be the major source for short-period comets that now reside within a few astronomical units of the Sun. The Centaurs appear to be former KBOs.[17,18] That is, they are recently departed members of the Kuiper Belt, on their way to the inner solar system. As mentioned above, Chiron displays cometary activity. It seems that a Centaur may represent an intermediate stage of dynamical evolution between KBOs and short-period comets. The observed Centaurs are larger members of this intermediate class.

Dramatic advances in our knowledge of the structure and composition of several trans-neptunian objects have taken place concurrently with advances in our knowledge of the dynamical relationships between the different classes of objects. Voyager observations of Triton and Earth-based observations of Pluto have provided information on the physical processes operating on these larger trans-neptunian objects. A suite of volatile ices has been discovered on Pluto and Triton, and it has been established that both bodies possess atmospheres. Moreover, the list of chemical compounds observed in cometary comae continues to grow, posing interesting questions about the chemical relationships between the largest denizens of the trans-neptunian region (Pluto and Triton) and the smallest (comets).

The small, volatile- and organic-rich bodies of the outermost solar system represent the frozen leftovers from planet formation in the solar nebula. As such, they 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. The ices and organic materials constituting Pluto, Charon, Triton, and the objects in the Kuiper Belt formed from solid material that originated in the molecular clouds of the interstellar medium. Chemistry on the icy grains of the interstellar medium is capable of producing the fundamental organic molecules from which life on this planet (and possibly other planets) arose. Because of the cold temperatures at trans-neptunian distances and because smaller objects are less likely to have undergone internal differentiation, the smaller KBOs are thought to have been 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. Such knowledge may open the window to our understanding of the deepest and most compelling issues of the origin of life and its possible presence elsewhere.

Progress in the last decade on the relationships among trans-neptunian objects enables the formulation of specific questions about the formation of the outer solar system and suggests spacecraft and ground-based observations capable of answering these questions. It is in this light that COMPLEX reviews recent developments in this field and attempts to establish priorities for future research. COMPLEX has identified five major themes that characterize the importance of the new worlds beyond 30 AU:

1. Exploration of new territory,
2. Reservoirs of primitive materials,
3. Processes that reveal the solar system's origin and evolution,
4. Links to extrasolar planets, and
5. Prebiotic chemistry.

A substantial body of observational studies and theoretical understanding already exists for the first three items on this list. They are all well-established areas of scientific inquiry. The last two, in contrast, are more speculative. They represent relatively new areas of inquiry where the interests of planetary scientists begin to overlap with those of astrophysicists and life scientists. Although much less is known about these themes than the other three, they suggest a number of interesting possibilities whose exploration will require an interdisciplinary approach. An additional theme, the possible effect of the trans-neptunian region on the inner solar system, is touched on briefly for completeness. It is not explored in detail in this report, because it is beyond the scope of the current study.

This report includes a general discussion of the five themes that characterize the outstanding scientific issues of the outer solar system, a review of current understanding of objects in the distant outer solar system, a description of observations that could address the outstanding issues, and a discussion of the technological developments that are necessary for these measurements. COMPLEX closes this report with recommendations for further exploration.

EXPLORATION OF NEW TERRITORY

Telescopic discoveries of new Kuiper Belt objects are being made monthly. With ongoing access to suitable telescopes, these discoveries will continue for many years since very little of the sky has been surveyed to date. While telescopes are showing us that these objects exist in the trans-neptunian region, spacecraft missions are necessary for exploring the detailed nature of these icy bodies.

The pre-telescope solar system ended at Saturn. Uranus, Neptune, and Pluto were discovered over a period of 148 years (in 1782, 1846, and 1930, respectively). In the 62 years from Pluto's discovery to 1992, Pluto's moon (Charon) and two Centaurs (Chiron and Pholus) were found. Since 1992, some 60 objects have been discovered in the trans-neptunian region (see Figure 1.1). This explosive increase in the rate of discovery is due to the enhanced capabilities of electronic cameras with large, efficient detectors on modest (2-meter) ground-based telescopes to scan relatively large regions of the sky (e.g., 60 square minutes of arc) for faint (24th-magnitude) objects.[19]

Trans-neptunian objects have very slow orbital motion and take 160 to 800 years to orbit the Sun. By observing them at opposition, when Earth's motion creates greater apparent angular motion, a change in location relative to the background stars apparent in images taken a few hours apart can be simply related to their distance. The parallactic motion of KBOs tells us that most are located at a distance between 30 and 50 AU. Without knowledge of their albedo, it is not possible to directly determine the size of each object. But assuming they have an albedo similar to that observed for cometary nuclei (0.04), their sizes are estimated to range from 50 to 400 km, although smaller bodies may have escaped detection. Searches have covered only a small fraction of the ecliptic plane (<0.1%). If planetary scientists continue to have access to suitable telescopes with appropriate instrumentation, and the current rate of discovery (about 10 to 15 objects per year) continues, then approximately 100 KBOs will be known by the end of the century. Since the number of smaller objects generally exceeds the number of larger objects, access to more powerful facilities, particularly the Hubble Space Telescope (HST) and the new generation of 8-meter ground-based telescopes, will allow the discovery of fainter (i.e., smaller, farther, or darker) objects.

Exploration of this new frontier should not be limited to telescopes. Voyager 2's flyby of Triton demonstrated the enormous value of getting close to a planetary object.[20] One brief flyby and a dozen images told us about Triton's size, mass, surface geology, surface composition, active outgassing, atmosphere, and ionosphere, and its interaction with surrounding magnetospheric plasma. The close-up view of Triton (see Plate 1) has given us a glimpse of a large Kuiper Belt object that is believed to have been captured by Neptune. The value of this information about Triton will be magnified when we have a similar level of detailed information about a Kuiper Belt object that has not been captured, such as Pluto. While HST pictures of Pluto (see Plate 2) are impressive, it must be remembered that the resolution is comparable to that of the pre-Voyager images of the Galilean satellites of Jupiter. Full exploration of the trans-neptunian region of the solar system will require spacecraft missions.

NASA's plans for a Pluto mission have undergone significant revision over the last few years. A Pluto mission was originally conceived as a Cassini-class project costing more than $1 billion. Budgetary pressures, combined with technical advances, have now pushed the estimated cost of such a mission down to such a point that the initiation of a Pluto mission in the early years of the next decade is now conceivable.

RESERVOIRS OF PRIMITIVE MATERIALS

While KBOs may not be pristine relics of the original solar nebula, it is in the outer solar system that we might expect to find the least-modified materials as well as samples that have suffered a range of degrees of modification. These bodies can provide the links for understanding the relationships among the interstellar medium, the solar nebula, and current materials in the solar system.

The material within some 30 AU of the Sun has been strongly modified by the interplay of physical and chemical processes responsible for the formation of the major planetary bodies and their evolution to their current state. The trans-neptunian region is by far the largest part of the solar system (see Figure 1.1), and it is likely that those expanses retain clues regarding the formation and evolution of our solar system.[21] Materials originally formed and processed in the interstellar medium (ISM) are believed to have been incorporated into the early solar nebula (Plate 3, top right). The gases and dust of the early solar nebula probably accreted into relatively small planetesimals (<10 km) that then accreted to form larger bodies (>100 km). Some of the accreted bodies formed the cores of the giant planets. The gravity of these cores led to the capture of nebular gases by Jupiter and Saturn.

In the inner solar system, the growth of the planetesimals to Earth-size bodies occurred in a largely gas-free environment over a period of approximately 100 million years. Formation of the cores of the giant planets, however, required the runaway growth of objects of some 10 Earth masses prior to the removal of the remaining gas from the solar nebula. Thus, accumulation must have taken place at a much faster rate (~10^6 to 10^7 years for Jupiter and Saturn and somewhat longer for Uranus and Neptune) in the outer solar nebula than in the inner solar nebula. Comets and the trans-neptunian objects are the relics of bodies in the outer solar system that failed to be incorporated into the giant planets during the runaway growth of their cores. During and after the accretion of Uranus and Neptune, most of the remaining planetesimals and larger objects in this region were ejected from the solar system or stranded in the Kuiper Belt (Plate 3, bottom). Beyond Neptune a fraction of the initial planetesimals and smaller protoplanets probably remain in the region in which they formed.

Various physical and chemical processes operated within the solar nebula, such as the mixing of nebular material with infalling gas and grains, ultraviolet processing of materials, and condensation of volatiles (Plate 3, upper left). The condensed grains must have formed aggregates, but the process whereby the grains stuck together is poorly understood. Low-velocity micron- and submicron-size particles readily stick to each other or to surfaces. They stick because their large surface-area/mass ratios enhance the effectiveness of surface forces (e.g., van der Waals, electrostatic forces, adhesion, and so on). The aggregation of centimeter-size and larger particles is more of a mystery. It has been suggested that either carbonaceous or siliceous grains with a mantle of carbon compounds could have been "sticky" enough for accretion, but this is unlikely in the context of the cold environments in the outer solar system. An alternative model suggests that the growth of fluffy, fractal-like structures is the primary accumulation process for solids. Porous particles yield inelastic collisions where fine-grained components absorb the kinetic energy of the impact.

Figure 1.2 illustrates the processing and ultimate fates of the interstellar material that was incorporated into the solar nebula. Dynamical processes such as accretion, gravitational perturbations, and collisions resulted in the planetesimals ending up in very different parts of the solar system. Those objects likely to retain some information related to the initial materials incorporated into the solar nebula are the icy planetesimals represented by comets, Kuiper Belt objects, Centaurs, and possibly some asteroids.

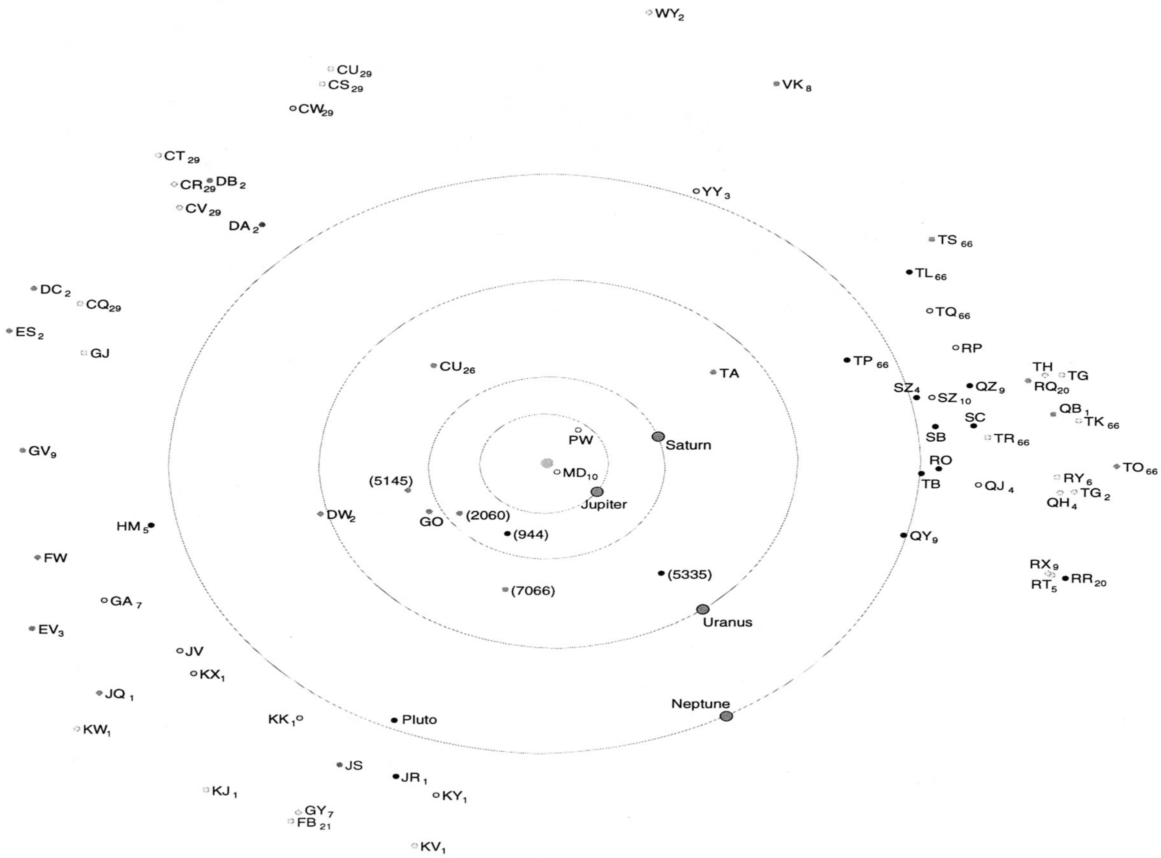

FIGURE 1.2 An evolutionary tree for planetesimals. At the top of the tree are the materials that originally formed in the interstellar medium. As one goes downward along the tree, the materials become incorporated into the solar nebula and eventually the growing planetesimals. At the bottom of the tree, the planetesimals undergo several processes that can result in their being incorporated into various objects currently recognized in the solar system. Figure courtesy of Dale Cruikshank, NASA Ames Research Center.

Most of the inner solar system is devoid of remnants of these planet-building bodies. Some remnants remain in the asteroid belt, but because of their relative proximity to the Sun their surfaces may have been altered by external processes (e.g., collisional events, incident solar energy, and so on). Internal processes (e.g., differentiation) may also have occurred due to their relatively rock-rich composition. Moreover, the relatively high temperatures experienced by bodies in the inner solar system imply that fewer volatile components of the early solar system are retained in asteroids. In contrast, the Kuiper Belt's greater distance from the Sun implies minimal processing and dynamical perturbation, which leads to confidence that KBOs formed fairly close to where they are found today. Thus it is possible that the Kuiper Belt holds a sample of planetesimals that have suffered less modification.

Comparison with asteroids is important because KBOs are believed to contain volatiles that have been largely lost from asteroids. Comparison with Centaurs and comets is important because KBOs are thought to have remained more or less in place in the outermost regions, whereas Centaurs and comets have undergone large variations in their distance from the Sun.

PROCESSES THAT REVEAL THE SOLAR SYSTEM'S ORIGIN AND EVOLUTION

The observable characteristics of objects tell us about the processes they have experienced. The distribution of a population of objects in orbital phase space provides clues about their origins and the dynamical processes that control them over long periods. The distribution of sizes within a population reveals the relative importance of accretion versus collisional erosion. The wide range of sizes and different collisional histories among objects in the trans-neptunian region implies varying degrees of internal differentiation. Surface geology provides important constraints on an object's thermal history. Surface chemistry and atmospheric properties reveal processes of outgassing, photochemistry, transport, and redeposition of volatiles.

The physical and chemical characteristics of objects in the outermost region of the solar system provide clues about the physical and chemical processes they have experienced. The smaller bodies of the outer solar system pose an interesting problem: Are they basically primitive, or have they been significantly modified? Spectroscopic evidence suggests that the KBOs are not pristine and have suffered some surface processing, and the diversity of their colors implies a wide range of degree of modification.[22] Since researchers believe that the accretion of these objects was arrested in the early stages of solar system formation, studies of the dynamics, geology, surface chemistry, and atmospheres of KBOs may provide the best opportunity to probe the processes that occur during this phase.

Dynamics

KBOs are widely believed to be the source of short-period comets.[23,24] Many of the detected KBOs seem to be, like Pluto and Charon, in the "safe havens" of orbital resonance with Neptune. The Centaurs are a dynamically separate family of objects in unstable orbits whose semimajor axes fall between Jupiter and Neptune. Centaurs may be bodies that have been dislodged from the Kuiper Belt region and are in the process of being scattered by the gravitational effects of the giant planets. Their dynamical lifetimes are measured in millions of years, clearly separating them from the much more stable objects in the Kuiper Belt. The degree of orbital evolution of the trans-neptunian objects tells us about their orbital history, their relationship to Neptune, and possibly Neptune's orbital evolution.

The size distribution of KBOs is expected to be the net result of a combination of accretion into larger objects and collisional erosion into smaller objects.[25] Recent observations already suggest that the size distribution of KBOs is complex and has a different form for the smaller objects (radius <100 km) as compared to the larger objects (radius >100 km). For objects with a radius of ~100 km, the distribution is relatively flat, suggesting that objects smaller than 100 km across are eroding whereas larger objects may still be accreting. Moreover, there is a jump from the largest KBOs (radius <400 km) to Pluto and Triton (radius >1,000 km), which may reflect a real gap in the sizes of these objects or may instead be owing simply to the incompleteness of observations.[26]

If the shortage of objects with a radius of >400 km is real, then this suggests that Pluto and Charon may be the result of runaway accretion, i.e., that they accumulated much of the available material, denying other planetesimals the chance to grow to comparable size. The size distribution of objects in the trans-neptunian region provides vital information about the collisional processes that lead to erosion or accretion of material and how these processes vary with size of the object, its location, and time.

Geology

Voyager images of the icy satellites of the giant planets suggest that the level of geological activity depends on composition, silicate content (which leads to radioactive heating), and the presence or absence of tidal heating.[27] Further complications arise if relatively large impacts have disrupted the satellites in question: a situation argued to occur for moons close to their parent giant planets whose strong gravity focuses impactor trajectories or for satellites that may have undergone major collisions during capture.

For Kuiper Belt objects, low-melting-point ices are expected, but the amounts and types are uncertain. Internal reworking may have been powered by radioactive heating alone if low-melting-point ices (e.g., ammonia) were sufficiently abundant to lower the viscosity and allow the ice-rock mixture to creep. However, the amounts of radiogenic elements and low-melting-point ices in the KBOs are not known. Tidal heating is less important for KBOs, but collisions have affected the dynamically evolved, inner portion of the Kuiper Belt. Thus, the larger KBOs may have been sufficiently heated during earlier epochs to be at least partially differentiated. Collisions may even have broken up the objects, exposing these interiors to view in much the same way that the asteroids today reveal the separation of rock and metal in an earlier generation of inner solar system planetesimals.

Thermal stresses caused by internal heating and by subsequent exothermic crystallization of ices may have resulted in fractures that vented volatiles to the surface and to space. Loss of surface volatiles during impacts might have increased the concentration of rocky or organic materials. The strong magnetic field associated with the Sun in its T Tauri phase may have generated substantial currents in planetesimals, heating the interiors by electromagnetic induction. It is possible, therefore, that even the smaller objects in the trans-neptunian region could be differentiated. Comparison of the mean density and surface composition of these objects would provide clues about their interiors and their thermal histories.

Surface Chemistry

Having formed in the outer regions of the solar nebula at temperatures of only 40 to 50 Kelvin, trans-neptunian objects are thought to possess interiors rich in molecular ices (H_2O, CO_2, CO, and N_2). The composition of icy planetesimals can be used to identify and understand the degree of chemical heterogeneity of the solar nebula and the chemical evolutionary processes that have acted on these objects. Currently, although the color of some of the KBOs has been measured,[28] there is little information about their surface compositions, and it is useful to consider the Centaurs Pholus and Chiron as illustrations of how comparison of surface composition may provide information about the different surface processes experienced by trans-neptunian objects. If it is assumed that both Pholus and Chiron began with similar complements of surface materials, then the observed strong difference in color and near-infrared spectral features suggests that these bodies experienced very different processes that produced their current surface compositions.

As illustrated in Plate 4, light hydrocarbons (e.g., methane and methanol) can be converted to materials that are relatively enriched in carbon. This chemical transformation tends to eliminate spectral features associated with certain molecular vibrations, and it results in materials that have low albedos and spectra relatively devoid of features. Thus, for example, the observed spectral signature of light hydrocarbons on Pholus indicates that its surface has been less chemically processed than that of Chiron.

Dynamical analysis of the chaotic orbit of Chiron suggests that it has been relatively close to the Sun for much longer than Pholus, and may once have been a short-period (Jupiter family) comet.[29] This would have exposed the surface of Chiron to higher thermal and solar ultraviolet flux, providing a mechanism for transforming any original light hydrocarbons to more spectrally neutral organic solids.

An alternative explanation would be that Chiron and Pholus were originally formed in different parts of the solar system from different materials. The few measurements of KBOs show a wide dispersion in optical color, indicating non-uniform surface properties. Statistical studies of the surface characteristics of many objects, combined with understanding of their dynamical histories from orbital studies, will help to distinguish between variations in original composition and different degrees of surface processing.

Atmospheres

Pluto and Triton have tenuous atmospheres with surface pressures of about 10 microbars.[30,31] The compositions of these atmospheres are related to these objects' surface compositions, an important clue to their origin. These atmospheres tell us that the objects are venting and losing volatiles, an important evolutionary process.

Trans-neptunian objects may have tenuous atmospheres because the cold temperatures in the outer solar system permit the existence of volatile ices on the surfaces. A cometary (i.e., gravitationally unbound) atmosphere has, for example, been detected on the Centaur, Chiron. Claims of the existence of a bound dust atmosphere about Chiron remain controversial.[32] Such a feature is both difficult to explain theoretically and difficult to observe, being beyond the resolution of all telescopes other than HST. The extent of a bound dust atmosphere will depend on Chiron's mass and on the density/size ratio of the dust grains (i.e., how much solar radiation pressure can perturb them). If such an atmosphere is real, careful measurements of its extent and the colors of Chiron's coma (to infer grain sizes) may give a direct estimate of the Centaur's density. The smaller KBOs cannot possess a gravitationally bound gaseous atmosphere, but outgassing events are possible. For the larger KBOs, bound dusty atmospheres may be a possibility, given the similarity in size to Chiron.

The atmospheres of trans-neptunian objects are an important aspect of volatile evolution. Although the low temperatures beyond Neptune have permitted trans-neptunian objects to retain many ices, the more volatile species still can be lost through atmospheric escape. It is likely that atmospheric escape has affected the budget of volatiles on Pluto and Triton. Moreover, as the orbits of some trans-neptunian objects evolve inward, increased outgassing at higher temperatures (as on Chiron) will alter the inventory of volatiles. Understanding these processes is essential to investigations of the chemical compositions of objects in the trans-neptunian region and to understanding the effects of volatiles delivered to the inner solar system by comets.

Atmospheres present a unique opportunity for the study of the composition of trans-neptunian objects. Studies of cometary comae show how the composition of the parent body can be measured from the evolved gases to a degree that is not possible with spectroscopy of the surfaces. Moreover, chemical processes occurring in an atmosphere influence the surface composition of a body. The simplest example of this process is the photochemical destruction of methane in the atmospheres of Pluto and Triton. Although photochemical by-products have yet to be found, there is every reason to believe that destruction of methane leads to the creation of more complex organic molecules, implying that atmospheres can play a role in the inventory and form of organic material in the trans-neptunian region.

LINKS TO EXTRASOLAR PLANETS

Some of the nearby stars similar to the Sun are surrounded by disks of dust that are thought to be derived from collisions between comets. It is natural, therefore, to relate such dust disks to the Kuiper Belt. Applying knowledge of the Kuiper Belt to stellar dust disks suggests that the inner boundary exhibited by some disks may be an indication of the existence of planets. Comparisons of the Kuiper Belt with these dust disks is an important component of the new field of comparative studies of solar systems.

It has been known for more than a decade that some stars, including ones similar to the Sun, are surrounded by extended disks of dust. These dust disks are distinguished by their extra infrared emissions as observed by the Infrared Astronomical Satellite (IRAS). The dust is probably derived from colliding and sublimating comets. It is only natural, therefore, to draw parallels between the dust disks around other stars and the Kuiper Belt.[33]

From our vantage point on Earth, looking out through the Kuiper Belt, we are not yet able to detect the disk of dust that has presumably been produced by collisions between KBOs. Space-based instruments being designed for detection of extrasolar planets from orbits beyond Mars (where there is less interference from zodiacal light) might be capable of detecting our own dust disk.[34] Furthermore, it is interesting to note that many of the dust disks around other stars appear to have an inner edge, similar to the inner edge of the Kuiper Belt.[35] Since the inner boundary of the Kuiper Belt is thought to be carved out by the dynamical influence of Neptune, it seems reasonable to infer that extrasolar dust disks with inner boundaries indicate the presence of planets.

PREBIOTIC CHEMISTRY

As remnants of the early solar system, trans-neptunian objects can provide critical clues about processes of prebiotic chemistry and about the materials that would have been delivered to the early Earth. Such material may have been the source of volatile materials from which life arose here and possibly on other planets of this and other solar systems.[36]

The evolutionary process from primordial chemical systems to current biological systems is poorly understood. The process must, however, encompass the transition from simple chemical reactions involving a wide range of simple chemicals to a morphological chemical diversity antecedent to biological systems. Current life on

Earth is characterized by a relative uniformity of biochemical processes, i.e., domination by a few elements—carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur (CHNOPS)—and the same processes being continuously repeated in many places. Before life began, there must have been a period of chemical evolution in which the primordial chemical diversity underwent a process of selection that eventually led to self-organizing chemical systems. The low temperatures found in the outermost regions of the solar system inhibit chemical interactions, and such regions thus are likely to preserve evidence of this diversity.

Kuiper Belt objects may be repositories of evidence about the process of solar system formation and may offer insights on how the biogenic elements (CHNOPS) and their compounds can affect the formation of the planets themselves. The Kuiper Belt should be the place to find evidence of carbonaceous materials that may have played a role in the aggregation of grains in the early solar nebula. Even though a direct relationship between these carbon compounds and the chemistry of life has not been demonstrated and remains controversial, it is possible that some of the compounds essential for life may have been essential to planetary formation as well. As such, it may be that the existence of Kuiper Belt objects about a star could be an indication that prebiotic chemical evolution might also be occurring in that solar system. Observational programs designed to detect extrasolar planets might someday provide information that could be correlated with the distribution of life elsewhere in the galaxy.

EFFECTS OF THE TRANS-NEPTUNIAN REGION ON THE INNER SOLAR SYSTEM

Objects from the trans-neptunian region are periodically perturbed into the inner solar system, where they are likely to play an important role as a source of volatiles and as potential impactors.

There is mounting evidence, both from modeling and from measurements of terrestrial samples carrying mantle-derived gases (e.g., basalts from mid-ocean ridges), that the initial noble-gas inventories on and in Earth were similar to those of the Sun.[37] If so, where did these gases come from? The noble gases trapped in most meteorites, for example, have a nonsolar isotopic composition. Many possible sources have been suggested. These include accreted material irradiated by an early solar wind; direct adsorption of solar-composition nebular gases on planetary accretion cores or on preaccretion dust; and low-temperature occlusion of nebular gases in icy bodies from the outer solar system which were later perturbed inward and rained down on the inner planets. While the concept of an icy-planetesimal source has many supporters, it is somewhat ad hoc because the noble-gas abundances of trans-neptunian objects have not been observed directly.

In addition to their role as possible conveyors of volatile materials to the inner solar system, the trans-neptunian objects perturbed into the inner solar system (i.e., comets) have a finite probability of colliding with planetary surfaces. In doing so, these impactors not only influence the formation and evolution of planetary surface features, but also may possibly influence the evolution of living organisms. A prime example of this is the theory that the mass extinction of dinosaurs and other species at the end of the Cretaceous period was triggered by a cometary impact.

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2

Current Knowledge and Outstanding Issues

The amount of information available about individual objects in the trans-neptunian region is highly variable. The most extensive are available from the Voyager 2 spacecraft's encounter with Triton, but only telescopic observations are available for Pluto, Charon, the Centaurs, and the KBOs.

TRITON

Triton is by far the best-explored icy body in the distant outer solar system[1] and, as such, sets the context for the discussion of the other bodies. Triton is in an inclined, retrograde orbit around Neptune, which suggests that it was captured. Triton is a rock-rich icy body, with the fraction of rock approaching 70% by mass. It is the only satellite other than Titan with a substantial atmosphere. It also has a complex seasonal cycle, leading to the possibility of climatic changes on a wide range of time scales. Only about 180 impact craters were detected at Voyager resolution (1 km/pixel), suggesting that Triton's surface is relatively young. Within the region observed in detail by Voyager 2's cameras, Triton exhibits a wide array of features produced by tectonic, volcanic, and atmospheric processes (see Plate 1). As with other icy satellites, the energy sources for the volcanic and tectonic activity on Triton are not well understood, but they may involve catastrophic tidal heating associated with Triton's capture from solar orbit in the distant past.

Triton's Interior

Voyager 2's observations revealed that Triton's mean density is 2.06 g cm^{-3} (Table 2.1). This density, combined with surface spectroscopy and theoretical considerations, suggests that Triton is composed of silicates, water ice, organic materials, and other ices with low melting points (e.g., N_2, CH_4, CO_2). If Triton had suffered a major collision(s) with other neptunian satellites at the time of capture,[2] then its interior would have been disrupted. It is not clear, however, whether a collision with a satellite would lead to a higher or lower bulk density. Triton probably is differentiated into a rocky core surrounded by a mainly water-ice mantle. The case for differentiation of Triton's interior is based both on the large rock fraction, which enhances radioactive heating of Triton's interior, and on tidal heating of the interior during the circularization of its orbit following capture from a heliocentric orbit. The icy mantle is probably about 400 km thick and may include a large organic fraction.[3]

TABLE 2.1 Physical Properties of Pluto, Charon, and Triton

Object	Distance from Sun (AU)	Radius (km)	Mass (10^{21} kg)	Density (g cm^{-3})	Estimated Percent Rock (by mass)
Pluto	29.7-49.5	1168 ± 33[a]	13.14 ± 0.18[a]	1.79-2.17[a,b,c]	50-70[d]
Charon	29.7-49.5	626 ± 24[a]	1.62 ± 0.09[a]	1.33-1.87[a,b,c]	<60[d]
Triton	29.86-30.28	1352.6 ± 2.4[e]	21.398 ± 0.053[e]	2.053-2.076[e]	65-72[e]

SOURCES:

[a]G.W. Null and W.M. Owen, Jr., "Charon/Pluto Mars Ratio Obtained with HST CCD Observations in 1991 and 1993," *Astronomical Journal* 111:1368, 1996.

[b]L.A. Young et al., "The Charon-Pluto Mars Ratio from MKO Astrometry," *Icarus* 108:186, 1994.

[c]J.A. Foust et al., "Determination of the Charon-Pluto Mars Ratio from Center-of-Light Astrometry," *Icarus* 126:362, 1997.

[d]W.B. McKinnon, D.P. Simonelli, and G. Schubert, "Composition, Internal Structure, and Thermal Evolution of Pluto and Charon," *Pluto and Charon*, S.A. Stern and D.J. Tholen, eds., University of Arizona Press, Tucson, Arizona, 1997, p. 347.

[e]W.B. McKinnon, J.I. Lunine, and D. Banfield, "Origin and Evolution of Triton," *Neptune and Triton*, D.P. Cruikshank, ed., University of Arizona Press, Tucson, Arizona, 1995, p. 807.

Triton's Surface

About 30% of the surface of Triton was imaged by Voyager 2 at resolutions ranging from about a kilometer to tens of kilometers (see Plate 1). The geology of the imaged portion is among the most complex and varied of any of the solar system's icy satellites.[4] There is no evidence for preserved ancient heavily cratered terrain, which implies that Triton was internally active for at least several hundred million years following its formation. The total crater population is low and indicates an average age for Triton's surface on the order of several hundred million years. This is a relatively short time and suggests that Triton has been internally active in the recent past and may still be active.

Most of the surface of Triton appears to be composed of materials that have erupted from the interior, and many of the landforms present are clearly of cryovolcanic (i.e., ice eruption) origin. This observation supports the interpretation of continued internal activity. A crude stratigraphy has been defined. The enigmatic "cantaloupe terrain," a complex landscape of pits, ridges, and troughs, is the oldest part of the preserved surface. Superimposed on this terrain are smooth materials in the valley floors. The youngest materials, of presumed endogenic origin, make up walled plains. The bright surficial materials, generally considered to represent ephemeral frosts condensed from the atmosphere, are not thick enough to obscure the underlying geological material units. The dark materials are thought to be carbonaceous materials, possibly vented from the interior.

The degree of differentiation of the interior of Triton is a major issue. A generally accepted model for the history of Triton includes its capture from solar orbit by Neptune.[5] The initial capture may have involved gas drag with the protoneptunian nebula (if captured early) or collision with one or more satellites (if captured after satellite formation).[6] In either case, the subsequent circularization of Triton's orbit would cause significant tidal heating, melting, and differentiation. Alternatively, it is possible that Triton's youthful geology may have been powered by radiogenic heating alone if low-melting-point ices (e.g., ammonia) were sufficiently abundant to lower the viscosity of the upper layers and allow the crust to creep. A greater understanding of Triton's surface geology and interior structure could provide evidence of Triton's thermal history. It would be interesting to compare Triton with Pluto, which is not believed to have been heated tidally but has probably undergone a major collision with Charon.

Triton is one of three places (with Earth and Io) in the solar system where active eruptions have been seen. Voyager images revealed dark eruptive plumes—geysers—which were highly collimated and roughly 1 km in diameter, rising vertically from the surface.[7] At an altitude of ~8 km, the ascending material was abruptly sheared laterally, and the aerosols were carried horizontally for ~100 km by prevailing winds. The amount of mass injected into the atmosphere by the geysers at the time of the Voyager encounter was small relative to the seasonal interhemispheric mass transport, but very large by geological standards. If the geyser activity persists over geological time, it is likely to be one of the dominant processes controlling the nature of Triton's atmosphere and surface. Only two plumes were unambiguously identified by Voyager, although there was evidence for several more "spent" geysers. The observed plumes appeared to be clustered near the subsolar latitude, but this was also one of the best-observed regions of the planet, and the apparent correlation may be due to a selection effect.

An unresolved controversy is the energy source for production of the geysers. Some believe that the geysers represent true volcanism, with the heat coming from the interior of Triton. Others have suggested that the features are surficial, with most of the energy being solar heating. In the latter case, infrared radiation is trapped under an ice "lid" by a solid-state greenhouse effect. In either case, the geysers' existence depends on the presence of highly volatile ices beneath the surface. Determination of the extent, vigor, duration, geographic distribution, and energy source for the geysers is of fundamental importance. Knowledge of this process is essential to understanding the evolution of the atmosphere, and the process may represent the link between Triton's interior and its surface-atmosphere system.

Earth-based spectroscopic observations reveal that Triton's surface is covered by a variety of volatile ices.[8] The spectra imply that N_2 is the dominant ice species with trace amounts (<1% by mass) of CO, CH_4, and CO_2, if the surface grains are mixed at the granular level. Greater amounts of CO_2 may be present if the CO_2 occurs as a discrete component not mixed with the other ices at the granular scale. Water ice has been detected, but its relative abundance is currently unknown. The CH_4 is present as a dilute contaminant within N_2 ice. Unfortunately Voyager 2 did not have the instrumentation to identify these molecules, and consequently their geographic distribution can only be guessed at.

Voyager did discover extensive deposits of bright material covering most of Triton's southern hemisphere. Because ground-based spectroscopy indicates that N_2 is the most abundant ice, the extensive bright deposits may well be an N_2 polar cap. Curiously, Triton's summer hemisphere was in the midst of a so-called major summer at the time of the Voyager encounter, and so the existence of extensive frost deposits at this location is difficult to understand.[9] Many theories have been offered, but with the information at hand none of the explanations is truly compelling.

Triton's Atmosphere

Voyager 2's flyby provided the first accurate measurement of Triton's surface temperature (38 ± 3 Kelvin) and definitive evidence of a thin atmosphere with a surface pressure of 14 microbars.[10] Voyager observations showed that Triton's atmosphere is complex. Combined Voyager and ground-based spectroscopic data suggest that Triton's atmosphere is predominantly N_2 with trace amounts of CH_4, H_2, and CO, consistent with the detected surface ices. Recent ground-based spectroscopic observations have yielded an N_2 ice temperature of 38.3 ± 1 Kelvin, in agreement with the surface temperature measured by Voyager.

Discrete clouds and pervasive hazes as well as aerosols from the geysers were observed by Voyager 2. The cloud motions and features on the surface interpreted as wind streaks indicate a circulation pattern that is consistent with the expected seasonal transport at low altitudes but that abruptly changes direction within the first 10 km above the surface. The implication is that the equatorial atmosphere is warmer than the polar atmosphere, but there are no observations that test this hypothesis.

The following properties of Triton's atmosphere were derived from Voyager data:

- The lower atmosphere at summer latitudes has a saturated adiabatic lapse rate (about –0.1 Kelvin km^{-1});
- N_2 clouds exist; and
- A 37-Kelvin tropopause exists at about 8 microbars (8 to 12 km).

Recent ground-based stellar occultation measurements suggest that part of Triton's lower atmosphere may be isothermal at 0.1- to 1-microbar pressures.[11] Above this level, Triton has been inferred to have a thermosphere with temperature rising to an isothermal value near 96 to 102 Kelvin at ionospheric heights (200 to 400 km) due to solar extreme ultraviolet radiation and magnetospheric energetic electron heating.[12] Heat is conducted down to the tropopause or surface and also partially radiated away by CO. Based on the temperature profile, Triton's extended atmosphere is inferred to have an exobase located at 750 to 800 km, above which thermal escape of light species occurs.

The hazes in Triton's atmosphere are thought to be the result of photochemistry. Photolysis of methane and molecular nitrogen produces complex hydrocarbons and nitriles. These photochemical products are produced at a rate that results in partial pressures larger than their vapor pressure at the ambient atmospheric temperature; consequently, the photochemical products condense, creating atmospheric hazes. Voyager observations and inferences concerning photolysis rates, haze properties, sedimentation rates, and geographical and vertical distributions are consistent with this general picture.

Discrete cloud formation is more difficult to understand. Because the clouds are confined to the troposphere where N_2 is near its saturation point, the clouds are generally thought to be composed of N_2 ice; however, too little is known about the temperature, distribution of volatiles, and wind fields on Triton to develop a detailed understanding of the generation and geographical distribution of the clouds. What is clear is that the properties of the atmosphere are dependent on surface conditions and that the atmosphere is an essential element of the volatile cycle: to understand the distribution and transport of volatile ices, researchers need to understand the atmosphere.

Voyager radio occultation measurements showed a well-developed ionosphere on Triton with peak electron densities of about 2 to 5×10^4 cm^{-3} at 340 to 350 km and, above the peak, plasma scale heights of about 260 to 300 km. Identification of the major ion is still a subject of debate; it may consist of one or more of three abundant atomic ions: H^+, C^+, and N^+.[13]

Although we have little detailed knowledge and a small number of observational constraints on the photochemistry of Triton's atmosphere, we do know enough to recognize that Triton's atmosphere is in an interesting regime. Its atmospheric temperatures are much lower than those in other planetary atmospheres. As a consequence, many neutral chemical reactions, which typically have energy barriers, are inhibited so that ion-neutral reactions and reactions on aerosol surfaces assume increased importance. The dominance of ion-neutral reactions is well established in the chemistry of the interstellar medium, where they play an important role in helping to shape the composition of molecular clouds, the raw material for solar system formation. Thus, Triton presents us with a nearby environment in which researchers can study these processes.

Interactions Between Triton and Neptune's Magnetosphere

A major source of plasma in Neptune's magnetosphere is thought to be thermal escape of neutral H, H_2, and N from Triton's upper thermosphere (10^{25} nitrogen and 10^{26} hydrogen atoms sec^{-1}). Because Neptune's magnetic field is highly tilted with respect to the planet's spin axis, Triton encounters a large range of magnetic latitudes as it moves through Neptune's magnetosphere. Each pass through the magnetic equator subjects Triton to an energetic electron energy flux that is about 20 times larger than the solar extreme-ultraviolet energy flux. Some of these electrons enter the upper atmosphere and deposit power estimated to be as large as 10^8 watts.[14] Significant magnetospheric energetic electron power input is suggested by the high thermospheric temperature (~100 Kelvin), the large inferred nitrogen atom escape rate, and the high peak electron densities. At the same time, the magnetospheric plasma bombards and alters the satellite's lower atmosphere and surface.

PLUTO AND CHARON

Pluto remains the only planet not visited by a spacecraft. Nonetheless, some information is available from telescopic observations, including detailed studies of the 1985 to 1990 series of mutual eclipses and transits ("mutual events"), stellar occultations, radiometric measurements, near-infrared spectra, and ground-based and HST images (see Plate 2). These observations provide reasonably accurate estimates of size, albedo, system mass, surface composition, atmospheric pressure (upper limits) and composition, and surface temperature, as well as crude albedo maps.[15]

Interiors of Pluto and Charon

Models of the interiors of Pluto and its satellite Charon are based mainly on knowledge of their radii and masses.[16] Radii have been determined by observations of stellar occultations and mutual events, and from study of HST images (see Table 2.1). The relative masses of Pluto and Charon can be determined from observations of their motions about the system's center of mass.[17] Such observations reveal that Pluto is approximately twice the diameter of Charon and eight times more massive. The uncertainties in the radii and masses suggest that the mean densities of Pluto and Charon are in the range from 1.79 to 2.17 g cm^{-3} and 1.33 to 1.87 g cm^{-3}, respectively (see Table 2.1).

Based on cosmochemical relative abundances and these densities, Pluto and Charon are inferred to be mixtures of mainly water ice and rock (i.e., silicates). Pluto's density corresponds to that of a rock-rich body, while the uncertainty in Charon's density allows for either rock-rich or ice-rich composition. The large uncertainties in the densities of Pluto and Charon mean that the percentage of rock is much less constrained for these bodies than for Triton (see Table 2.1). An additional major unknown about the interiors of Pluto and Charon is whether the ice and rock are essentially homogeneously mixed (i.e., no differentiation) or the rock has separated from the ice to form a rocky core surrounded by an ice mantle (i.e., differentiation has occurred). A collisional capture and subsequent orbital evolution would imply substantial melting of the interior. An intriguing possibility for the interior of Pluto is that it might contain amounts of relatively refractory organic solid.[18]

Surfaces of Pluto and Charon

Some 12 major "regions," where the surface is either bright or dark, can be discerned in HST images of Pluto (see Plate 2). These images show that Pluto is an unusually complex object, with more large-scale contrast than any planet except Earth. Some of the variations across Pluto's surface may be caused by topographic features such as basins or fresh impact craters. However, most of the surface features unveiled by HST, including the prominent northern polar cap, are likely produced by frosts that migrate across Pluto's surface in response to its orbital and seasonal cycles and chemical by-products deposited by Pluto's atmosphere.

Earth-based spectroscopic observations show that Pluto's surface, like Triton's, is covered with ices and relatively volatile compounds.[19] Current models of the reflectance spectra suggest that N_2 is the dominant species on Pluto, with trace amounts (<2% by mass) of CO and CH_4, if the surface grains are mixed at the granular level. Water ice has been detected but is not yet incorporated into models; thus its relative mass fraction at the surface is currently unknown. As on Triton, the positions of the CH_4 absorption bands do not correspond to those of pure CH_4. However, the bands appear broader than those seen on Triton and suggest two reservoirs of CH_4. One CH_4 reservoir is perhaps a solid solution within the N_2 ice (as is suspected for Triton); the other reservoir may consist of discrete locations on Pluto's surface composed of relatively pure CH_4. Unlike the case for Triton, no evidence has been found for CO_2 ice on Pluto or Charon.

Earth-based spectroscopic observations indicate that H_2O ice is present on Charon. There also appears to be a relatively dark, spectrally neutral material that lowers the overall albedo throughout the visible and near infrared. Due to the low spectral resolution of the existing data, other volatile species such as N_2, CO, and CO_2 may be present on Charon and yet remain undetected.

Pluto's Atmosphere

Pluto's atmosphere was first detected during a stellar occultation observed at various ground-based observatories and from the Kuiper Airborne Observatory.[20] Observations of the occultation yielded a ratio of temperature to mean molecular mass (T/μ) of ~3.6 Kelvin amu^{-1}. In striking contrast, stellar occultations by Triton at the same microbar pressure levels yield temperatures at least a factor of 2 lower, $T/\mu \sim 1.6$ Kelvin amu^{-1}. If Pluto has an N_2 atmosphere, the implied isothermal temperature is ~100 Kelvin.

A remarkable feature of the Pluto occultation data is the "knee or kink" (change in slope) in the light curves at a radius of 1,215 ± 11 km (about 2 microbars). This feature has been variously interpreted as evidence for the following:[21]

1. A haze layer with an extinction optical depth of >0.15,
2. A steep temperature inversion with a gradient of 10 to 30 Kelvin km^{-1} at the surface, or
3. The same steep temperature gradient on top of an underlying troposphere of moderate depth (<40 km).

In other words, researchers cannot ascertain whether Pluto has a thin atmosphere (e.g., 3 microbars surface pressure) or a thicker one (albeit only 100 microbars). An increased surface pressure would correspond to a smaller radius and thus a higher mean density for Pluto.

The density and thermal structure of Pluto's upper atmosphere and ionosphere are unknown. At the microbar level, it is probably the least gravitationally bound N_2 atmosphere in the solar system, and it could, potentially, be a hydrodynamically escaping atmosphere. At the very least, light constituents such as H, H_2, C, CH_4, and N are probably escaping rapidly, and some of these gases may be captured by Charon.

Knowledge of Pluto's atmospheric composition is limited. From its spectrum in the 1.6-micron region, a CH_4 column density of about 3×10^{19} cm^{-2} was inferred.[22] Other atmospheric species, in particular N_2 and CO, must be estimated from vapor pressure equilibrium considerations. By analogy with Triton, N_2 is expected to be the dominant atmospheric gas. The spectroscopic N_2 ice temperature is 40 ± 2 Kelvin on Pluto,[23] which implies surface N_2 atmospheric pressures in the range from 18 to 157 microbars, assuming vapor pressure equilibrium. From the observed abundance of CO ice, the atmospheric CO mixing ratio is inferred to be about 5×10^{-4}.[24]

Plasma Interactions on Pluto

The interaction of the tenuous solar-wind plasma with Pluto critically depends on the flux of material escaping from the planet's atmosphere.[25] If the escape rate is greater than about 10^{27} molecules sec^{-1}, then Pluto acts like a comet with the solar wind ionizing the outflowing material upstream, slowing down the solar wind, and pulling the mass-loaded solar wind into a downstream ion tail. If the atmospheric escape rate is lower, then the interaction will be more like that of Mars and of Venus, where the solar wind induces currents in each planet's ionosphere that deflect the solar wind around the planet. The Galileo spacecraft's discoveries of magnetic signatures at the asteroids Gaspra and Ida (as well as the Galilean satellites) raise the possibility that Pluto might also be magnetized. Because the solar-wind pressure is weak in the outer heliosphere, even a weak (20-nT) surface magnetic field would produce a magnetosphere around Pluto.

KUIPER BELT OBJECTS

Since the first Kuiper Belt object[26] was discovered in 1992,[27] the number of KBOs directly detected has increased to almost 60,[28-31] and more will undoubtedly be revealed. In addition, a team using HST has developed statistical arguments to infer the existence of a large population of smaller objects in the trans-neptunian region.[32]

The radial distances and azimuthal location of all objects discovered as of October 1997 are shown in Figure 1.1. The full orbital elements have been determined for many of these objects.[33] The orbital inclination (i) can be determined to within 0.5° after a few nights of observations, whereas the eccentricity (e) and semimajor axis (a) can take months to converge.[34] Figure 2.1 shows these orbital parameters for the detected objects plus the locations and widths of the main orbital resonances with Neptune.[35]

The orbits of the so-called classical Kuiper Belt objects fall into two main categories:[36]

1. Objects with $a < 41$ AU and $e > 0.1$ (e.g., Pluto and Charon) that are in mean motion resonances with Neptune; and
2. Objects with $41 < a < 50$ AU and $e < 0.1$ (e.g., 1992 QB1) that are not in resonant orbits.

Theoretical studies and observations of the recently discovered object 1996 TL_{66} suggest the existence of an

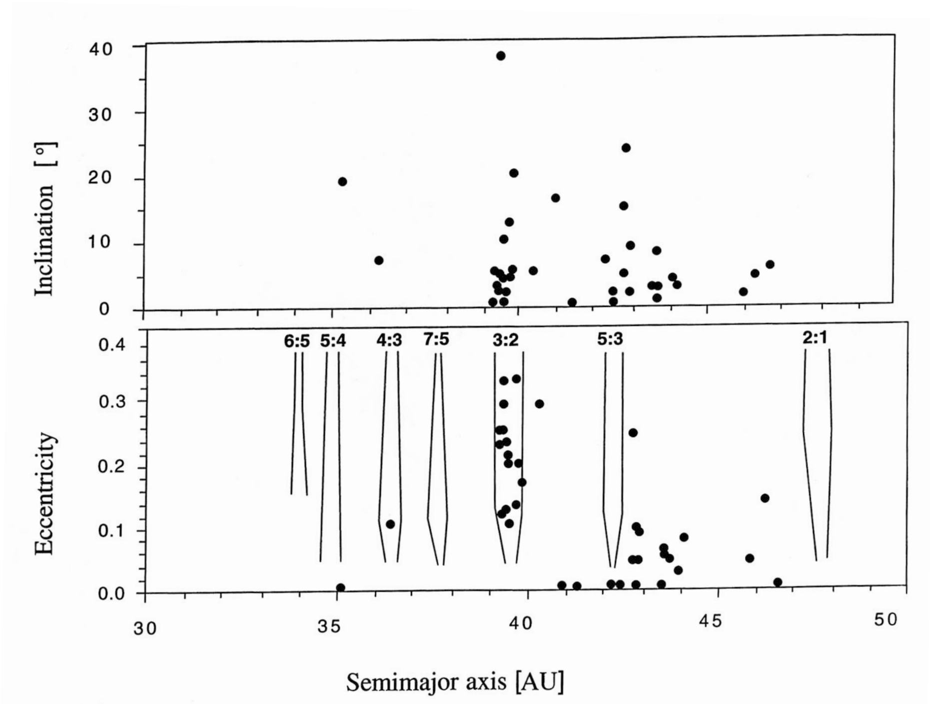

FIGURE 2.1 Orbital eccentricity and inclination versus semimajor axis for Kuiper Belt objects (KBOs). Also indicated from theoretical studies are the orbital resonances with Neptune. Many of the KBOs lie within the 4:3 and 3:2 resonances with Neptune that tend to stabilize their orbits. A significant number of KBOs fall outside these resonances and are prone to perturbation by Neptune and Uranus. Adapted from D.C. Jewitt, J.X. Luu, and J. Chen, "The Mauna Kea-Cerro Tololo (MKCT) Kuiper Belt and Centaur Survey," *Astronomical Journal* 112:1225, 1996; and R. Malhotra, "The Origin of Pluto's Orbit: Implications for the Solar System Beyond Neptune," *Astronomical Journal* 110:420, 1995.

additional component to the trans-neptunian region, the so-called scattered Kuiper Belt.[37,38] These objects are characterized by highly eccentric orbits extending to ~130 AU. They may have been planetesimals that were scattered out of the Uranus-Neptune region into eccentric orbits. Their existence poses the question of whether the Kuiper Belt extends as far as the Oort Cloud. Dynamical studies of the trans-neptunian region show that orbits with $a < 35$ AU and with $40 < a < 42$ AU are very unstable to gravitational perturbations by Neptune and Uranus.[39,40] These studies show that a small fraction of KBOs continue to stray into these unstable zones where they are likely to suffer major perturbations,[41,42] confirming an earlier suggestion that the disklike Kuiper Belt is the more probable source of low-inclination, short-period, Jupiter-family comets than is the isotropically distributed Oort Cloud.[43]

Although the absence of KBOs within 35 AU can be explained by Neptune's perturbations, the lack of objects in the dynamically stable region of low-eccentricity orbits between 36 and 39 AU remains an important mystery.[44] Malhotra has proposed that Neptune's orbit has evolved outward, sweeping up objects into the stable 3:2 resonance and clearing the inner Kuiper Belt.[45] Others have proposed the presence of as-yet-undetected massive perturbers that have cleared the 36- to 39-AU gap.[46,47]

Jewitt and colleagues have argued that the inclination distribution of the trans-neptunian objects is important because it controls the velocity dispersion among these objects and hence determines whether the collisional regime is erosive or agglomerative.[48] The upper part of Figure 2.1 suggests that objects located in resonant orbits have higher inclinations, consistent with the dynamical studies.[49,50] Malhotra's work also shows that the fraction of KBOs whose orbits are pumped up into higher inclinations as they are swept into resonances depends on the time scale for outward migration of the giant planets. She also points out that these resonant orbits tend to put the

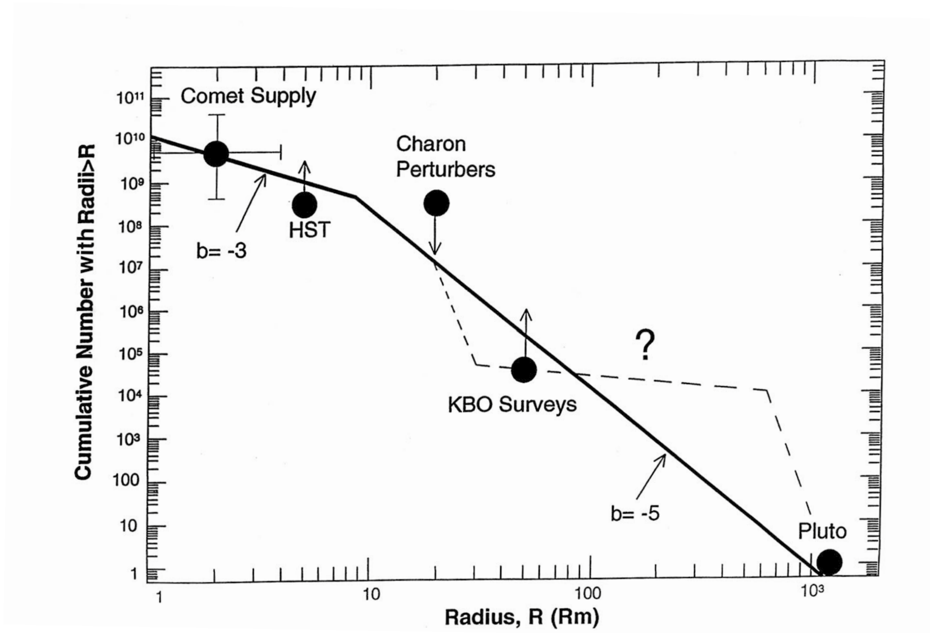

FIGURE 2.2 Sketch of the size distribution of trans-neptunian objects. The horizontal axis is the object radius, *R*. The vertical axis is the cumulative number of objects with radii greater than *R*. The references for the 5 points are given in the text. Power-law functions with slopes of $b = -3$ and $b = -5$ are shown by the solid curve. The dashed line shows how the distribution might be modified if the slope were flatter in the 50- to 500-km region as suggested by simulations of the KBO surveys. Adapted from P.R. Weissman and H.F. Levison, "The Population of the Trans-Neptunian Region: The Pluto-Charon Environment," *Pluto and Charon,* S.A. Stern and D.J. Tholen, eds., University of Arizona Press, Tucson, Arizona, 1997, p. 559.

objects farthest from the ecliptic at perihelion (when they are brightest) so that searches need to cover a broad band of latitudes in order to avoid a selection bias in sampling the KBO population.[51]

The size distribution of a population of objects has been a useful diagnostic for understanding the processes that lead to the erosion and/or accretion of planetary bodies. From recent observations and theoretical studies, it is emerging that objects in the trans-neptunian region probably follow a complex size distribution (Figure 2.2). Apart from Triton, the only firm observations of size are those of Pluto and Charon, and these still have substantial uncertainties (see Table 2.1). All other sizes are derived from brightness values and assume that the objects have an albedo of 0.04, comparable to the albedos of observed comets. Thus, there are at least factor-of-two uncertainties in estimates of the sizes of KBOs.

Estimates of the number of comet-sized objects (1 to 5 km in radius) in the Kuiper Belt are based on the supply of short-period comets to the inner solar system and have large error bars (see Figure 2.2). From HST observations, Cochran and colleagues inferred the presence of $10^{8\text{-}9}$ objects each 5 to 10 km in diameter.[52] This claim remains controversial.[53] An upper limit on the number of objects in the 20- to 330-km size range was derived by Levison and Stern based on limits to perturbations of Charon's orbit.[54] Recent ground-based surveys have produced the recent detections of 50- to 300-km objects and estimates of their size distribution.[55,56] Earlier surveys put limits on the number of objects in the 1,000-km range.[57,58]

The diameter distribution for comets within the solar system is estimated to have a power-law slope of $b = -3$.[59] If this power law is also applicable and if there are 5×10^9 comet-sized objects (as inferred from the supply of small-period comets) in the Kuiper Belt, then the $b = -3$ distribution predicts two orders of magnitude more 50- to 200-km objects than observed. This discrepancy suggests that the slope in the distribution must steepen at larger sizes (e.g., $b = -5$, as shown by the solid line in Figure 2.2). Simulations of the ground-based

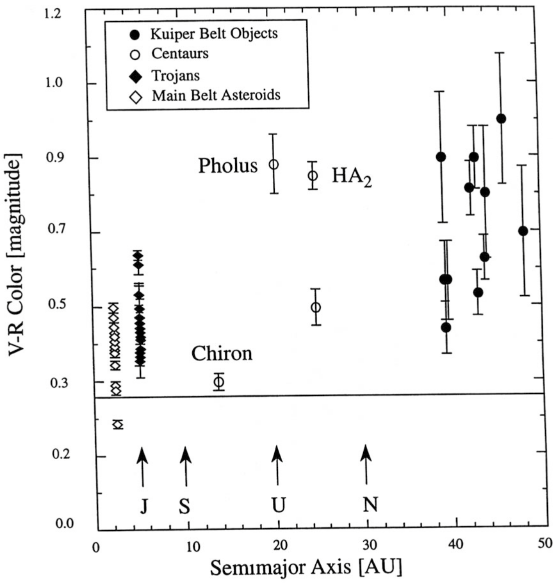

FIGURE 2.3 The visual color of trans-neptunian objects, defined as the visual magnitude minus the *R* magnitude (*V-R*) versus semimajor axis. Larger values of *V-R* indicate redder color. The horizontal line near 0.27 indicates the intrinsic solar color. It appears that there is a trend of increasing redness with increasing heliocentric distance. These differences in color may be due to heterogeneity among the bodies or differences in their degree of surface modification. Adapted from D.C. Jewitt, J.X. Luu, and J. Chen, "The Mauna Kea-Cerro Tololo (MKCT) Kuiper Belt and Centaur Survey," *Astronomical Journal* 112:1225, 1996.

surveys of KBOs suggest a much flatter slope for 50- to 300-km objects (e.g., $b \sim -1$, as shown by the dashed line in Figure 2.2). This shallow slope cannot persist over a wide range of sizes without predicting too few comets and too many Pluto-sized objects. Thus, it is possible that the size distribution in the Kuiper Belt is steep at large and small sizes and flat in between. The flatter distribution is consistent with a suggestion by Stern that larger objects are still accreting while smaller objects are eroding due to collisions.[60] A flat slope at ~100 km would indicate the boundary between these two regimes.

Very little is known about the physical characteristics or compositions of KBOs. Their sizes are only very roughly estimated. In 11 cases, broadband colors have been determined (Figure 2.3), revealing a diversity of color even within this small sample, although the bodies tend to be red. This wide range of colors, exceeding the range of colors exhibited by asteroids or comets, either may suggest diversity of composition (e.g., the red color suggests the presence of organic compounds), or may provide evidence for further surface modification of the bodies. Luu and Jewitt argue that the range of colors suggests surface inhomogeneity due to collisional resurfacing.[61] They predict that newer areas will be lighter, that objects with lower albedo will be redder, and that the color variation will be less among larger objects.

CENTAURS

A handful of bodies (seven as of December 1997) have been identified with orbits that cross those of Saturn, Uranus, and Neptune. These bodies are referred to as Centaurs. The importance of the Centaurs is that, based on dynamical calculations, they are located in orbits that are not stable over the lifetime of the solar system.[62] This suggests that the Centaurs formerly resided in the Kuiper Belt and only relatively recently have been delivered into their current orbits. Another argument for a common origin of Centaurs and KBOs is that the color diversity and redness of the Centaurs match those of KBOs but are not comparable to those of either asteroids or comet nuclei.[63] A more recent study has, however, challenged this view.[64] It suggests that the color diversity of cometary nuclei is just as great as that of Centaurs and KBOs, the principal difference between the objects being that cometary nuclei are not as red as Centaurs and KBOs. This claim is limited by the sparsity of published data on the colors of cometary nuclei. If additional observations establish a common origin for Centaurs and KBOs, then the Centaurs can provide compositional information on the more distant Kuiper Belt objects and information about their subsequent processing.

The characteristics of the known Centaurs include the following:

1. Perihelia between 8.5 and 10.6 AU;
2. Aphelia between 19 and 36 AU;
3. Orbital eccentricities ranging from 0.38 to 0.58;
4. Orbital inclinations between 5.4 and 25 degrees; and
5. Estimated diameters between 20 and 200 km, based on Earth-based telescopic observations at thermal wavelengths and assumed low visual albedo (Chiron and 5145 Pholus have independent assessments of their diameters).

Three of these objects (Chiron, Pholus, and 1993 HA2) are large enough and bright enough for Earth-based telescopic spectral observations to be obtained at visual and near-infrared wavelengths (0.4 to 1.0 microns). With larger telescopes spectral observations could be made of fainter objects.

Chiron is a uniquely complex body. It apparently undergoes sporadic outbursts of activity that may be driven by the sublimation of CO. Its orbit is chaotic, and it may have spent a considerable amount of time in the inner solar system. If this is the case, understanding its inventory of volatiles is a major issue—if aging effects are clearly visible in short-period comets, why not in Chiron? At visible wavelengths, Chiron has a flat reflectance spectrum similar to that of the C-type asteroids. Thermal-infrared observations suggest that its visual albedo appears to be low (0.04 to 0.1), further indicating a similarity to the C-type asteroids. The similarity in reflectance to the C-type asteroids extends to the near infrared, where measurements show a flat, featureless continuum.

Chiron's cometary outbursts are both short-lived (on time scales of hours) and long term (large peaks of up to a year or more). The outbursts are clearly not related to perihelion passage, since Chiron was actually less active at perihelion than it was at 12 AU shortly after discovery of its variability. The duration of the long-term outbursts may be related in a complex way to modulation from the bound-dust atmosphere suggested by recent HST observations. This makes Chiron an interesting laboratory for studying the physics of exospheres. Although the existence of the bound coma remains controversial, its confirmation would provide a means of estimating Chiron's density. Preliminary estimates suggest a low density (~0.5), which is consistent with recent models of planetesimal accretion.[65]

Several observations of Chiron appear to be in conflict in terms of brightness and color. Indeed, Chiron's color seems to vary with its state of activity. At times of outburst Chiron's coma clearly becomes bluer. Although chemical surface processing may be thought to play a role in this behavior, it is more likely to result from the complex effects that the gravity has on the particle-size distribution in the inner and outer coma. The coma becomes bluer during an outburst because of the injection of a large number of small grains that subsequently escape into space. Very recent observations hint at a possible color effect in Chiron's rotational light curve. Preliminary dynamical atmospheric models suggest that surface albedo features on Chiron would not be completely covered by fallback from the bound-dust atmosphere.

In marked contrast to Chiron's bluish color, the visible reflectances of 5145 Pholus and 1993 HA2 are extremely red (see Figure 2.3) and exhibit steep upward slopes toward longer wavelengths.[66] This spectral behavior is not characteristic of ice, rock, or minerals, but a variety of organic solids exhibit a range of red slopes throughout the visible region. Unfortunately, the red slope alone is insufficient to identify a specific solid material. Several near-infrared spectral observations have been obtained of Pholus. The presence of several distinctive absorption features has led to suggestions that the surface of Pholus is composed of a mixture of H_2O ice and a variety of organic materials (newer high-resolution spectra indicate NH_3 is not a detectable constituent). The organic materials suggested to date include light hydrocarbons or methanol ice, Titan tholin, polymeric HCN, and carbon black. The presence of the light hydrocarbons suggests that Pholus has been less chemically processed than comets and asteroids. Intriguingly, extrapolations of orbital calculations suggest that Pholus's current orbit is dynamically new, suggesting that it may have arrived recently from the Kuiper Belt.

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3

Key Measurement Objectives

In its past reports, COMPLEX has advocated a strategy for the planetary sciences that emphasizes a balanced program of ground- and space-based telescopic observations, laboratory measurements, theoretical studies, and remote-sensing and in situ measurements by spacecraft.[1] There are good reasons to believe that such an approach is called for to further our knowledge of Kuiper Belt objects. In this chapter COMPLEX indicates the priority of the scientific measurements and studies that, based on current knowledge, are needed to advance understanding of objects at the fringe of the outer solar system.

ORBITS

Distribution of Orbits

A meaningful comparison between the distribution of orbital properties of KBOs and dynamical models of their orbital evolution requires accurate observations of a large population of objects. Furthermore, the full range of orbital properties—specifically, semimajor axis, inclination, and eccentricity—must be derived to understand the effects of orbital resonances with the giant planets on the relationships among these parameters. Because of the very long orbital periods of KBOs—typically more than 200 years—and faintness, typically 23rd to 24th magnitude, high-precision astrometric measurements are required over an extended period. A temporal baseline of a few months is barely sufficient to ensure that an object can be recovered at the next opposition. Observations of 1992 QB_1, the first KBO detected, suggest that astrometric studies over a period of at least 5 years are necessary to establish a good orbit. Even after 5 years of study, the orbit of 1992 QB_1 is still not secure enough for this KBO to be given a permanent designation.

Although almost 60 KBOs have been found to date, 30 to 40% have been lost because of the lack of timely follow-up observations. Of the remainder, roughly 40% reside in the 3:2 resonance at 39 AU. The rest are dispersed between 35 and 50 AU, but their spatial distribution cannot be characterized because their population density is so small. Thus, predictions that resonances other than the 3:2 should be populated cannot be verified because not enough objects are known to give statistically significant results. In short, we are far from having a large enough sample of KBOs to map out the dynamical properties of the trans-neptunian region. Additional search and astrometric programs are necessary. The rarity of KBOs necessarily means that search programs are long-term undertakings requiring significant amounts of telescope time.

Key Measurements Relating to Orbits

- Conducting an extensive survey of the ecliptic plane at optical wavelengths (increasing coverage from ~15 to 100 square degrees should reveal ~400 objects).
- Surveying regions up to 40° away from the ecliptic plane to investigate if ecliptic surveys underestimate the number of objects with high inclinations.
- Performing precise astrometric observations of ~100 KBOs over a period of at least 5 years for accurate orbit determinations.

BULK PROPERTIES

Measuring Bulk Properties

To estimate the density and, hence, bulk composition of a planetary body requires separate measurements of its mass and size. Of all trans-neptunian objects, this has been accomplished only for Triton, where Doppler tracking of the gravitational deflection of Voyager 2 yielded its mass and Voyager 2 images gave accurate measurements of size. The lack of precise radii and masses for Pluto and Charon makes it difficult to reach a robust conclusion on their densities. Improved values of the masses of Pluto and Charon will probably be provided by more precise measurements of the barycentric wobble. To achieve the necessary accuracy in measurements of their sizes will require a spacecraft flyby with a solar occultation. To determine the degree of differentiation of these bodies it will be necessary to measure high-order moments of their gravitational fields via Doppler tracking of a close flyby.

While the current location and orbital parameters are useful information for dynamical studies of the Kuiper Belt, better estimates of the sizes of KBOs are vital for estimating the total mass of the Kuiper Belt. The size distribution of the population (i.e., the number of objects as a function of their size) is a key indicator of collisional and accretional processes. Currently, the sizes of KBOs are inferred from their brightness by assuming a value for their albedo. Another way to measure size is to compare an object's thermal output with the amount of sunlight that it receives. At trans-neptunian distances from the Sun, equilibrium temperatures are 30 to 50 Kelvin so that thermal emissions from KBOs peak, according to Wein's law, in the infrared region at wavelengths between 10 and 100 microns. Accurate size measurement therefore requires a radiometric observation of a KBO's thermal flux at wavelengths of ~10 to 100 microns.

The smaller KBOs are at current lower limits for detectability with moderate-aperture telescopes. Deep searches have, in the past, been confined to the ecliptic plane and have covered only a small region of the sky. Statistical results imply that many bodies lie just at the edge of detectability by HST. For larger KBOs, search efforts on 2-meter-class telescopes must be continued to answer the question of the existence of objects with diameters between 200 and 2,400 km, objects apparently missing from the current population-number distribution.

Key Measurements Relating to Bulk Properties

- Determining the sizes and masses of Pluto and Charon to constrain their densities.
- Measuring the magnetic and gravity fields of Pluto and Triton during a spacecraft flyby to constrain the internal structure.
- Performing precise radiometric observations of KBOs in the far-infrared (100-micron) region.
- Conducting further searches for the smaller objects suggested by the HST statistical study.
- Searching for objects with diameters in the range of 200 to 2,400 km.

SURFACES AND CHEMICAL COMPOSITIONS

The Importance of Surface and Chemical-Composition Measurements

Of the trans-neptunian objects, only Triton has been imaged at a resolution sufficient to allow interpretation of some of its geological processes and history (70% of Triton's surface remains unmapped). Because of the possibility that Triton was captured from solar orbit by Neptune, its geological history may not be an adequate model for Pluto even though the two bodies are of roughly similar size and mean density. Large areas of different albedo are known to occur on Pluto, suggesting that a heterogeneous surface geology is possible. Images obtained by a future mission would permit several types of geological analysis relevant to inferring internal activity and surficial processes. From geological mapping of material units, combined with application of basic stratigraphic principles, it is generally possible to arrange material units in a chronological sequence. If these units are characterized by very different densities of impact craters, it will be possible to place approximate age limits on them. Thus, the combination of geological mapping and crater studies can provide a first-order estimate of Pluto's geological history.

Additional motivations exist for studies of the chemical compositions of objects in the distant outer solar system. The particular volatiles contained in these small bodies and their relative proportions are sensitive thermometers of the conditions in the solar nebula. In addition, compositional information can contribute to greater understanding of how much processing the interstellar material underwent prior to incorporation into planetesimals. The first-order indicator of the identity of the volatiles present is the distances at which there is evidence of activity. If objects are bright enough, spectroscopic observations at radio wavelengths may be able to identify the active molecules. Repeated observations of the same object at different heliocentric distances will be important because deviations from the inverse-square law of brightness are a particularly sensitive indicator of possible activity, even when a coma is not detectable. Such studies will, of course, require knowledge of any rotational modulation of the object's light curve.

Existing ground-based near-infrared spectroscopy of Pluto, Triton, and Pholus illustrates the potential for gaining surface compositional information about the relative abundances of volatile components (N_2, CO, CH_4, CO_2, CH_3OH, H_2O, and more evolved hydrocarbons) on the other Centaurs and KBOs. However, the other known Centaurs and KBOs are fainter and smaller, and often more distant, such that similar spectroscopic measurements are currently not feasible with existing 4-meter-class ground-based telescopes and instruments. Thus, obtaining compositional information on their surfaces requires access to large-aperture ground-based telescopes (e.g., the existing 10-meter Keck telescopes or the 8-meter, infrared-optimized Gemini telescope now under construction) or future space-based facilities with appropriate spectroscopic capabilities in the infrared and millimeter regions of the spectrum. Additionally, near-infrared spectroscopic observations can be made by remote sensing from robotic spacecraft that could identify spatial variation in composition over the surface of these objects. This knowledge could be used to identify physical and/or chemical processes that have been active on the surfaces.

The Near Infrared Camera and Multi-Object Spectrometer (NICMOS) recently installed on HST may provide the ability to determine compositional information for some of the brighter KBOs. Future space-based telescopes, such as the 4-meter-class facility recommended by the report of the HST & Beyond (Dressler) Committee[2] or the 6- to 8-meter Next Generation Space Telescope,[3] will be suitable for compositional studies in the 1- to 5-micron regions if they have the capability to observe moving targets.

Key Measurements Relating to Surfaces and Chemical Compositions

- Imaging the unmapped 70% of Triton's surface.
- Obtaining visual and near-infrared images of Pluto-Charon during a spacecraft flyby to enable geological mapping and crater population studies, as well as a search for evidence of tectonics, indicators of the distribution of frosts, and evidence of cryogenic volcanism.
- Performing multispectral observations of a statistically useful number (tens) of KBOs to determine their surface composition and variability over a rotation period.

• Obtaining deep images to search for comas and/or other evidence of cometary activity in the Centaurs, KBOs, and distant comets.

• Gathering visible and infrared images of Centaurs and KBOs with flyby missions.

ATMOSPHERES

Probing Atmospheres

The vertical density and temperature structure of Pluto's lower atmosphere needs to be measured to determine whether there is a troposphere. Likewise, a measurement of the vertical temperature profile at the sub-microbar level can yield a signature of a hydrodynamically escaping atmosphere. The former measurement can be accomplished by a radio-occultation experiment, and the latter measurement can be obtained from an ultraviolet solar-occultation experiment on a robotic spacecraft passing behind Pluto and looking at Earth and the Sun, respectively.

A more fundamental but inherently more difficult set of measurements would be needed to determine what controls Pluto's surface pressure and temperature. A similar set of occultation measurements should be performed at Charon, whose atmosphere is probably much thinner than Pluto's. A solar-occultation measurement can yield the composition, density, and temperature profiles on Charon at sub-microbar pressures.

Ground-based stellar-occultation measurements should continue to be made when the opportunity arises in order to determine the time evolution of the density and thermal structure of Pluto's and Triton's atmospheres at the microbar level. It is preferable that these measurements be recorded at multiple wavelengths, which may lead to a better understanding of the "knee" structure in Pluto's light transmission curve.[4]

The thermal structure of the atmospheres of Pluto and Triton, and perhaps Charon, depends critically on the vertical density distributions of minor constituents that absorb either incident sunlight or thermal infrared radiation emitted by these objects themselves. The most important species are CH_4, CO, and HCN, the last photochemically produced from N_2 and CH_4. Measurements of their height distributions can be made by solar occultations, near-infrared remote sensing, and possibly millimeter spectroscopy. The latter two types of measurements may be accomplished by ground-based telescopes.

Technology developments in near-infrared detectors may allow sufficiently high spectral resolution measurements of outer solar system objects to detect atmospheric CO absorption features from reflected sunlight. Atmospheric methane absorption features near 1.6 microns have been detected on Pluto, but not on Triton. The development of interferometric capability at millimeter wavelengths may allow the detection of rotational line emission from HCN and CO from Pluto, Charon, and other KBOs. The fact that a single radio telescope can routinely measure rotational line emission from these molecules in Triton's much denser atmosphere suggests that this technique may be extended to thinner and more distant atmospheres.

Key Measurements Relating to Atmospheres

• Performing solar and radio occultations of Pluto's atmosphere with ultraviolet and radio instruments during a flyby mission.

• Conducting stellar-occultation measurements of Triton, Pluto, and Charon.

• Obtaining infrared and millimeter-wave spectroscopic measurements of molecular species in the atmospheres of Triton and Pluto.

• Searching for atmospheres around the larger known KBOs and Centaurs using observations of stellar occultations.

PLASMA INTERACTIONS

Particles and Fields in the Trans-Neptunian Region

Plasmas in the outer solar system are tenuous, and magnetic fields are weak. Over the lifetime of objects in the trans-neptunian region, the particle bombardment of icy surfaces and erosion of their thin atmospheres can be significant. Measurement of the interaction of the solar wind with an object's surface, atmosphere, and/or ionosphere requires in situ measurements of the plasma environment by robotic spacecraft. For example, an accurate measure of the escape rate of Pluto's atmosphere can be obtained only by measuring the deceleration of the solar wind resulting from ionization of the escaping neutral material. Detection of an object's intrinsic magnetic field from a spacecraft requires a magnetometer that can measure <1-nT fields.

Key Measurements Relating to Plasma Interactions

- Determining the magnetic fields of Pluto, Triton, and the interplanetary medium.
- Studying the plasma density and flow velocity of the 30-AU solar wind.
- Measuring the velocity distributions and composition of particles from Pluto's atmosphere that have been ionized and picked up by the solar wind.

LABORATORY STUDIES

The Importance of Laboratory Studies

Observational and theoretical programs depend heavily on the results of laboratory studies to make advances in our understanding. Thus a vigorous program of cryogenic laboratory measurements and related studies are required to provided a balanced, broad study of KBOs. For example, spectroscopic measurements of the atmospheric and surface composition of KBOs require supporting laboratory data on the optical properties of ices at ~30- to 50-Kelvin temperatures in order to interpret the observational data and identify composition. Vapor pressures for pure ices and ices of varying composition are poorly understood, or unknown, at these temperatures. Studies of photochemistry in the atmosphere and on the surface require data on kinetic-reaction rates at low temperatures. Although they are important for modeling geological processes, the mechanical properties of the identified materials at these low temperatures are as yet poorly determined.

For example, it has been argued that Pluto's atmosphere will diminish at aphelion, because the surface temperature in radiative equilibrium will decrease with increasing distance from the Sun and, based on vapor-pressure equilibrium, the nitrogen surface pressure will drop precipitously. Laboratory studies suggest that nitrogen ice undergoes a dramatic alteration in its physical properties (including its emissivity) when it undergoes a phase change that occurs at 35.5 Kelvin.[5,6] Thus it is possible that Pluto's surface temperature never drops below 35.3 Kelvin over a plutonian year. Further laboratory research is needed to quantify the emissivity of different phases of nitrogen ice.

Other areas in which laboratory investigations may provide useful data include studies relating to the photochemical production of complex organic molecules and to reactions between ions and neutrals and ions and the surfaces of aerosols. The surface composition of planetary bodies can be influenced by chemical processes occurring in their atmospheres. The photochemical destruction of methane in the atmospheres of Pluto and Triton could, for example, lead to the creation of complex organic compounds on the surfaces of these bodies. Although such compounds have not yet been identified, laboratory studies of relevant reaction rates could provide useful guidance on the inventory and form of complex organic materials likely to exist in the trans-neptunian region. Such reactions assume increased importance when neutral chemical reactions are suppressed, as they are at the extremely low temperatures found in the atmospheres of Pluto and Triton. Since neutral reactions are also suppressed in interstellar molecular clouds, laboratory studies could, potentially, provide a synergistic link between the material from which the solar system formed and the remnant material existing today in the trans-neptunian region.

Investigation of the adhesion of gases to ices at low temperatures is another area in which laboratory studies are likely to be important. Such studies may yield important insights into problems relating to the abundances of inert gases and the deuterium-hydrogen ratios observed in comets.

Key Laboratory Studies

- Determining the physical and chemical properties of ices of various compositions at temperatures of the outer solar system (30 to 50 Kelvin).
- Studying the photochemical reactions leading to the creation of complex organic compounds.
- Investigating ion-neutral reactions and reactions of ions with aerosol surfaces.
- Measuring the adhesion of gases to ices at low (30 to 50 Kelvin) temperatures.

Because some of these laboratory studies are of interest to communities broader than the space sciences, they may be appropriate topics for interdisciplinary cooperation between NASA, the National Science Foundation, and other relevant agencies.

THEORETICAL STUDIES

Researchers need the complementary efforts of theoretical and computational studies to analyze and interpret observational data and provide a framework for understanding its significance. Theory also plays an important role in suggesting future directions for observational and laboratory research.

Key Theoretical Studies

- Studying orbital dynamics (e.g., the evolution of KBO orbits and the processes responsible for the sunward migration of the Centaurs).
- Understanding the physics and chemistry of the solar nebula (e.g., modeling the temperature evolution of the solar nebula and the acquisition and/or removal of its volatiles).
- Investigating the evolution of ices exposed to radiation and low temperatures.
- Analyzing prebiotic chemical processes.
- Determining the thermal evolution of objects <2,000 km in diameter.
- Studying major collisions involving bodies such as Triton and Pluto-Charon.
- Modeling the process or processes by which Triton was captured by Neptune and Charon was captured by Pluto.
- Comparing the effects of possible collisional histories and tidal heating on the interior structures of Triton, Pluto, and Charon.

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4

Technology Issues

Exploration of the outermost regions of the solar system is a demanding task, especially in the current environment of tight financial limitations. Advances in technology are needed to improve telescopic observations and to enable spacecraft exploration of the trans-neptunian region.

TELESCOPIC OBSERVATIONS

The technical challenge posed by surveys to detect KBOs is to efficiently search the sky for faint objects with parallactic motion corresponding to the trans-neptunian region. Currently, less than 0.1% of the ecliptic has been surveyed to <24th magnitude for KBOs. Faint objects require an efficient detector on a modest (2-meter) telescope, as well as dark skies. To illustrate the scale of the task, examining the entire area within ±10° of the ecliptic (7,200 square degrees) with a field of view typical of current searches (~0.02 square degrees) at approximately 12 sets of images per night[1] would take ~82 years of observing every night (ignoring such matters as the full moon and bad weather). The efficiency of searches could be improved by using detectors with larger arrays (currently 2,048 × 2,048 pixels) and shortening their readout time to allow a greater area of sky to be covered per night. Additional improvements in array technology are, however, unlikely to help future ground-based studies because current detectors are already background limited.

Telescopic observations of the trans-neptunian region make demands on infrared astronomy. When integrated with large-aperture telescopes, existing near-infrared (~1-micron) instruments can barely detect the brightest objects, allowing the determination of the chemical composition of their surfaces (requiring resolving powers of a few hundred) and atmospheres (requiring resolving powers of several thousand). Access to these instruments and the equivalent of their next generation(s) on large-aperture telescopes (existing and planned), allows the sampling of smaller or more distant objects, providing a more statistically significant sampling of the KBO population (Figure 4.1).

Access to 8-meter-class facilities (e.g., the Gemini telescope now under construction on Mauna Kea) would enable some limited studies of the compositional variations of the brightest KBOs. Indeed, the 10-meter Keck telescope has already been used to obtain near-infrared (1.42- to 2.40-micron) spectra of 1993SC.[2] Even using the largest telescope in the world to observe this KBO, one of the brightest known, proved extremely challenging, and the resulting spectrum was not of high quality. Moreover, observing time on the Keck telescope and other such facilities is heavily oversubscribed, and it is far from clear that a long-term program focused on KBOs would

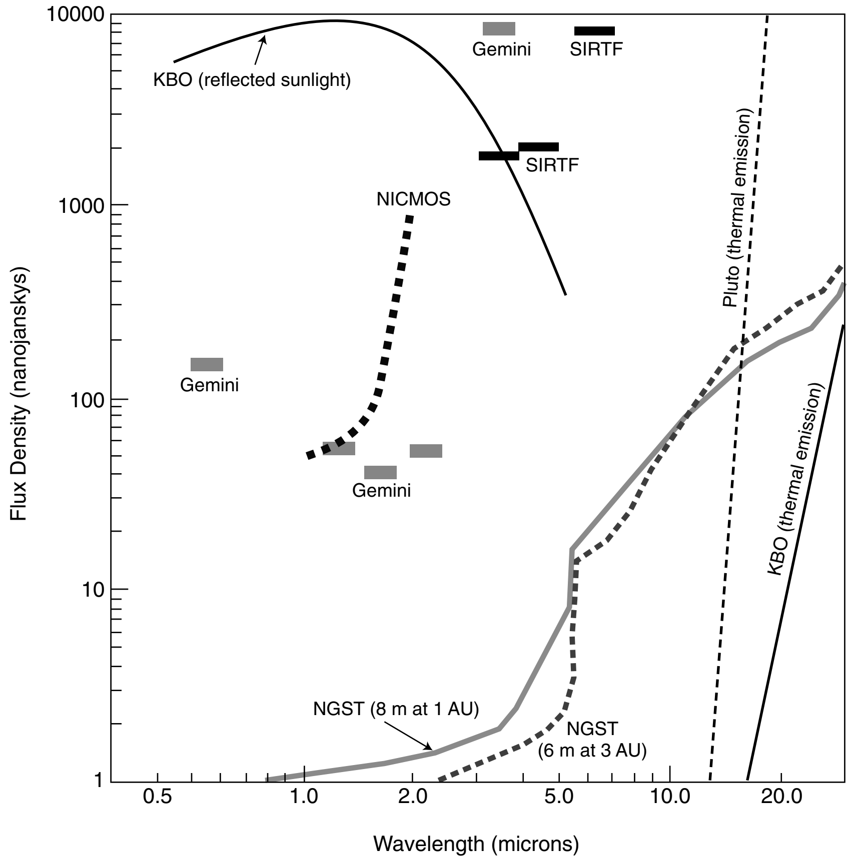

FIGURE 4.1 The estimated sensitivities of various ground- and space-based facilities likely to play roles in studies of trans-neptunian objects in the next 10 to 15 years. The current capabilities of the Hubble Space Telescope's Near Infrared Camera and Multi-Object Spectrometer (NICMOS) are plotted relative to those of the 8-meter Gemini telescope currently under construction in Hawaii, and the Space Infrared Telescope Facility scheduled for launch in 2001. Also shown are two different concepts for NASA's proposed Next Generation Space Telescope (NGST). The 6-meter NGST is in a heliocentric orbit at 3 AU, i.e., in the outer portion of the asteroid belt where the zodiacal emission is 30 to 100 times lower than it is at 1 AU. The 8-meter NGST is in a heliocentric orbit at 1 AU. Gemini (outfitted with low-order adaptive optics), NICMOS, SIRTF, and NGST will readily detect the reflected sunlight from Pluto (off scale) and a typical KBO out to wavelengths of ~5 microns. Pluto's thermal emission should be detectable by either of the two NGST concepts at wavelengths greater than ~15 microns. The thermal emission from the KBO, however, appears to be beyond the capability of any of the facilities in the wavelength range illustrated. SIRTF will, however, be able to detect such a KBO at wavelengths greater than 35 microns (not illustrated). The capabilities indicated assume a 10,000-sec integration, a 10-σ signal-to-noise ratio, and a wide bandpass of $\lambda/\Delta\lambda = 3$. The Kuiper Belt object is taken to have a radius of 100 km and is located at 35 AU. Its temperature is 35 Kelvin; it has a visual magnitude of 22.0 and a *V-K* color index of 2.0 (i.e., the red color characteristic of some, but not all, trans-neptunian objects). Pluto is assumed to have a diameter of 1,200 km and a temperature of 40 Kelvin, and to be located at its current distance from the Sun. Adapted from *The Next Generation Space Telescope: Visiting a Time When Galaxies Were Young,* H.S. Stockman, ed., Space Telescope Science Institute, Baltimore, Maryland, 1997, with information on Pluto and the KBO courtesy of D.P. Cruikshank.

receive support. The cost of such support is, however, small compared with the cost of a spacecraft, and funding agencies will have to make the necessary decisions regarding trade-offs.

The Near-Infrared Camera and Multi-Object Spectrometer (NICMOS), recently installed on HST, was designed to obtain near-infrared images and spectra. NICMOS could provide compositional information for some of the brighter KBOs. However, due to technical difficulties, spectra cannot currently be obtained, and so compositional inferences based on NICMOS observations are limited to broadband photometric measurements (see Figure 4.1). If these technological difficulties can be overcome, then the spectra of a limited number of KBOs could be obtained.

The low temperatures (<40 Kelvin) of objects in the trans-neptunian region mean that their thermal emissions are in the far-infrared (~10- to 100-micron) region of the spectrum. The detectors on the Space Infrared Telescope Facility (SIRTF) are very close to providing background-limited performance and will be capable of radiometrically detecting KBOs (with diameters of >100 km) at wavelengths greater than approximately 35 microns.[3] However, if telescopes larger than SIRTF were available, then the diffraction-limited performance would improve as a result of the lower background. In this case, improved detector performance would be important, although in some cases the current detectors are near the theoretical limit of performance.[4] Much work is needed to construct larger detector arrays, as well as the cooling systems that would be required for long-term operation in space. Advancing our knowledge of the physical and chemical properties of the KBOs using both Earth- and space-based telescopes to determine accurate photometry and radiometry is directly related to having large, efficient detector arrays, especially in the far infrared. Procuring appropriate arrays may present some problems. Although those operating in the 1- to 40-micron bands are available commercially, ones operating at longer wavelengths are only being made by a few university research groups for use in, for example, SIRTF.[5]

For observations of comet-size (<10-km) objects in the Kuiper Belt we look to the next generation of space telescopes. The report of the HST & Beyond (Dressler) Committee recommended the construction of a 4-meter space-based observatory optimized for imaging and spectroscopy in the 1- to 5-micron region.[6] In response to this recommendation NASA initiated the planning for the Next Generation Space Telescope (NGST).[7] This 6- to 8-meter facility would be suitable for composition studies of KBOs if it had the capability to observe moving targets (see Figure 4.1). This capability could, potentially, place severe demands on the systems that control the spacecraft's attitude and point the optical system. The ability to track will probably need to be incorporated from the earliest phases of the spacecraft design, possibly by provision of an internal steering mirror capable of tracking objects within a limited angular range without moving the entire telescope.

SPACECRAFT MISSIONS

The demands of exploring the outer solar system under tight fiscal constraints have led to a major change in approach to mission design, development, and operation.[8,9] The high costs of sending large and heavy, spacecraft with a dozen separate scientific instruments to the giant planets (e.g., Voyager, Galileo, Cassini) have resulted in the interval between missions increasing to nearly 20 years. The past few years have seen the emphasis change to small, integrated spacecraft with highly focused science objectives that use new technologies to improve efficiency. Reducing the cost of missions by at least a factor of 10 brings the possibility of more frequent missions to the outer solar system. The move away from large missions has had an additional, indirect benefit to studies of the trans-neptunian region. Many of the "smaller, cheaper, faster" missions initiated in the last few years are targeted at asteroids and comets. Given the close connection between these objects and those found in the distant outer solar system, our overall knowledge about primitive bodies is likely to increase greatly over the next few years. Thus, New Millennium missions such as Deep Space 1 and Deep Space 4, together with Discovery missions like Near-Earth Asteroid Rendezvous and Stardust, not only will provide valuable experience on how to design and conduct low-cost science missions but also are likely to greatly expand the overall context within which all studies of primitive bodies are conducted.

While considerable progress has been made in developing new-style missions to the outer solar system, particularly Pluto flyby missions (Box 4.1),[10-12] the technological obstacles of returning substantial scientific data from >30 AU remain formidable. The issues that drive technological development to enable lower-cost, higher-output missions to the outer solar system include the following:[13]

1. *High launch energy*—To climb out of the Sun's gravitational well and reach >30 AU, a spacecraft must be launched by a powerful launch vehicle (or take lengthy detours via other planets). Alternatively, the size and cost of the launch vehicle can be reduced by lowering the mass of the spacecraft. The spacecraft mass can be reduced by designing the spacecraft functions around a limited number of integrated scientific instruments and by using lightweight components (e.g., integrated microelectronics; lightweight telecommunications; precise, low-impulse attitude thrusters; and advanced, stellar-navigation cameras). To achieve orbit around Triton or to fly past multiple objects, the spacecraft will require an efficient propulsion system.
2. *Long mission duration*—Spacecraft missions to the trans-neptunian region last on the order of 10 years, a duration that places serious demands on the reliability and longevity of components as well as requiring long-term mission operations. Technologies required to enable long-duration missions include spacecraft autonomy and active fault management. The difficulty in longer missions is to focus the scientific objectives and limit the complexity of operations to lower the cost of operation without reducing the scientific return.
3. *Low sunlight*—The low levels of sunlight in the outer solar system provide insufficient solar energy to power the spacecraft, and longer exposures are required for taking images of scientific targets (which puts demands on attitude control to prevent smearing). Advances in radioisotope power sources as well as in the development of low-power electronics and instrumentation will be important for outer solar system missions.
4. *Long telecommunications links*—Sending information efficiently across >30 AU requires major advances in telecommunications (e.g., carbon-composite antennas, efficient amplifiers, optical telecommunications, and on-board data processing and compression).
5. *Radiation-hardened electronics*—A consequence of the long duration of missions to the outer solar system is that spacecraft might accumulate significant doses of radiation. The development of reliable, radiation-hardened, integrated solid-state electronics capable of surviving the extreme conditions of the trans-neptunian region may thus be important.
6. *Microinstrumentation*—The budgetary pressure leading to NASA's increasing emphasis on small spacecraft developed on rapid time scales has created a parallel pressure to develop a new generation of highly capable microinstruments to fly on these missions. Many first-generation small missions (e.g., Mars Global Surveyor) are equipped with copies of instruments designed to fly on traditional, "large" missions. This trend cannot continue, and COMPLEX has previously recommended that NASA devote more attention to the development of microinstruments for planetary missions.[14]

The programmatic constraints likely to be imposed on future missions to the outer planets will have important consequences for the types of instruments that can be flown. Limited spacecraft resources (e.g., power, mass, data rate, and so on) will favor the development of integrated instrumentation. In other words, the functions of several instruments will be ingeniously combined in one package proposed by a single team of investigators. An example of this trend is the Mars Volatiles and Climate Surveyor integrated payload selected for the Mars Surveyor 1998 lander or the Plasma Experiment for Planetary Exploration to be carried by Deep Space 1. Similarly, the combination of rapid advances in instrumentation technology and short mission development schedules is likely to promote the flight of instrumentation incorporating more technically advanced components than has been the case for traditional missions with decades-long development schedules. A full discussion of the likely ramifications of these and other trends with respect to issues such as strategic planning by NASA and groups such as COMPLEX is beyond the scope of this study.

Exploration of the outer solar system will probably benefit from the testing of new technologies in spacecraft components and scientific instruments on missions to the inner solar system under the New Millennium and Discovery programs. For example, Deep Space 1, the first flight in NASA's New Millennium technology demonstration program, will test the Miniature Integrated Camera Spectrometer (an integrated camera, ultraviolet imaging spectrometer, and infrared imaging spectrometer), which is a candidate for use on a Pluto mission. Similarly, NASA's recently published Roadmap for the exploration of the solar system highlights specific technologies that are required to enable missions to the trans-neptunian region.[15] The Roadmap's discussions of the Pluto/Kuiper Express and Neptune Orbiter with Triton Flybys "portrait" missions, for example, note the importance of solar-electric propulsion, autonomous operations, and lightweight spacecraft systems.

Box 4.1
History of NASA's Pluto Mission Concepts

The Space Science Board's 1986 report *A Strategy for the Exploration of the Outer Planets: 1986-1996* (National Academy Press, Washington, D.C., 1986) identified the Pluto-Charon system as a likely and logical long-term candidate for a flyby reconnaissance mission. Since then, NASA plans for a Pluto mission have been repeatedly redesigned. Each iteration has been geared toward producing a mission architecture that could, in general, be accomplished either more rapidly or at lower cost than could its predecessors.

NASA's 1991 *Solar System Exploration Division Strategic Plan* called for a Pluto Flyby/Neptune Orbiter program, in which a pair of Mariner Mark II (Cassini-class) spacecraft would be launched in the period 2001 to 2003 by Titan IV/Centaurs on a 15- and 20-year cruise to Pluto and Neptune, respectively. Each 5,000- to 6,000-kg spacecraft would carry a payload of 14 instruments and cost in excess of $2 billion. By 1992, however, it was becoming clear that space science funds through the turn of the century would not support such an ambitious architecture. The project was officially descoped to a single Mariner Mark II Pluto Flyby or Neptune Orbiter mission and then quietly dropped.

At the same time, the idea for a Pluto Very Small or Pluto Fast Flyby program was born out of technological feasibility studies at NASA's Jet Propulsion Laboratory. In this scenario, two spacecraft, each carrying four instruments, would be launched toward Pluto in the period 2001 to 2003. Even though each spacecraft would have a mass of approximately 150 kg, launch on a Titan IV/Centaur would be required to reduce the flight time to 7 to 8 years. A $400 million price tag included mission development and operations up until 30 days after launch, but excluded both the cost of the radioisotope thermoelectric generators necessary to power the spacecraft in the outer solar system and the cost of the two Titan IV/Centaurs. Actual mission costs would be around $1.2 billion plus expenditures for lifetime operations.

At about the same time the Pluto Fast Flyby concept was developed, a number of alternative missions were investigated. Prime among these was the so-called Pluto Flyby 350 concept developed for NASA's Discovery Program Science Working Group. It envisaged a somewhat larger, fully redundant spacecraft (~300 kg), carrying a greater range of instruments than the Pluto Fast Flyby concept. To limit total mission costs, Pluto Flyby 350 eliminated launch by a Titan IV and, instead, relied on Earth and Jupiter flybys to inject it on course to Pluto. If launched on an Atlas or Delta in 2001, Pluto Flyby 350 would have reached Pluto more than 11 years later. The missions savings on its launch vehicle costs were, however, negated by the need for a more elaborate spacecraft with a significantly longer operational lifetime.

At about the same time, consideration was also given to a Pluto orbiter mission. Studies indicated that a 35-kg spacecraft could be placed into orbit about Pluto by following a trajectory similar to that of Pluto Flyby 350. This concept was highly unattractive because the total flight time was more than 16 years and,

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more importantly, the orbiter could carry no useful scientific payload. Increasing the orbiter's mass to 100 kg to allow for a useful payload would have increased the flight duration to more than 20 years. Faced with these insuperable difficulties, work on an orbiter was dropped and all efforts were focused on the Pluto Fast Flyby concept.

Two years later, in 1994, the out-year funding profile for the space sciences had deteriorated even further. Even with plans for Russian participation (providing launch vehicles) in the Pluto Fast Flyby, the costs to the United States still hovered around $600 million. New start plans for a Pluto mission were put on hold as scientists and engineers worked on a way to reduce costs even further.

In parallel with efforts to develop a realistic Pluto mission, another concept, the Kuiper Express "sciencecraft," was devised to investigate the feasibility of a mission to the Kuiper Belt. By removing the usual compartmentalization between spacecraft and instrument design to such a degree that the dividing line between spacecraft systems and scientific instruments becomes blurred, the sciencecraft reaps significant mass and, therefore, cost savings. Since a mission to a Kuiper Belt object would have many similarities to a Pluto mission, the sciencecraft concept was borrowed to form the basis of the Pluto Express mission detailed in *Pluto Express: Report of the Science Definition Team* (NASA, Washington, D.C., September 1995).

At first blush, the Pluto Express mission looks very similar to that proposed for the Pluto Fast Flyby. The Pluto (or Pluto-Kuiper) Express mission design does, however, include the option of an extended mission into the Kuiper Belt after the Pluto-Charon encounter, provided that no mission requirements are driven by this option. The Pluto-Kuiper Express concept envisages the launch in 2002, 2003, or 2004 of two spacecraft with four instruments apiece on Delta II launch vehicles. Use of the smaller Delta launch vehicle affects both the cost and the duration of the cruise to Pluto. For the ~$77 million cost of launch on a Delta II with an upper stage—as opposed to the Titan IV's cost of around $350 million—cruise time is lengthened from 7 to between 10 and 13 years depending on the exact launch date. An option to utilize solar-electric propulsion in place of a chemical upper stage could yield flight times under 10 years. In addition, the innovative engineering of the sciencecraft concept reduces development expenditures to $145 million to $200 million, depending on whether the mission flies one or two spacecraft. The mass of each spacecraft currently stands at ~100 kg.

While NASA includes discussion of the Pluto-Kuiper Express in its recent report *Mission to the Solar System: Exploration and Discovery—A Mission and Technology Roadmap* (NASA, Washington, D.C., 1996), where it is given a nominal launch date of 2001 to 2003, the only representation the mission currently has in NASA's budget is implicit; an "Outer Planets/Solar Probe" line item, slated for a new start in FY 2000, is included as an element of the Origins Initiative approved as a part of NASA's FY 1998 budget.

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5

Conclusions and Recommendations

Three of the themes for the scientific exploration of the trans-neptunian region (exploration of new territory, reservoirs of primitive materials, and processes that reveal the solar system's origin and evolution) involve using methods that have proven successful in the past. The methods required to push the boundaries of our knowledge beyond 30 AU are telescopic observations, spacecraft missions, and harnessing new technologies and human ingenuity. Addressing the remaining two themes—making links to extrasolar planet detection and studies of prebiotic chemistry—will require planetary scientists to take interdisciplinary approaches and to venture into new fields of research in cooperation with astronomers, chemists, and biologists.

For the next 10 to 15 years, the prime task on the path to exploring this new frontier of planetary science is to document fully the chemical and physical makeup of the objects that compose the trans-neptunian region. **COMPLEX recommends an approach that combines remote, telescopic observations of the bulk properties of a large sample of Kuiper Belt objects with close-up, spacecraft studies of the detailed properties of a few specific objects.** Ground- and space-based telescopic studies and spacecraft missions are ideally suited to surveys and detailed investigations, respectively. Since planetary missions are expensive and thus likely to be few in number, they must be directed toward specific objects likely to provide the greatest amount of information about the trans-neptunian region.

Subsequent sections outline how spacecraft, telescopic, and research and analysis programs can each contribute to the exploration of the trans-neptunian region. For each area, COMPLEX makes a baseline recommendation and then recommends one of more possible augmentations.

SPACECRAFT MISSIONS

The highest scientific priority for the exploration of the trans-neptunian solar system is extensive and detailed measurement of the fundamental physical and chemical properties of the Pluto-Charon system. Pluto is unique in that it is the largest known object in the trans-neptunian region and thus represents one of the end members of the Kuiper Belt population. Because Pluto and Charon are barely spatially resolvable from Earth, many of the relevant properties can be measured only by a robotic spacecraft. The evolution of NASA's thinking about the scope of a Pluto mission from the Cassini-class approach envisioned in the early 1990s to the "sciencecraft" concept formulated more recently by the Pluto Express Science Definition Team[1] (see Box 4.1) strongly suggests that the initiation of such a mission is consistent with NASA's budgetary expectations for the early years of the next decade.

A Pluto-Charon mission should be capable of characterizing the following:

- Precise sizes, masses, and shapes of Pluto and Charon to constrain models of their interior structures;
- Global geology and geomorphology to investigate endogenic and exogenic processes and to determine crustal evolution;
- Distribution and chemical composition of surface materials to elucidate the processes that probably led to outgassing, transport, redeposition, and chemical alteration of volatiles;
- Structure, composition, and escape rate of the atmosphere of Pluto;
- Nature of the solar wind interaction with Pluto's atmosphere and/or surface; and
- Magnetic field that might be remnant or generated in Pluto's interior.

Two spacecraft are essential for redundancy and to provide full coverage of the surfaces of Pluto and Charon. Spacing the encounters by a period of, say, 6 months would allow retargeting of the second spacecraft in response to observations made during the first encounter.

Augmented Spacecraft Program

A possible augmentation to the baseline Pluto-Charon mission described above is to consider the possibility of extending it to include flybys of one or more other Kuiper Belt objects (KBOs). **The scientific potential of any Pluto-Charon mission would be greatly enhanced by the spacecraft continuing on to visit another KBO and thus providing measurements of the size and surface characteristics of two different KBOs that have different histories.** While the probability of finding a KBO within range of a Pluto-Charon mission may be small, high priority should be given to telescopic searches for candidate targets along the trajectory of a Pluto mission. Such an augmentation should be considered only if it has no serious cost or schedule impact on a Pluto-Charon mission.

The outer solar system contains a wide variety of objects. Some of the underlying causes of this diversity (such as differentiated vs. homogeneous interiors, degrees of surface processing, and so on) can be fully explored only by space missions. COMPLEX hopes that experience with the Rosetta mission to a comet and Discovery-class missions to the inner solar system will pave the way for affordable spacecraft missions to outer solar system objects. Scientific priorities for spacecraft missions to the trans-neptunian region in the more distant future, after the successful conduct of a Pluto-Charon mission and a KBO flyby, are, in rank order, as follows:

1. **Returning to Triton,** one of the largest Kuiper Belt objects, to complete the characterization of the Pluto-Charon-Triton triad. Goals of such a mission should include exploring the unmapped hemisphere, constraining models of the interior with measurements of gravitational and magnetic fields, and investigating the expected temporal variations in Triton's atmosphere. Comparison of Triton with Pluto is especially important because these objects are of similar size and are thought to have similar origins, but Triton has probably experienced a very different thermal history owing to its capture by Neptune.
2. **Visiting a Centaur,** those icy objects that have orbits among the giant planets and are thought to be Kuiper Belt objects whose orbits have been perturbed by Neptune. Thus, close comparison of a Centaur object with objects that continue to reside beyond Neptune is important for understanding the processes that occur when an icy object is brought closer to the Sun.
3. **Encountering a suite of Kuiper Belt objects and/or Centaurs with different spectral and/or orbital characteristics.** Spectroscopic and photometric observations suggest that a wide variety of objects exist in the trans-neptunian region, and their different orbits indicate a range of sources. Each flyby provides ground truth for disk-integrated, telescopic observations. To fully interpret statistical studies of the properties of many Kuiper Belt objects, the range of object types needs to be sampled and studied in detail with spacecraft missions.

Spacecraft Technology

The technical challenges posed by returning substantial scientific data from the distant outer solar system remain formidable. Thus, **the development of mission-enabling technologies is an important adjunct to any program for the exploration of the trans-neptunian solar system.** To achieve the high launch energy required to get to distances >30 AU with current launch vehicles requires that the spacecraft mass be considerably reduced if outer solar system missions are to be affordable. The >10-year duration of missions demands high reliability of components and efficient mission operations. Spacecraft power and communication systems will require new technologies to improve efficiencies to allow the spacecraft to operate and transmit data back from >30 AU.

The development of spaceflight instruments capable of characterizing the physical and chemical properties of cold (<40 Kelvin) icy objects at distances >30 AU is another important adjunct to a trans-neptunian exploration program. Lightweight, multiwavelength cameras have been designed for inner solar system missions. The low temperatures of the trans-neptunian region require instruments that can image at longer (far-infrared) wavelengths (~100 microns). In addition to building larger detector arrays with very low power consumption, passive and active cooling systems need to be developed.

TELESCOPIC OBSERVATIONS

Even in an era of spacecraft missions to the distant outer solar systems, Earth- and space-based telescopic studies will remain an important source of information about Kuiper Belt objects. **Thus, continued support for both ground- and space-based telescopic studies is an essential aspect of a program for the exploration of the trans-neptunian solar system.** The highest priority for both ground- and space-based studies is significant access to existing and future moderate- to large-aperture telescopes equipped with modern instrumentation designed to meet the needs of planetary observers.

The primary source of information about the number and spatial distribution of outer solar system objects continues to be systematic use of ground-based telescopes to search for KBOs near the ecliptic plane. An efficient survey requires a modest telescope (2-meter class) with a large, efficient electronic detector. Detection of small, distant objects requires continued access to ~2-meter telescopes and, for the faintest objects, substantial access to 4-meter-class (and larger) telescopes in the future. In the absence of numerous dedicated spacecraft missions, high-resolution infrared and millimeter spectroscopy and far-infrared radiometry are the only means of determining the chemical composition and albedo of outer solar system objects. Thus, continued support of NASA's Infrared Telescope Facility and, in the near future, the Stratospheric Observatory for Infrared Astronomy for planetary studies is essential.

Observations of the distant outer solar system should be a primary goal of the next generation of space-based telescopes. These facilities will likely have higher spatial resolution, wider spectral range, and/or greater photometric sensitivity than either HST or the current generation of ground-based telescopes. **To be capable of making the critical measurements of trans-neptunian objects, future large space telescopes should be designed from the outset to incorporate the ability to track moving targets and to measure the thermal emission from small, cold (<40 Kelvin) objects.**

While access to telescopes is essential, the provision of adequate instrumentation is also important. **Support for the development of instruments that enhance telescopic observations of the trans-neptunian region is an important augmentation to a program of ground- and space-based observations of the distant outer solar system.** Efficient large detectors arrays are needed to increase the discovery rate of KBOs to allow the determination of statistical properties of KBO populations. Advancing our knowledge regarding the physical and chemical properties of the KBOs using both Earth- and space-based telescopes to determine accurate photometry and radiometry is directly related to having large, high-quantum-efficiency detector arrays, especially in the far infrared.

RESEARCH AND ANALYSIS

A combination of spacecraft missions and telescopic observations will provide much new data relevant to the trans-neptunian solar system, but this does not necessarily equate to new understanding. Only after the raw data have been thoroughly analyzed and placed in the context of existing research is new knowledge likely to arise. **Continued support for research and analysis programs and for relevant theoretical and laboratory studies is an essential component of a program of spacecraft and telescopic observations of the trans-neptunian solar system.** Theoretical and laboratory studies of the physical and chemical processes that influence the structure and evolution of cold (<40 Kelvin), icy bodies located in the trans-neptunian region should be fully supported to enhance the scientific return from spacecraft missions and telescopic observations.

The trans-neptunian solar system presents a range of environmental extremes quite unlike those found in more familiar parts of the solar system. As a result, common materials can exist in exotic states about which very little is known. Volatiles such as CH_4 and CO can, for example, exist as rocklike ices or as gases with chemistries more akin to that of the interstellar medium than that of any well-studied planetary atmosphere. **Enhancing the facilities available for laboratory studies of the properties of planetary materials at low temperatures (<40 Kelvin) and low pressures will be a useful augmentation to existing research efforts.**

REFERENCE

1. Pluto Express Science Definition Team, J.I. Lunine (chair), *Pluto Express: Report of the Science Definition Team,* NASA, Washington, D.C., 1995.

Glossary

Adiabatic—Describing a physical process occurring without the loss or gain of heat.

Adiabatic lapse rate—The rate at which the temperature of a parcel of gas changes with height as it moves vertically in a planetary atmosphere, in the absence of heating.

Albedo—The fraction of incident light reflected by a body.

Aphelion—The point at which a body is farthest from the Sun in its orbit.

Astronomical unit, AU—The mean distance from the Sun to Earth.

Atomic mass unit, amu—A unit commonly used to measure molecular masses, equivalent to the mass of one proton.

Centaur—A planetary body found in orbit around the Sun between the orbits of Neptune and Saturn, e.g., Chiron. These bodies typically display a variety of characteristics, ranging from asteroidal in appearance to cometlike. The nature of the Centaurs' orbits indicates relatively recent arrival at their present positions, leading scientists to theorize that Centaurs are migrated Kuiper Belt objects.

CHNOPS—Carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur: the key elements of living organisms.

Coma—The spherical envelope of gas and dust surrounding the nucleus of an active comet, created when the ambient heat causes the vaporization of comet material.

Comet—A volatile-rich body that develops a transient atmosphere, or coma, as it approaches the Sun. Most observed comets have highly elliptical orbits, sometimes approaching parabolic.

C-type asteroids—The largest class of asteroids, grouped according to their spectral characteristics. In general they have low albedos and are believed to have significant mineralogical similarities to the carbonaceous chondrite meteorites.

Declination—Celestial latitude, measured in degrees north or south of the ecliptic.

Differentiation—The process by which a planetary body becomes heterogeneously mixed, as heavier material sinks to its core and lighter materials float toward its surface.

Ecliptic—The plane of Earth's orbit around the Sun.

Endogenic—Relating to geological processes of internal origin such as mantle convection, volcanism, or plate tectonics.

Exobase—The bottom of the exosphere, the level at which a large fraction of atmospheric atoms and molecules can leave the atmosphere without colliding with another atom or molecule (those with sufficient speed will escape from the atmosphere).

Exogenic—Relating to geological processes of external origin such as impacts or fluvial erosion.

Galilean satellites—The four brightest moons of Jupiter—Io, Europa, Ganymede, and Callisto—first observed by the astronomer Galileo.

Hubble Space Telescope, HST—A 2.4-meter-aperture, low Earth-orbiting optical/ultraviolet telescope developed by NASA and the European Space Agency.

Interstellar medium, ISM—The gas and dust particles found between stars.

Kuiper Belt—A region of space containing icy planetesimals distributed in a roughly circular disk in the outer regions of our solar system, 50 to 100 AU from the Sun. Pluto is believed to circumscribe the innermost region of the Kuiper Belt.

Kuiper Belt object, KBO—A general name for the bodies found in the Kuiper Belt, a region in the outer solar system.

Major summer—Triton's seasonal cycle is extremely complex due to the peculiarities of its orbital geometry. Its seasons are modulated by the period of its motion around Neptune (14 days), the precession of its orbit (688 years), and Neptune's rotation around the Sun (165 years). The net result is that Triton experiences a series of major and minor seasons as the amplitude of its seasonal cycle is driven by these various modulations.

Material unit—A generic term used in place of rock unit, sediment, formation, and so on when the exact geological nature of a three-dimensional body of material is unknown.

Mutual events—A series of occultations and transits in which a number of celestial bodies form apparent alignments along an observer's line of sight.

Occultation—The obscuration of one celestial body by another of greater apparent diameter, as occurs, for instance, in the passage of an asteroid or comet in front of a star.

Oort Cloud—A spherical distribution of comets having semimajor axes between 1,000 and 50,000 AU, typically with low orbital eccentricity.

Orbital resonance—A phenomenon that occurs when the mutual gravitational interaction between two planetary bodies causes their orbital periods to have a ratio expressible in small, whole numbers. For example, for every two times that Neptune orbits the Sun, Pluto revolves three times.

Perihelion—The point at which a body's orbital motion takes it closest to the Sun.

Phase space—A multidimensional plot showing the positions and velocities of particles in a dynamical system. The trajectory followed by any particular particle represents the evolution of that particle's dynamics as a function of time.

Planetesimals—The planetary bodies that formed the building blocks of all the solar system's planets and satellites.

Radiogenic heating—Heating of a celestial body due to the decay of radioactive isotopes.

Retrograde motion—The rotational or orbital motion of a planetary body opposite to the dominant direction of the orbiting and rotating of the Sun and planets. In our solar system, retrograde motion is clockwise as viewed from the north pole of the ecliptic. Triton's orbit around Neptune and Venus's rotation are both examples of retrograde motion.

Solar nebula—The cloud of gas and dust from which our Sun, planets, and other bodies in our solar system formed.

Spectrum—The characteristic emission or absorption of certain electromagnetic frequencies by elements and compounds.

Stratosphere—The region above the troposphere where the atmosphere becomes stably stratified as a result of solar heating.

Thermosphere—The uppermost region of an atmosphere, where the temperature increases with height as a result of strong heating from above and where molecular diffusion of heat plays a major role in vertical heat transport.

Tholin—the reddish tarlike organic residue created in simulations of the action of ultraviolet radiation on gases typically found in planetary environments.

Tidal heating—The internal heating of a planetary body due to friction caused by the differential gravitational effect of an external body on the mass in question.

Transit—The apparent passage of one body across the disk of a larger companion.

Tropopause—The top of the troposphere and the base of the stratosphere.

Troposphere—The lowermost portion of a planetary atmosphere, in which temperature decreases with height and thermal convection takes place.

T Tauri star—A type of irregular variable star whose spectrum shows broad and very intense emission lines. They are believed to be very young stars that have not yet reached the main sequence.

Voyager—A pair of deep-space missions launched by NASA to the outer solar system in 1977. Combined, Voyagers 1 and 2 have conducted close-up observations of Jupiter (1979, 1979), Saturn (1980, 1981), Uranus (1986), and Neptune (1989).

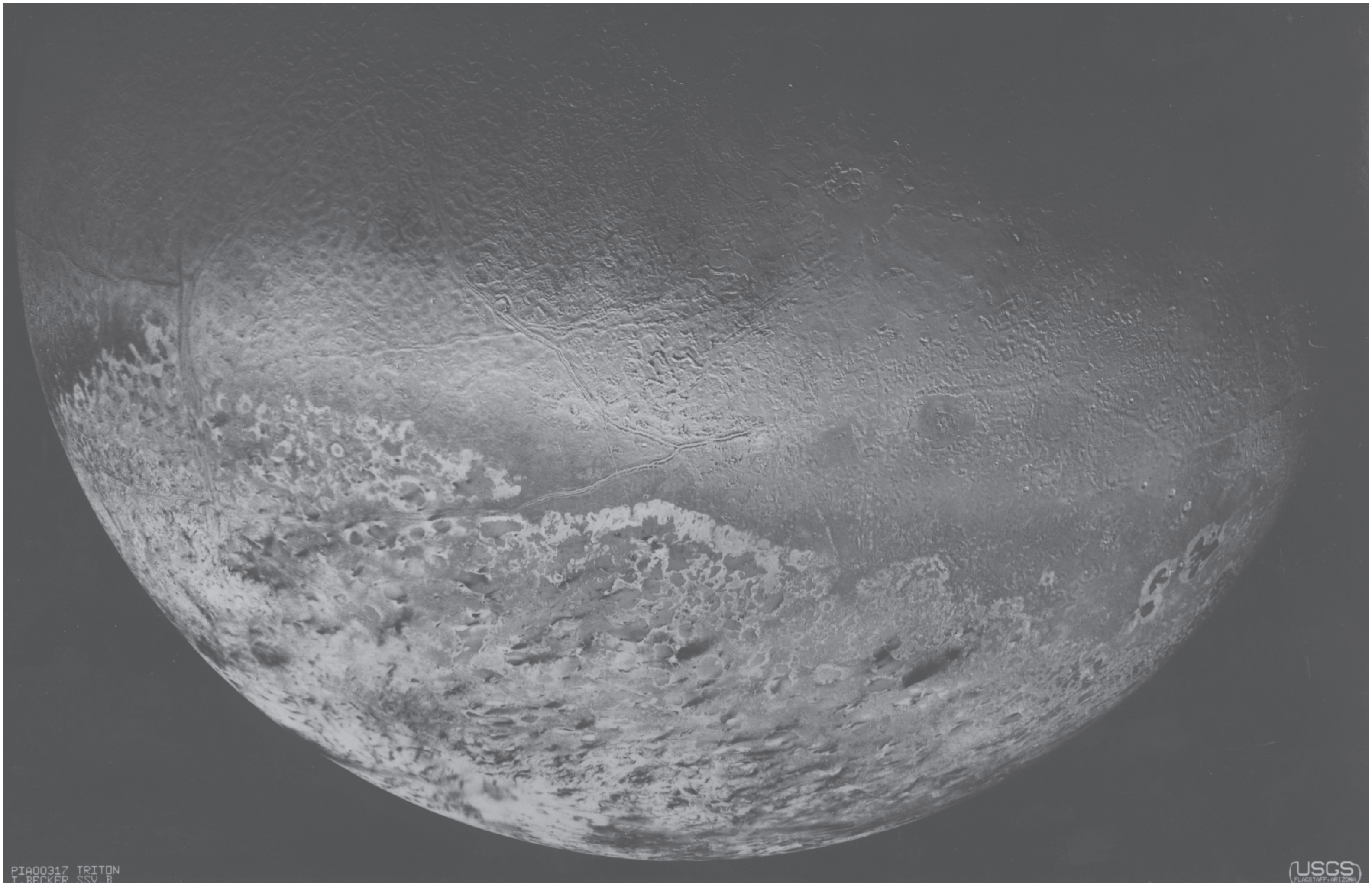

PLATE 1 Voyager 2 image of Triton. This photomosaic provides an overview of the portion of Triton's surface seen at high resolution (1 km/pixel). The equator runs approximately through the center of the bright, bluish swath across the middle of the mosaic. Bright materials irregularly blanket most of the southern hemisphere, at the bottom. The darker plains consist of the rugged "cantaloupe" terrain, at the upper left, and a complex mix of smooth and knobbly plains, at the right. The bright material is interpreted to be deposits of solid nitrogen incorporating small amounts of methane. The bluish tint is characteristic of fresh frosts, while the reddish tint is interpreted as being due to partially irradiated methane. Image courtesy of A.S. McEwen, U.S. Geological Survey.

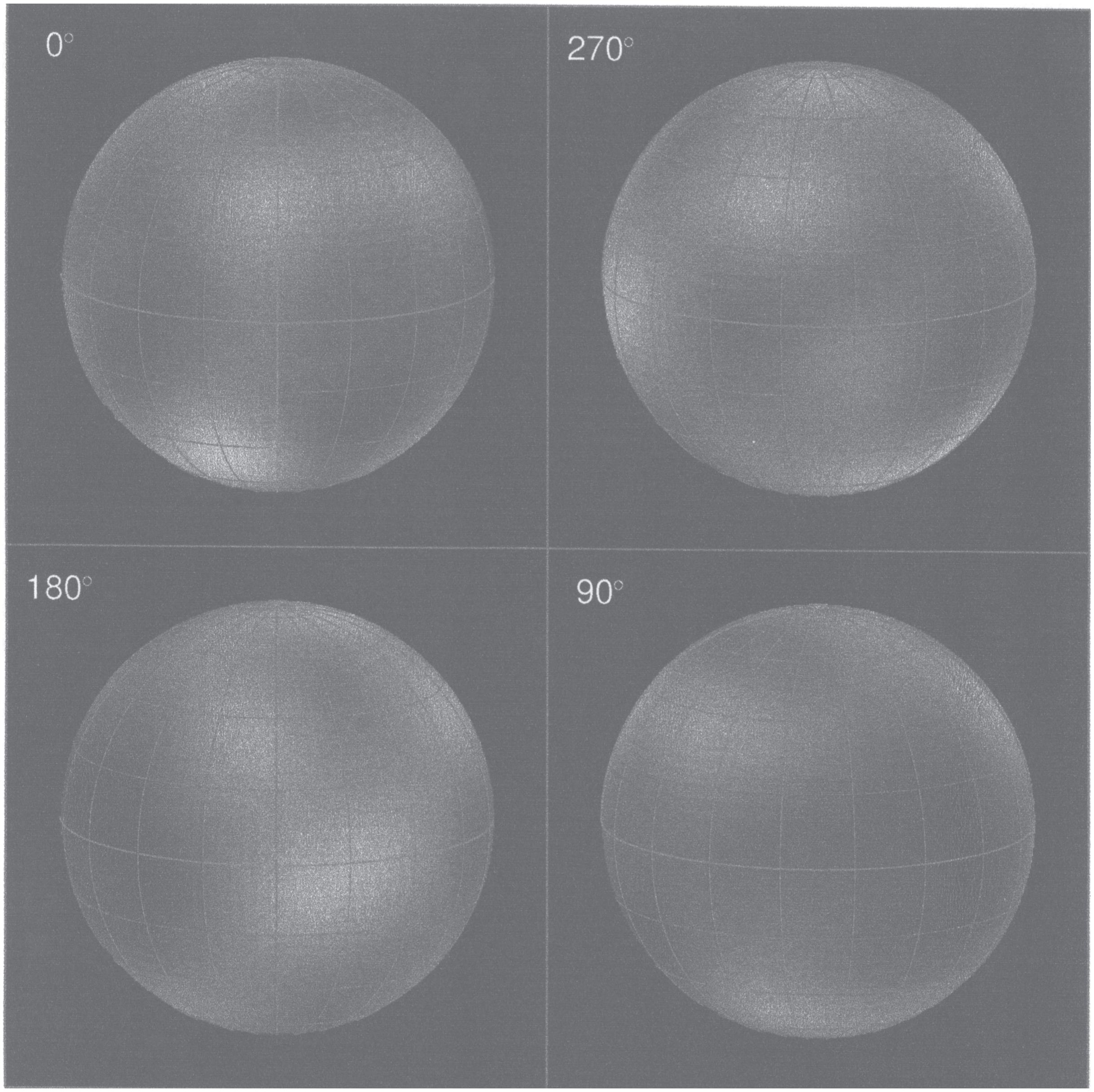

PLATE 2 The European Space Agency's Faint Object Camera on the Hubble Space Telescope (HST) imaged most of the surface of Pluto, as it rotated through its 6.4-day period, in late June and early July 1994. The maps shown here are from a global map constructed through computer image processing performed on the Hubble data and rendered onto three-dimensional globes at 90° increments in longitude. The rendered color was derived from the rotationally averaged ground-based observations of Pluto. With a resolution corresponding to more than 600 km, HST discerns roughly 12 major "regions" where the surface is either bright or dark. These images show that Pluto is an unusually complex object, with more large-scale contrast than any planet except Earth. Some of the variations across Pluto's surface may be caused by topographic features such as basins or fresh impact craters. However, most of the surface features unveiled by HST, including the prominent northern polar cap, are likely produced by the complex distribution of frosts that migrate across Pluto's surface with its orbital and seasonal cycles and chemical by-products deposited out of Pluto's nitrogen-methane atmosphere. Image courtesy of Alan Stern, Southwest Research Institute; Marc Buie, Lowell Observatory; NASA; and ESA.

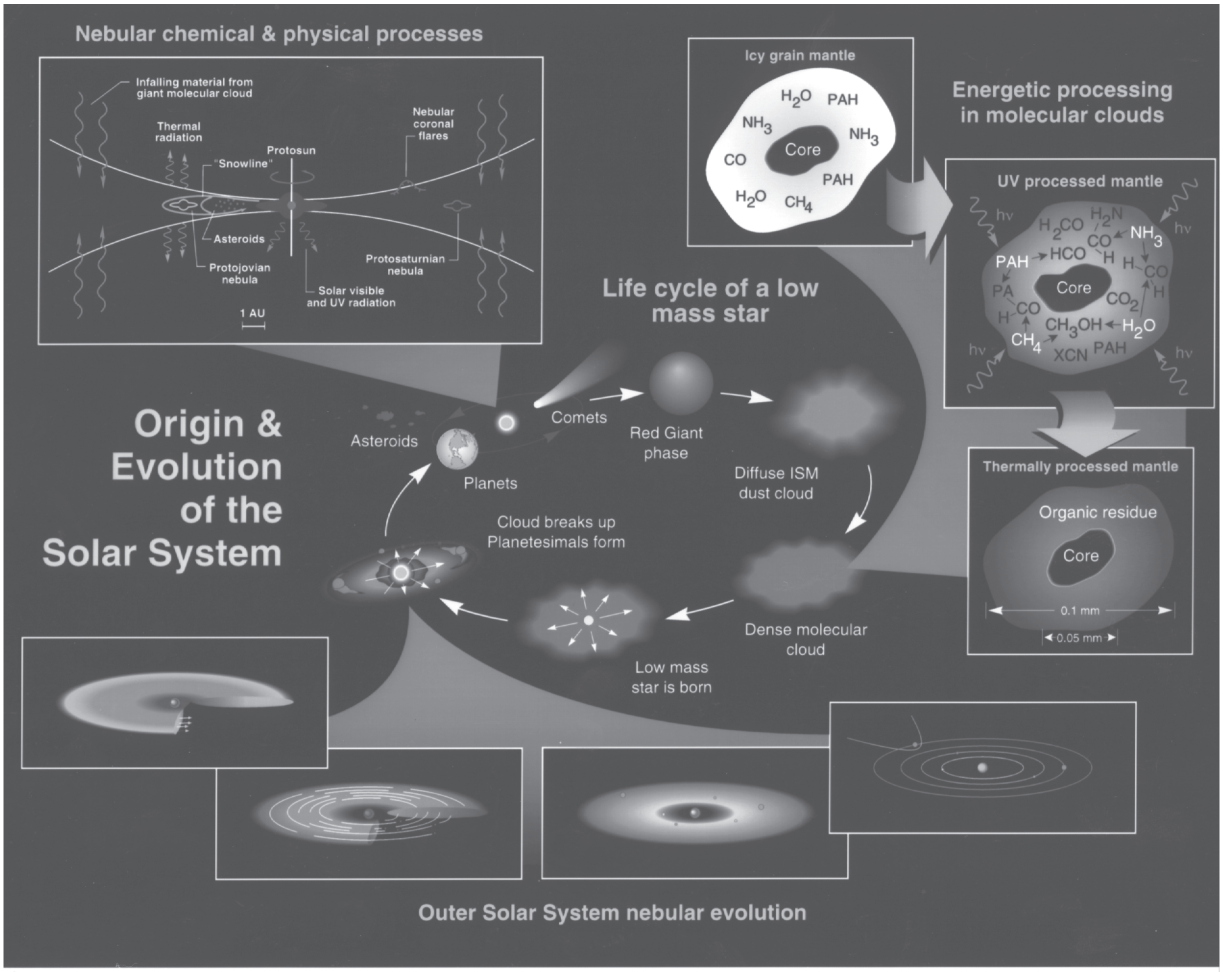

PLATE 3 Schematic of the various stages of solar system origin and evolution. The central panel outlines the life cycle of a typical low-mass star. It shows, in particular, the intimate connection between the interstellar molecular clouds within which stars like the Sun condensed and the planetary systems formed by accretion within the protoplanetary disk surrounding the new star. The chemical elements created by nuclear reactions in the star's core and dispersed into the interstellar medium during the star's red giant phase become the raw material for new generations of stars and planetary systems.

The three panels in the upper right illustrate how initially pristine icy grains can be energetically processed within dense molecular clouds to yield more chemically complex materials. The four lower panels outline various stages in the evolution of the planetary bodies of the outer solar system. They illustrate (from left to right) the evolution of the gas and dust forming the protoplanetary disks through the formation of planetesimals, the accretion of the cores of the major planets, and the subsequent dissipation of remnant nebular material and the ejection of any remaining planetesimals into the Kuiper Belt and Oort Cloud. The panel in the upper left shows some of the various physical and chemical processes that acted within the protoplanetary disk during the various stages in the formation of the planets. The resulting solar system contained a diversity of objects and regions, some of which, like the Kuiper Belt, are beginning to be explored.

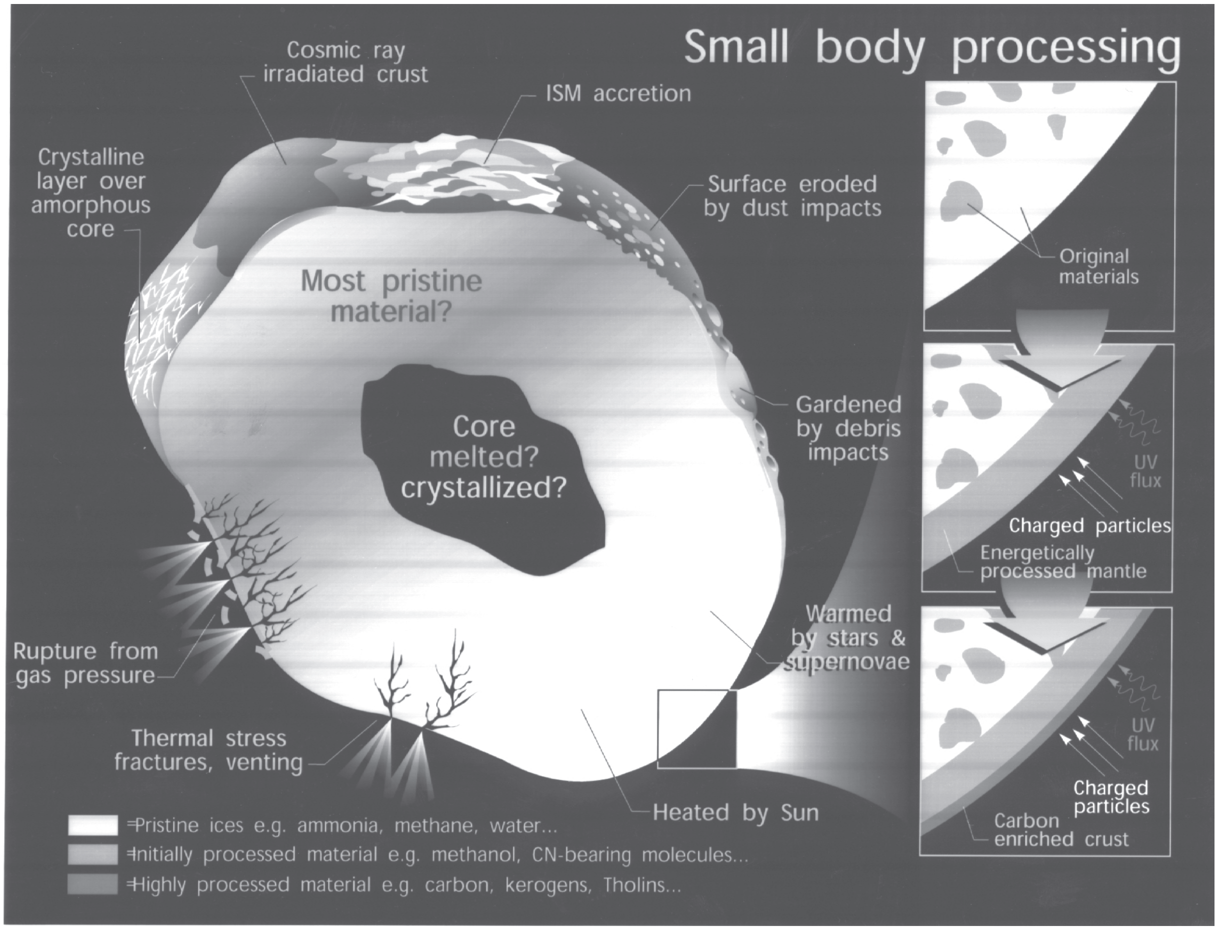

PLATE 4 Small-body processing. This diagram illustrates the variety of processes that can occur on small bodies. These include heating events from external sources (e.g., the Sun), as well as internal events, provided the object can incorporate enough radiogenic components. At the right is a schematic of the influence of energetic processing that can alter the original materials and produce a carbon-enriched crust.