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Strategy for Exploration of the Outer Planets: 1986-1996

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Over the past decade COMPLEX has published three strategy reports which, taken together, encompass the entire planetary system and recommend a coherent program of planetary exploration. The highest priority for outer planet exploration during the next decade is intensive study of Saturn -- the planet, satellites, rings, and magnetosphere -- as a system. The Committee additionally recommends that NASA engage in the following support activities: 1) increased support of laboratory and theoretical studies; 2) pursuit of earth-based and earth-orbital observations; 3) commitment to continued operation of productive spacecraft; 4) implementation of the instrument development plan as appropriate for the outer solar system; 5) studies of deep atmospheric probes; 6) development of penetrators or other hard landers; 7) development of radiation-hardened spacecraft; and 8) development of low-thrust propulsion systems. Longer-term objectives include exploration and intensive study of: 1) the Uranus and Neptune systems; 2) planetology of the Galilean satellites and Titan; and 3) the inner Jovian system.

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1986-1996

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A STRATEGY FOR EXPLORATION OF THE OUTER PLANETS: 1986-1996

Committee on Planetary and Lunar Exploration
Space Science Board
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

NATIONAL ACADEMY PRESS
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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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I
Introduction

Over the past decade, the Committee on Planetary and Lunar Exploration (COMPLEX) has published three strategy reports, which, taken together, encompass the entire planetary system. The first, *The Outer Planets*, is included in the Space Science Board's *Report on Space Science, 1975* (published in 1976). *Strategy for Exploration of the Inner Planets: 1977-1987* and *Strategy for Exploration of Primitive Solar-System Bodies—Asteroids, Comets, and Meteoroids: 1980-1990* were published in 1978 and 1980, respectively. Together with the present report, these volumes recommend a coherent program of planetary exploration. It is impossible to balance so large a program at any instant, but over a time scale of 10 to 15 years it is achievable. A challenging and responsive effort along the broad front of planetary science will incorporate the three phases of *reconnaissance*, *exploration*, and *intensive study*. As defined in the 1976 report, these phases involve the identification of major characteristics; systematic discovery and understanding; and in-depth pursuit of sharply formulated, specific problems. It is nearly always a mistake to depart from this orderly sequence.

The principal recommendations of the 1976 report have been implemented in part by the successful Voyager reconnaissances of Jupiter, Saturn, and Uranus. Implementation will be complete if all parts of the intensive study of the Jupiter system by Galileo are successful. The two outer planets, Neptune and Pluto, were considered in the 1976 report to be too distant to include as goals in the 1975-1985 exploration strategy.

A new strategy for the outer solar system is therefore needed, and is provided here. Its principal recommendation, for intensive study of the Saturn system, was foreseen in the 1976 report. Reconnaissance of the Neptune system by the 1989 Voyager-Neptune encounter is an important element of the new decadal strategy. Further studies of the Jupiter, Uranus, and Neptune systems are likely to be important; they should not be defined until the Voyager and Galileo encounters, and may need technological development as well. Despite its great interest, the Pluto system has been omitted from current consideration.

The purpose of planetary science is to discover and understand the nature of solar system bodies, including their enveloping atmospheres, magnetospheres, and rings. Specifically, we need to understand the origin and evolution of individual objects in the context of the solar system, the present physical and chemical states of the bodies, and the processes operating in them. A complete understanding also must eventually encompass all scales of the solar system from the giant gaseous planets of the outer region to the microscopic particles that make up the zodiacal light and the interplanetary medium. The proper appreciation of the most important planet to mankind—Earth—requires the perspective acquired from knowing the different ways in which planets evolve and the controlling factors in this process. In addition to its primary goals, a vigorous program of planetary exploration has important secondary consequences, such as the fostering of the technological innovations and awareness critical to modern society. An additional benefit can be a flow of young scientists who have both a broad interdisciplinary knowledge of the natural and physical sciences and a familiarity with advanced technology.

A strategy such as this one should serve several related purposes. Primarily, it gives long-term guidance to agencies (in this case almost exclusively NASA). For others, including the legislative branch, it can serve as a guide to a proper pace of the overall effort. Later, it can be used as a standard to help assess the actual program and its accomplishments. COMPLEX strategies define a baseline, or minimum planetary program for the United States. A greater level of effort than recommended here is highly desirable. The present strategy contains prioritized scientific objectives for the next phase of outer solar system investigations. As in the past, COMPLEX has set general goals independent of specific missions.

Nevertheless, the recommendations have considered technical feasibility with the consequence that some very important objectives (e.g., exploration of Pluto by orbiting spacecraft) are not currently recommended.

Assuming a successful encounter by the Voyager 2 spacecraft with Neptune, the end of the decade will have produced at least preliminary reconnaissance of eight of the nine planets and the Moon, as well as many of the other large satellites and rings. These have, without exception, turned out to be fascinating and unique objects. The Martian volcanoes and channels, the elevated regions of Venus, and the Io volcanoes are spectacular examples. However, our degree of knowledge ranges from a slim characterization of many smaller outer planet satellites to comparatively detailed understanding of the Moon. Except for the Giacobini-Zinner flyby by the ICE satellite in 1985, the small primitive bodies—comets and asteroids—remain largely or completely unvisited by spacecraft. This serious observational gap has been only partly filled by the Soviet, European, and Japanese encounters of Comet Halley, and a likely future asteroid flyby of the Galileo mission. Meteorites retain their importance as representing a surprisingly diverse array of material, most of which dates to early periods of the solar system, and carries isotopic, chemical, and mineralogical signatures of proto-solar conditions. Planetary objects formed from similar material. Overall, two decades of solar system exploration, beginning with the first Pioneer, Mariner, and Ranger spacecraft, have transformed discussion of the solar system from near-science-fiction levels, given the vast uncertainties then existing, to an important and vigorous branch of science. In our perceptions, planetary bodies have evolved from mere points of light, a challenge to the observational skills of even the best astronomers, into mapped, textbook objects. Planetary science will continue to be an area of major scientific importance for the next decade and beyond, and continuing vigorous activity in this field is fully justified.

The next chapter summarizes the principal recommendations. In Chapter III the accomplishments of Pioneers 10 and 11 and Voyagers 1 and 2 are set out. Chapter IV is organized by planetary body, giving for each the current state of knowledge and the principal open questions. Chapters V and VI contain discussions and recommendations for support activities such as laboratory and theoretical science and Earth-based observations, and hardware developments needed for future planetary exploration. The recommended strategy is given in Chapter VII.

II
Summary of Strategy and Recommendations

The detailed recommendations of this report appear in Chapter VII, and the rationale for them in Chapters IV through VI. For convenience, a summary is given here.

A. MAJOR OBJECTIVES

1. The Saturn System

The highest priority for outer planet exploration in the next decade is intensive study of Saturn—the planet, satellites, rings, and magnetosphere—as a system. Implementation of this strategy should address several broad areas of study and provide a basis for their cross-comparison. Important scientific objectives are as follows: reconnaissance of the physical state of Titan's surface; measurements of the composition and structure of the atmospheres of Titan and Saturn; detailed, long-term studies of Saturn's rings; and investigation of Saturn's small satellites and Saturn's magnetosphere.

Specifically, the recommended exploration and intensive study of the Saturn system includes the following objectives:

- *Titan's atmosphere—measure the composition, structure, and circulation of Titan's atmosphere, and characterize the atmosphere-surface interaction.*
- *Titan's surface—carry out a reconnaissance of the physical properties and geographical variability of Titan's surface: solid or*

liquid, rough or smooth. Emphasis should be given to any information needed to guide the design of a lander vehicle.

- *Saturn's atmosphere—determine the elemental composition, dynamics, and cloud composition and structure, to a level well below the H_2O cloud base.*
- *Saturn's rings—measure particle composition and its variety, spatial distribution of particles, and determine the evolution of dynamic structures.*
- *Saturn's small satellites--make comparative determinations of surface composition, density, geologic history, and geomorphological processes.*
- *Saturn's magnetosphere—specify the structure, dynamics, and processes, and the material interactions of the magnetosphere with Saturn's atmosphere, rings, icy satellites, Titan, and the solar wind.*

The preferred strategy addresses the central elements of the Saturn system. Such an integrated, multidisciplinary study of the Saturn system is the top priority for outer solar system planetary exploration during the next decade. It is expected to provide major scientific returns in broad areas of planetary science. Such a system approach implies implementation by a large, expensive mission. If smaller missions are required by financial constraints, the interrelated nature of the system must be kept in mind, as well as the urgency of a reconnaissance of Titan's surface. If any of the major Galileo objectives is not realized, the implementation of this strategy would have to be reconsidered.

2. Longer Term Strategy for the Outer Solar System

The next priority for outer planet exploration is assigned to post-1995 objectives that depend on the results of current missions (reconnaissance by Voyager and exploration by Galileo), developments in instrumentation, and demonstrations of technical feasibility. Specifically, these longer term objectives include exploration and intensive study of the following:

- *Uranus and Neptune systems—(1) elemental composition, cloud structure, and meteorology of the planetary atmospheres; (2) rings and satellites (especially Triton); and (3) structure and dynamics of magnetospheres.*

- *Planetology of the Galilean satellites and Titan—surface composition and physical properties, seismic activity, heat flow, and, where applicable, atmospheric composition and meteorology.*
- *Inner Jovian system—density, composition, and energy of magnetospheric particles; large-scale structure, rotation, and time-dependent phenomena in the Io torus, and relation to Io and other satellites, orbiting gas and plasma, auroral activity on Jupiter, and electromagnetic emissions.*

From a purely scientific point of view, these objectives for the longer term have high priority. However, further investigation of Uranus and Neptune should follow reconnaissance by Voyager, and should follow intensive studies of Jupiter by Galileo and of Saturn to make use of the technical and scientific experience of such missions. The environment of the inner Jovian magnetosphere is a serious hazard to the electronics and detectors of spacecraft and instruments. Close-in studies of the Galilean satellites and in situ studies of the inner magnetosphere may be impossible until these problems can be solved.

B. SUPPORT ACTIVITIES

A scientifically balanced strategy for exploration of the outer solar system includes not only building and flying deep space probes with existing technologies, but also developing new enabling technologies, expanding laboratory facilities, and promoting excellence in data analysis, theoretical interpretation, and modeling. These issues are discussed in Chapters V and VI. Accordingly, *the following recommendations are made to meet the near-term and long-term objectives for exploration of the outer solar system*:

1. *Increased support of laboratory and theoretical studies (section V.A).*
2. *Pursuit of Earth-based and Earth-orbital observations (section V.B).*
3. *Commitment to continued operation of productive spacecraft (section IV.C).*
4. *Implementation of the instrument development plan as appropriate for the outer solar system (section VI.A).*
5. *Studies of deep atmospheric probes (section VI.B).*

6. *Development of penetrators or other hard landers (section VI.B).*
7. *Development of radiation-hardened spacecraft (section IV.D.2).*
8. *Development of low-thrust propulsion systems (section VI.C).*

III

Current Activities and Missions

This strategy for study of the outer planets is based on the accomplishments of active and past missions. Current knowledge informs us of the important scientific questions and of the likely return from proposed investigations. Spacecraft missions provide so much new information that much of the previous understanding is outdated; even if the new information does not wash away some earlier ideas, our interpretations are strongly influenced by it. The strategy is dependent also on results expected from currently approved missions that are under development or en route to their targets. COMPLEX strategy is directed toward systematic planning of intensive studies, based on results from reconnaissance and exploration by earlier missions. Thus, mission cancellations and failures may mean a return to an earlier phase: parts of the new strategy proposed here may need to await the completion of the objectives of the 1976 Outer Planets Strategy.

COMPLEX reports, such as the present one, lay out a strategy but do not discuss its implementation by specific missions. Two other bodies have been charged with working out such implementations and recommending specific sequences of missions. They are NASA's Solar System Exploration Committee and the Joint Working Group on Cooperation in Planetary Exploration of the National Research Council and the European Science Foundation; their reports are discussed in section A. Findings of NASA's current missions and expectations for their future accomplishments are discussed in section B.

A. ADVISORY GROUPS

1. Solar System Exploration Committee (SSEC)

The SSEC was chartered in 1980 by the NASA Advisory Council to formulate a long-range program of planetary missions. This program was to take into account the published strategies of COMPLEX, and the membership included the past and the current chairmen of COMPLEX. Part 1 of the report was published in 1983 ("Planetary Exploration through Year 2000: A Core Program"; summary by D. Morrison and N.W. Hinners in *Science*, volume 220, pages 561-567, 1983). Part 2, recommending a small number of augmented missions, was published in 1986. COMPLEX reviewed Part 1 at a meeting in March 1983, seeking especially to judge the SSEC's proposed Core Program for consistency with, and responsiveness to, COMPLEX's published goals for scientific exploration of the solar system. This judgment had to be tempered by the fact that the Core Program is only part of the whole, and specifically excludes any missions requiring new "enabling technology," such as Mars sample return. The judgment was positive, with a few specific comments and suggestions, quoted from a letter of May 18, 1983, from the chairman of COMPLEX to the chairman of the SSEC:

> (1) The report is successful in defining a scientifically valid core program for planetary exploration through the year 2000. The emphasis on a stable, ongoing base of support for planetary exploration and the associated basic research programs is especially important.
>
> (2) COMPLEX endorses the approach of starting with a core program of Planetary Observer and, later, Mariner Mark II spacecraft.
>
> (3) COMPLEX endorses the SSEC's ongoing study of augmentations to the core program. Adoption of a core program should not lead to abandonment of larger, more exciting projects, if national priorities were again to shift toward exploring the solar system and understanding its origins.
>
> (4) The initial missions in the core program recommended by SSEC (Venus Radar Mapper, Mars Geoscience/Climatology Orbiter, Comet Rendezvous/Asteroid Flyby, Titan Probe/Radar Mapper) are consistent with the published COMPLEX recommendations and represent a reasonable balance. COMPLEX agrees with the SSEC that the Saturn system is the logical target for the outer solar system after the Galileo mission and the Voyager mission to Uranus. However, the published recommendations of COMPLEX for the Saturn system were formulated before the Voyager results were available, and are currently being reconsidered.

> COMPLEX regards both Titan and Saturn as having high scientific priority. SSEC's choice of Titan as the first target is reasonable in view of this option. (See the comment below.)
>
> (5) Endorsement of the report does not, and should not, imply endorsement of the specific instrument payloads suggested by SSEC for the various missions. They were meant to be illustrative and should be so regarded. All the missions require further definition, but especially those after the initial four.
>
> (6) The Space Science Board has also briefly reviewed the SSEC's proposals, particularly the cost projection at a level of 300 million dollars (FY 1984) per year. The Board points out that there is little or no growth in the Research and Analysis and the Mission Operations and Data Analysis lines to match the growth of flight programs, and is concerned that the level of scientific activity will be inadequate to support these programs.

Part (4) above anticipates the present report. Having reconsidered its 1976 recommendations for the outer solar system in light of Voyager results, COMPLEX now concludes that an integrated, multidisciplinary study of the Saturn system is the top priority for the next decade. The preferred strategy addresses the physical characterization of Titan's surface, determination of the atmospheric composition of Titan and Saturn, and further study of the Saturnian atmosphere, rings, magnetosphere, and satellites. The SSEC Core Program is more limited in scope, but is entirely consistent with the recommendations of the present report. A broader approach, such as the Titan Probe and Saturn Orbiter recommended by the Joint Working Group (JWG) and discussed below, would be preferable.

As of mid-1985, the Core Program was proceeding well, with the Venus Radar Mapper and the Mars Geoscience-Climatology Orbiter (now Mars Observer) approved and in development. However, the Comet Rendezvous-Asteroid Flyby (CRAF) mission, the third of the four basic components of the initial Core Program, was not approved on schedule in Fiscal Year 1987, and the status of the Program may have been heavily impacted by the Challenger disaster. Rapid approval of the CRAF mission is essential to the survival of the Core Program concept of planetary exploration, and to implementation of the current COMPLEX strategy for exploration of primitive solar system bodies. CRAF is to be the first flight of a Mariner Mark II spacecraft, and will use a considerable amount of inherited hardware and existing designs. However, future spacecraft will combine this approach with new designs, which will be inserted into the stream as they become available and cost-effective. COMPLEX views this approach as highly responsible. The space program, and its planetary component, should contribute to the technological state of the art; the program meets the nation's need to allow its managers and creative engineers to participate in such advances. The Mariner Mark II approach effectively combines the cost savings of inheritance and the valuable features of new hardware.

2. The Joint Working Group (JWG) on Cooperation in Planetary Exploration

The JWG was set up in the summer of 1982 by the Space Science Board of the U.S. National Research Council, and the Space Science Committee of the European Science Foundation. The final report of the JWG was accepted by the Space Science Board and was transmitted to COMPLEX for detailed review on its behalf. This review was accomplished at a meeting in December 1983 and subsequently by mail.

The JWG was established

> for the purpose of putting forward a framework for a new level of U.S.-European cooperation in planetary exploration. The JWG was charged specifically to explore the desirability of carrying out jointly planned and jointly executed space missions to planets and to primitive solar-system bodies. The JWG was also charged to examine the potential approaches to cooperation, to set forth the principles on which joint planetary science investigations are to be conducted, and, in consultation with NASA and ESA, to formulate a strategy, including specific missions, that would constitute a program of such collaboration.

The JWG recommended that a program of three missions be accomplished

> as cooperative projects, shared approximately equally by NASA and ESA, by the turn of the century. The projects, listed in order of the recommended launch sequence, are: (1) Titan Probe and Saturn Orbiter Mission; (2) Multiple Asteroid Orbiter with Space Electric Propulsion, and (3) Mars Surface Rover Mission. Of these three projects, two—the Titan Probe and Saturn Orbiter, and the Multiple Asteroid Orbiter—are scientifically exciting projects which can be accommodated within the agency programs as presently conceived. By this we mean that, for each of these two projects, each side's share of the costs is comparable to the costs of the projects currently included in the independent programs. The other one—the Mars Surface Rover—is a technically and scientifically ambitious mission that will require a special joint commitment of

the sponsoring governments beyond the ongoing agency programs in their present forms.

All these proposed missions fit well into the COMPLEX strategy. The Titan Probe and Saturn Orbiter concept combines two of the SSEC core missions and therefore would lead to an earlier implementation of part of the strategy of the present report. In 1984, NASA and the European Space Agency formed a joint science study team to do a joint engineering study of this "Cassini" mission. The orbiter would be a Mariner Mark II, with the probe vehicle supplied by ESA.

These welcome developments illustrate the benefits of international cooperation. Formal collaboration with the Soviet Union was regrettably almost shut off in the early 1980s as a consequence of political developments. Despite this lapse in formal agreements, considerable participation by U.S investigators on the Soviet VEGA (Venus-Halley) mission took place through arrangements facilitated by third countries. Information exchange still continues, and the biennial meetings of the International Council of Scientific Union's (ICSU) Committee on Space Research (COSPAR) are particularly valuable. There is great scientific value in actual exchange of experiments, as well as collaborative arrangements such as the proposed mission to Titan and Saturn. *COMPLEX reaffirms its position that such arrangements should be encouraged and broadened as much as other circumstances permit.*

B. MISSIONS IN PROGRESS

1. Jupiter

Voyagers 1 and 2 were launched in 1977 and flew by Jupiter on March 5 and July 9, 1979, respectively. Voyagers are three-axis stabilized spacecraft derived from the earlier Mariner series (the original name for the mission, used in the 1976 COMPLEX report, was Mariner Jupiter-Saturn). They were designed to follow up original studies by Pioneers 10 and 11, which encountered Jupiter in 1973 and 1974. The payload of the Voyager spacecraft includes cameras, spectrometers, and a polarimeter, a set of instruments to measure electromagnetic fields and charged particles, and several experiments based on the use of the radio system. The optical instruments are aligned with each other and mounted on a movable platform that can be commanded to point in a desired directio

Both Voyager Jupiter encounters were extraordinarily successful. More than 30,000 images were taken of Jupiter, its satellites, and its ring. These included the first close-up images of the Great Red Spot, the four large (Galilean) satellites, and the discovery of the ring. The magnetosphere of Jupiter was sampled along the spacecraft trajectories. Many unexpected phenomena were observed.

Jupiter's clouds were photographed in great detail. The motions of the clouds indicate the wind patterns on Jupiter: the winds are dominantly east to west, but smaller meridional motions are also seen. The wave component of the winds feeds energy into the mean zonal flow. The helium and nitrogen abundances on Jupiter are close to those found in the Sun and other stars. Pictures of the dark side of Jupiter show immense auroras and lightning storms.

The magnetosphere of Jupiter is an enormous physical domain 10 times the diameter of the Sun. It contains mostly ions of hydrogen, but also unexpectedly large amounts of sulfur, oxygen, and other elements ejected from the moon Io. Io's orbit is the locus of a very dense region of ions that emits optical and ultraviolet radiation of still unexplained intensity.

Although a narrow ring around Jupiter had been suggested from Pioneer 11 energetic particle data, the spectacular Voyager images of it came as a surprise. The ring is much narrower than the broad rings of Saturn and is made of very small, dark particles.

Each of the Galilean satellites of Jupiter is unique and is a world in its own right. Ranging in size from just smaller than the Moon to larger than Mercury, each has its distinctive geology. Callisto's surface is old and cratered; Ganymede has rayed craters and grooved terrain, showing some reworking of the surface; Europa is exceedingly smooth with intersecting bright and dark ridges; and Io's surface is the youngest in the solar system, splotched with pale tints of red, orange, white, and black by volcanic flows and fumarolic deposits.

Io is the most geologically active body in the solar system. Nine active volcanoes were seen by the Voyagers. The surface is covered by sulfur in various forms, including possible liquid, and SO_2 frost. The source of the energy that drives the volcanic activity is believed to be heating of Io's interior by tides of Jupiter. Huge electric currents that flow between Io and Jupiter generate intense radio emissions and may contribute to the heating.

The Galileo mission to Jupiter was developed for a 1986 launch from the Space Shuttle, but is now rescheduled for a late 1980s or early 1990s launch as a result of the Challenger accident. This mission, together with the completed Voyager-Uranus encounter and current planning for a Titan-Saturn mission, responds to the highest priorities for the outer planets recommended by COMPLEX in 1976. Galileo consists of an orbiter and a probe that will descend into Jupiter's atmosphere; the orbiter has both spinning and stabilized sections. A pointable scan platform supports the camera, spectrometers, and polarimeter. The instruments on the spinning part can survey magnetospheric fields and charged particle fluxes from nearly all directions. The orbiter will successively approach most of the large satellites of Jupiter, each encounter propelling it into a slightly different orbit. These successive orbits will sample regions inaccessible to flyby missions.

The probe will measure the following: profiles of atmospheric temperature and pressure down to below the water clouds on Jupiter; the locations and densities of cloud layers and the absorption of sunlight with depth; the chemical composition of the atmosphere in the region down to 12 to 20 bars; the presence of lightning; and energetic particles in the innermost magnetosphere. The orbiter has the following objectives: map the surfaces of the Galilean satellites at high resolution and yield inferences of surface compositions; monitor Io's volcanoes; sample all parts of the magnetosphere (including the "tail" extending far away from the Sun) and observe its time variation; permit inferences of sources, sinks, and lifetimes of charged particles; study the atmospheres and ionospheres of the satellites; observe properties of Jupiter's atmosphere and clouds, their history and their interaction; and allow extention of the probe results in a global context. With the successful completion of the Galileo mission, NASA will have implemented an in-depth exploration of the Jupiter system of the scope recommended in the 1976 COMPLEX report.

2. Saturn

On September 1, 1979, Pioneer 11 (renamed Pioneer Saturn) became the first spacecraft to fly through the Saturn system. Originally designed for studies of Jupiter, it was directed to Saturn by a gravitational assist from Jupiter. A simple spinning spacecraft, it had a low data rate and a limited scientific payload. The spin-scan camera provided the first close-up views of the planet with its rings and led to an enhanced scientific return from the Voyager flybys. Pioneer's trajectory passed through the ring plane at the exact distance Voyager 2 would later fly on its way to Uranus, showing the absence of a significant hazard from ring particles and allowing Voyager 2 to be placed on a trajectory that would take it on to Uranus.

Pioneer established the presence of the magnetic field of Saturn and found it to be very nearly aligned with the planet's axis of rotation. The newly discovered narrow F-ring is discussed further below. Several previously undetected satellites were inferred from their effects on charged particles.

Voyagers 1 and 2 flew by Saturn on November 12, 1980, and August 25, 1981. The rotation rate of Saturn was determined from the periodicity of radio emission as 10 h 39 m 24 s. Only half as much helium is seen on Saturn as on Jupiter: it may be that helium is drifting deep down into Saturn's interior, releasing heat. Wind speeds derived from tracking of clouds are as great as 1500 km/hr, 4 to 5 times faster than on Jupiter. Many details of the atmosphere are similar to those of Jupiter, with alternating bands of light and dark and a red oval similar to Jupiter's great red spot, but smaller. Auroral emissions are detected over Saturn's poles Saturn's magnetic moment is stronger than the Earth's, but much weaker than Jupiter's.

The inner satellites of Saturn are largely made of ice, and are heavily cratered. The moons Tethys, Rhea, and Dione show cracks and "wispy" terrain. The cracks are evidence of internal geologic activity, while the wisps may be deposits of frosts from internal gases that froze on the surface after escaping through the fissures. Enceladus has undergone substantial resurfacing by flowing material. Sinuous fissures and ridges are visible, and the surface shows evidence of widespread geologic activity, all unexpected in a cold, icy body. Iapetus remains a puzzle: one side is light, the other dark. Six new small moons were found in 1980, three by ground-based telescopes and three by Voyager. Some are sharing orbits with larger well-known moons, and three are very near the rings. Several others are inferred from single images or charged particle signatures.

Titan's surface radius is 2575 km, making it slightly smaller than Ganymede but larger than Mercury. Titan's atmosphere is mostly nitrogen. At the surface the temperature is 94°K and the pressure is 1.5 bars, 50 percent higher than the Earth's. It is likely that liquid ethane condenses on Titan and forms lakes and seas on the surface. Hydrocarbons derived from CH_4 probably form the haze and possible clouds that shield the surface from view.

Saturn's rings are much more complex and challenging than was earlier expected. The rings are not uniform, but contain thousands of radial variations in particle number. Transient, finger-like radial features extend across the B-ring. These "spokes" are composed of extremely fine material, perhaps moved about by electromagnetic forces. Many ring features are noncircular, with elliptical or more complex edges. The F-ring is formed of multiple, sometimes discrete, streams of particles. It is believed that this ring is held together by the action of two "shepherd" moons, one on either side. Wave phenomena seen in the rings include several dozen examples of compressional density waves as well as several examples of bending waves, which are corrugations of the ring plane. There is considerable structure in the rings on scales as fine as 100 m, and the thickness is no more than a few tens of meters. The rings probably play an important role in the dynamics of the entire Saturn system by transferring angular momentum among Saturn and its satellites. The total mass of the rings is about 5×10^{-8} of Saturn's mass, which represents an amount of material about equal to that in one of Saturn's small moons, such as Mimas.

3. Uranus

Uranus was observed at close range by Voyager 2 in 1986. This flyby determined the planetary rotation period, measured its magnetic field, and discovered new satellites and rings. A partial failure of the Voyager scan platform during the Saturn encounter did not recur: the spacecraft and all its systems and instruments performed well.

Uranus is of special interest because of its 98° obliquity; the axis was pointing nearly toward the Sun during the Voyager encounter. At that time, the Uranian system was observed in many of the same ways earlier applied to the Jovian and Saturnian systems: imaging of the planet and its moons; stellar, solar, and radio occultations; ultraviolet and infrared spectroscopy; measurements of the radio emissions from the planet; and in situ measurements of the fields and particles near Uranus.

Voyager investigated clouds and winds in the atmosphere from images. The structure of the atmosphere was characterized to a depth of a few bars by radio occultation, and at higher levels by infrared sounding measurements, ultraviolet spectroscopy, and photopolarimetry. The internal structure of the planet can be deduced from measurements of the planet's shape and gravity field. The rotation period of Uranus was estimated from periodicity in radio emission to be about 17.24 hours. Image sequences indicate that winds are predominately east-west and reach speeds of 200 m/s.

The rings of Uranus were discovered from ground-based observations of a stellar occultation. Optical and radio occultation studies from Voyager have resolutions 100 times better. The cameras took the first resolved images of the rings and discovered several shepherding satellites, which may confine some of the Uranian rings in the same way as the F-ring of Saturn is confined.

The flyby of Uranus provided high-resolution images of several satellites. These small satellites indicate a remarkable variety of geologic activity. The tiny moon, Miranda, shows multiple occurrences of tectonics, faulting, uplift, and resurfacing.

Uranus has a magnetic field and a magnetosphere. The strength of the magnetic field at the surface of Uranus is intermediate between that of Earth and that of Saturn. The field is tipped a surprising 60° to the rotation axis. Nonthermal emission from a magnetosphere was detected in advance of encounter by the radioastronomy instrument. The Voyager fields and particles instruments directly sensed the magnetic field and the Uranian magnetosphere. These instruments provided broad coverage of the plasma, energetic particle, and wave properties of the Uranian magnetosphere.

The Uranus encounter has provided a comprehensive first look at the planet, its rings and moons, and its space environment. The depth of this look and our subsequent understanding approached in many ways that of the first Voyager flybys of Jupiter and Saturn. This successful flyby of Uranus by Voyager 2 has accomplished the primary scientific objectives for reconnaissance of the Uranian system as set out by COMPLEX in 1976.

4. Neptune

After its 1986 Uranus encounter, the Voyager 2 spacecraft will reach Neptune on August 25, 1989, on a trajectory that will allow close encounters with Neptune and its largest moon, Triton. Current plans provide for studies of the system to be similar to those at Jupiter, Saturn, and Uranus. A functional spacecraft would provide us with comparable data on all four gas giant planets in the solar system from a single mission. The committee wishes to emphasize the value of the Neptune encounter as an integral part of the implementation of the current COMPLEX strategy for outer planet exploration.

5. Summary

We have extensive information and new understanding of the planets Jupiter, Saturn, and Uranus from recent spacecraft studies. This knowledge is sufficient for design of an in-depth study of these planets. The Galileo orbiter and probe mission will provide such an in-depth study for Jupiter.

The continued survival and functioning of the Voyager 2 spacecraft provided a high-quality reconnaissance of the Uranus system in 1986, thus fulfilling this recommendation of the 1976 COMPLEX report. In 1989, the spacecraft will reach Neptune, and is expected to carry out for a fourth time the scientific reconnaissance of a giant planet.

IV

Exploration of the Outer Planets

By 1990, Voyager is expected to have completed reconnaissance flybys of all the giant planets—Jupiter, Saturn, Uranus, and Neptune. At about the same time, the Galileo probe and orbiter will be launched to perform their in-depth exploration of Jupiter, with additional support from the Hubble Space Telescope and other Earth-based observatories. These missions will advance our understanding of the origin and evolution of the solar system, and of the physical and chemical processes that control conditions in planetary atmospheres, on planetary surfaces and interiors, and in the realms of magnetic influence. This understanding will evolve as we compare data from different planets, and thereby isolate the different initial conditions and environmental factors that control and influence planetary behavior.

Comparative planetology in the outer solar system is likely to involve Jupiter and Saturn as primary targets. Together they account for 92 percent of the extrasolar mass of the solar system. Their elemental composition is similar to that of the Sun, yet their physical and chemical behavior is planetary. They resemble each other in many respects, but there are significant differences. By the mid-1990s our understanding of Jupiter will have advanced to the point where in-depth exploration of Saturn will be essential for continuing progress. Such exploration will allow us to exploit fully the similarities and differences among the giant planets and deepen our understanding of the Sun's two principal companions. Because of the high priority given to the Saturn system in the COMPLEX recommendations, the next five sections are devoted to the various parts of this system.

A. SATURN

1. Atmosphere and Interior

The hydrogen to helium ratio, involving the two most abundant elements of the universe, is a fundamental quantity in astrophysics. Its initial value for the universe as a whole may be diagnostic of the conditions during the Big Bang. For Jupiter and Saturn, the hydrogen to helium ratio affects the bulk density and interior structure. The abundance of heavier elements in the interior may be inferred once the hydrogen to helium ratio is known.

The fractional abundance of helium relative to H_2 needs to be measured to an accuracy of 1 percent. A measurement of this ratio for both Jupiter and Saturn is essential if one is to evaluate possible fractionation effects and assess the role of the transition to metallic hydrogen. In particular, helium may condense at some level in the planet's interior, leaving the atmosphere depleted in helium relative to the planet as a whole. The effect depends on the internal temperatures, and is more likely to have occurred in Saturn than in Jupiter. By comparing the atmospheric helium abundances for the two planets, one can assess the extent of fractionation, and perhaps infer the hydrogen to helium ratio in the bulk of each. The approximate helium abundances inferred indirectly from Voyager IRIS and radio data are not accurate enough for precise modeling; in situ sampling at an accuracy of 1 percent or better is needed.

Other elemental abundances, notably carbon, nitrogen, oxygen, and the noble gases, provide clues to the mode of formation and subsequent evolution. Instruments on an atmospheric entry probe that function to the base of the H_2O clouds or below on Saturn are essential for in-depth exploration. If the abundance ratios resemble those on the Sun, formation might have occurred by accretion of gases and vapors; the heavier elements and their ices would not have condensed, and their vapors would have been incorporated into Jupiter and Saturn at the same rate as hydrogen and helium. On the other hand, if the abundances relative to hydrogen are enriched relative to those of the Sun, then Jupiter and Saturn may have formed partly by accretion of preexisting icy bodies. Spectroscopic estimates of C/H suggest enrichment, as does the presence of dense cores. However, it is necessary to sample the atmosphere below cloud base if realistic inferences about bulk abundance ratios are to be made. Measurements of light element ratios (C/H, N/H, O/H) to ±10 percent, and noble gas ratios (Ne/He, Ar/He, Kr/He, Xe/He) to ±30 percent or better are needed for meaningful comparison of atmospheric abundance ratios with the range of elemental compositions observed in the Sun, meteorites, and other planetary atmospheres.

Jupiter and Saturn are the only giant planets for which this requirement of subcloud sampling can be met at present. Uranus and Neptune may be liquid planets consisting largely of H_2O, CH_4, and NH_3. Thus it is possible that condensation and precipitation occur continuously all the way from the atmospheres down to the centers of these planets. If this were true, then no altitude range could be taken as representative of the planets' bulk composition.

Substances such as H_2O, NH_3, and H_2S that condense to form clouds are important for the meteorology of Jupiter and Saturn. All the visible markings are clouds or gaps between clouds. The cloud colors result from chemically active trace substances such as sulfur and phosphorus. The vertical extent of the clouds and their effects on atmospheric dynamics depend on the vapor pressures and latent heat capacity of the deep atmosphere. Measuring abundances of condensable vapors below cloud base to a factor of 2 or better is therefore also important for understanding meteorological processes.

Molecules such as H_2S, PH_3, NH_3, and CH_4 are destroyed in the upper atmosphere by known photochemical processes. Measurement of their vertical abundance profiles with uncertainty of a factor of 2 or less would provide quantitative information on the strength of vertical mixing in the atmosphere. Voyager observations suggest that mixing in the upper atmosphere of Saturn may be an order of magnitude more vigorous than that of Jupiter, and may be related to the circulation and thermal structure of the two planets at great depths. Again, comparison of Jupiter and Saturn helps the isolation of effects such as temperature, amount of sunlight, and convection that are different for the two planets.

Finally, atmospheric entry probe measurements can yield significant results concerning isotopes of hydrogen, carbon, oxygen, nitrogen, and the noble gases. The isotope deuterium gives information about the processing of matter between the times of the Big Bang and the formation of the solar system. Although there is some spectroscopic information, prior to Galileo such basic information is largely nonexistent for any body in the outer solar system. Isotopic data from the atmosphere of Saturn, and comparison with Galileo results from Jupiter, will yield many clues to planetary and solar system formation if the measurements are accurate enough to resolve these data within the range of isotopic compositions found in other solar system volatile reservoirs. Neon is a good illustration: 30 percent error in a $^{20}Ne/^{22}Ne$ ratio of 11 (for example) spans compositions observed in primitive meteorites (8.2), the terrestrial atmosphere (9.8), solar flares (~11), and the solar wind (13.7). With a 10 percent error, the same value is much more diagnostic. This criterion defines the following accuracy requirements: $^{13}C/^{12}C$, $^{18}O/^{16}O$ to ±1 percent or better and D/H, $^{15}N/^{14}N$ to ±1 to 5 percent in major molecular species (0.1 percent molecular abundance or greater), and He, Ne, Ar, Kr, and Xe isotopic ratios to ±5 to 10 percent or better, except for the rare isotopes ^{21}Ne, ^{78}Kr, and $^{124,126}Xe$, where this accuracy may not be attainable.

Voyager has characterized the horizontal wind field of Saturn at cloud top level. As with Jupiter and Uranus, the winds are largely zonal (east to west), running parallel to the light and dark cloud bands. Circulating ovals imbedded in this structure persist for tens to hundreds of years, either in spite of or because of the large wind shears that exist between the zonal currents. Attempts to understand these circulations hinge on answers to some key questions. How deep do the currents extend? What is the temperature profile at depth relative to an adiabatic profile? What is the cloud structure at depth and the latent heat capacity of the deep atmosphere? What is the latitudinal distribution of internal heating impinging on the atmosphere from below? These questions can best be answered by a probe or series of probes that sample the cloud zone and penetrate into the subcloud region.

For a solar composition atmosphere, the computed water cloud base pressure on Saturn is about 10 bars. However, if the planet is enriched by a factor of 10 in water and other condensable vapors, the computed cloud base pressure is about 25 bars. Then measurements to 30 bars would be required to sample the well-mixed lower atmosphere, rather than the 15 bars that could suffice for solar proportions.

Choosing the best site for an entry probe involves both science and engineering issues. The Galileo probe will enter in Jupiter's equatorial zone. However, definition of the preferred entry point for a Saturn probe requires further study.

Vertical profiles of ionization, neutral gas density, trace chemical constituents, aerosols, temperatures, wind structure, and radiative heating rates are needed at all altitudes for Saturn, and could be determined by a probe. Remote sensing observations by Voyager have characterized these quantities, but often with limited accuracy and limited vertical resolution. Understanding of physical and chemical processes requires improvements in both respects.

In situ and remote sensing measurements provide complementary information. For example, radio occultation temperature-pressure profiles are limited in their accuracy (but not precision) by the uncertainties in atmospheric composition, which in the reconnaissance phase must be inferred. In situ measurements can be used to anchor infrared spectroscopic sounding and radio occultation data in the vicinity of the probe entry point. Thus calibrated, the remote sensing instruments can then be used to obtain a global map of atmospheric structure with much higher accuracy and confidence. Such global extension would provide important information on day-to-day weather seasonal variations that could not be obtained at a single time and location. Measurements of atmospheric structure and motions should be made with at least the same accuracy and sampling rates as those on the Galileo probe. It is particularly important to resolve small deviations from the adiabatic lapse rate.

The magnetic field, gravity field, wind field, and cloud structure as functions of position on the globe are still not fully characterized after Voyager. A spacecraft with the capability of the Galileo orbiter could answer many outstanding questions. A key question concerns the magnetic field. Voyager observed radio emission at kilometric wavelengths emanating from the polar latitudes of Saturn. This radiation was modulated at a rate that has been associated with the planet's internal rate of rotation. The problem is that such a modulation requires asymmetry in the magnetic field, and almost none was observed in the limited Pioneer and Voyager data. Further mapping of the magnetic field and the radio emission is needed if one is to understand and use the latter as a measure of internal rotation.

Another unusual phenomenon is the impulsive radio bursts called Saturn electrostatic discharges. These short (30 to 250 ms) broadband (100 kHz to 40 MHz) radio bursts occur with an episodic period of 10 h 10 m. The probable source is lightning in Saturn's atmosphere: the period corresponds to the rotation period of the atmosphere at the equator.

Both the magnetic field and the gravity field are best measured by a low-altitude polar orbiter. Such an orbiter would be ruled out by the presence of the rings, and also is incompatible with other objectives of a Saturn mission. Nevertheless, some improvement in present knowledge can be expected from an orbiter that frequently encounters Titan. The current uncertainty in the gravitational moments J_2 and J_4 would be reduced by such an orbiter. These moments reflect the planet's response to centrifugal forces brought on by its own rotation. The magnitude of the response can be used to infer parameters of the internal density distribution and of the bulk composition. Remote measurement of magnetic fields (e.g., by radio scintillations) might be useful.

Voyager gave little information regarding the relation between cloud heights and colors, or the origin of colors. Imaging in the near-infrared bands of CH_4 can give cloud height. Near-infrared maps at slightly longer wavelengths can help identify the absorbing substances that make up the cloud particles. Both kinds of capabilities are present on the Galileo orbiter and are needed at the same performance level at Saturn.

With better knowledge of vertical structure, cloud tracking might be used to infer the winds at different levels. As mentioned earlier, the vertical distribution of winds is a major unknown in the meteorology of the giant planets. Theoretical models that start with different assumptions about this distribution usually give different results. The Voyager data, with good horizontal coverage and resolution, may help eliminate some models, but many others may survive. Conceivably, orbiter instruments, taking advantage of gaps in the clouds, might provide wind observations at levels between the nominal cloud base and cloud top, and thereby resolve some outstanding issues.

Although it seems likely that the Saturn electrostatic discharges originate in lightning bursts, the location and height are unknown, and a ring origin is not fully ruled out. A direction-finding radio wave analyzer and a long interval of observation should resolve these issues.

It would be desirable to visit Saturn at a different season than that of the Voyager encounter. Although the instantaneous global energy budget is now well determined, possible seasonal effects on both the outgoing emitted radiation and the absorbed solar radiation are not. It is possible that our estimate of the internal heat source would change as a result of measurements at a different season with its different ring shadowing. More likely, seasonal effects are confined to the stratosphere and upper troposphere. Nevertheless, seasonal changes are important to the meteorology, and may complicate our analysis of upper atmospheric chemistry.

2. Titan

Titan, the largest satellite of Saturn, is unique among satellites in having a dense atmosphere of predominantly nitrogen composition, but also containing a small amount of CH_4 and possibly argon. The surface pressure is 1.5 bars. With a surface gravity of 135 cm/s^2, the amount of gas per unit area is nearly 11 times that on the Earth.

A nearly uniform orange haze hides the surface and any condensation clouds that might exist. Titan has much in common with the terrestrial planets, but is much colder and much richer in ices (almost certainly of H_2O and CH_4, and probably also NH_3). The surface temperature near the equator is 94°K, a few degrees above the melting point of CH_4, and apparently constant with time of day. There is a global temperature minimum of about 71°K at an altitude of 42 km, above which the temperature rises to 170°K at 200 km, the stratopause. It remains near this temperature all the way to the exobase at 1600 km. At this height the gravity is less than half the surface value. There is some evidence for slightly colder conditions—a few degrees K—in polar regions. Very near the terminator there is no sign of an ionosphere at a sensitivity of 1000 electrons per cubic centimeter. Rather strong zonal winds have been inferred at altitudes of a few tens of kilometers, and there is evidence for internal buoyancy waves.

Strong absorption bands of CH_4 were discovered by G. P. Kuiper in 1944. Photochemistry initiated by ultraviolet absorption of CH_4 gives rise to heavier hydrocarbons and organic compounds, about 10 of which have been observed. The byproduct hydrogen escapes rather rapidly and goes into orbit around Saturn. The orange haze is likely composed of condensed hydrocarbons and nitrile compounds, among which polyacetylenes and HCN are likely to be important. It appears that there must be a deep layer of these materials lying on the surface or dissolved in any liquid, perhaps a mixture of C_2H_6, CH_4, and nitrogen, that may be present.

The atmospheric methane could be continuously replenished either from such oceans or by degassing from deeper regions. Dense CH_4 clouds some distance above the surface are a possibility, but any evidence for or against them is very indirect. This rich inventory of organics in a nitrogen medium provides a natural laboratory for the study of prebiotic organic chemistry germane to the question of the origins of life on Earth.

The origin of nitrogen on Titan is a fundamental unsolved question. Nitrogen could have been supplied in a clathrate ice during accretion; this would suggest the presence of up to several percent argon, which is allowed by Voyager observations. Two alternate sources have been suggested: photolysis of NH_3 and high-temperature formation from NH_3 during impacts. The other compounds mentioned so far can be plausibly derived by photochemistry of a nitrogen-CH_4 mixture. Traces of CO and CO_2 are a different matter; indeed, they are the only forms of oxygen that are actually observed. CO is the more abundant and stable form under Titanian conditions, and the much rarer CO_2 is probably in photochemical steady state with it. The CO could be degassing from the interior, or could be derived from the ice in incoming meteoric material, with the carbon coming from the atmospheric CH_4.

Titan is embedded in a torus of escaped gases which includes atomic hydrogen, observed by Voyagers 1 and 2, and probably also H_2 and N. The H extends from 8 to 25 Saturn radii, with an axial extent of ±7 Saturn radii, surrounding Titan's orbit at 20 Saturn radii. Ionized torus material contributes to the plasma in Saturn's magnetosphere; impact by magnetospheric particles is an important loss process for the neutral torus. When Titan is on the sunward side of Saturn, it is sometimes outside the magnetosphere and in a solar wind environment. Most of the time it is within the magnetosphere and subjected to a corotating wind of magnetospheric plasma. Since Titan's intrinsic magnetic field seems to be negligible, the interaction of Titan with either the magnetospheric or solar wind plasma is similar to that of Venus or a comet, but with the important difference that the relative velocity is subsonic instead of highly supersonic. Voyager 1 passed through the magnetospheric wake and observed a number of changes in the plasma and magnetic environment.

The simplest model that fits the mean density of 1.89 g/cm^3 gives a rock to ice ratio by mass of 52:48. The rocky core would have a radius of 1620 km and the icy mantle a depth of 950 km. Ice can still convect at temperatures somewhat below the freezing point, and such convection is believed to carry the internal radioactive heat to the base of the lithosphere." CH_4 can dissolve in ice as a clathrate at low temperatures. If it were accreted in this form, it may or may not degas readily, depending on the exact conditions. Since CH_4 is in the atmosphere and is being processed into more complex compounds, the current net rate of degassing or of evaporation must equal the destruction rate.

Among the myriad of questions suggested by the Voyager and earlier results are the following: Are there hydrocarbon oceans? lakes? clouds? Are there islands or continents? If so, are they water ice or something else? Is argon abundant? If so, is it primarily ^{36}Ar (as expected) or ^{40}Ar? What are the abundances and isotopic compositions of the other noble gases (He, Ne, Kr, Xe)? Did N_2 come from NH_3 photolysis or was it primordial (incorporated as a clathrate)? What byproducts, e.g., long-chain hydrocarbons, of CH_4 photolysis exist on the surface? Is CO generated from infalling meteoroids or was it primordial? Is there structure in the temperature profile between 200 and 1500 km? What governs this profile? Strong zonal winds have been predicted (20 m/s near the surface, 75 m/s in the stratosphere). Are they, or others, present? The ultraviolet dayglow is brighter (by a factor of 4) than the incident solar radiation can support. What is the other energy source and what confines it to the day side? Is there a small internal magnetic field? How does the corotating plasma interact with the upper atmosphere or magnetic field? In what ways are the plasma and atmosphere affected? Is Titan phase-locked to Saturn—rotating exactly once per orbit? What geological processes, internal or external, have modified its surface? Is Titan seismically active? To what extent does the gravity field indicate a differentiated interior?

These questions can be addressed by orbiters and probes. Landers, floaters, and balloons are best reserved for still later missions. The difficulties and measurement strategies for remote sensing are roughly similar to those for exploring Venus, except that Titan is much farther from the Earth than is Venus, and is a satellite of a large planet. Thus, a Saturn orbiter, like the Galileo orbiter of Jupiter, could visit Titan repeatedly while also investigating other parts of the Saturn system; a dedicated Titan orbiter is not necessary.

As with Venus, the global characterization of Titan's surface can best be done with an orbiting radar system. Because the variety of possible surface types (oceans, rocky or icy continents, uniform crust, etc.) is very large, the first mission will provide enormous scientific return. Simply characterizing the surface would be both significant and exciting. A fairly simple radar could obtain maps of large-scale topography (to within 100 m relative altitude), radar reflectivity, dielectric constant, and surface texture (with 1-km spatial resolution). In order to obtain a representative mapping of surface morphology with high confidence, upwards of 40 to 50 percent of the surface must be sensed; lower fractional coverage risks failure to observe major physiographic features. The rotation rate and pole direction could be measured.

Questions concerning atmospheric composition can be addressed with an entry probe. A mass spectrometer and gas chromatograph, or a combined instrument, could measure many substances of interest. Scarcity of free hydrogen and abundance of higher hydrocarbons are the relevant differences between Titan and the giant planets. Although the Galileo entry probe design could be used as a basis, the environmental and technical difficulties are much less severe at Titan than at Jupiter. Learning the detailed composition of Titan's atmosphere has high priority because Titan has an evolving atmosphere that might be similar to the early Earth's. Analysis of organic molecules should have particular emphasis. Requirements for compositional analysis and measurement accuracy are similar to those for Saturn's atmosphere, for similar reasons (section IV.A.1.). They include the elemental ratios Ar/N to ±10 percent or better, H/N, C/N, O/N, Ne/Ar, Kr/Ar, and Xe/Ar to ±30 percent or better, and an upper limit for He/Ar; the isotope ratios $^{13}C/^{12}C$, $^{18}O/^{16}O_2$ to ±1 percent or better, and D/H and $^{15}N/^{14}N$ to ±1-5 percent in major molecular species and the isotopic compositions of the noble gases to ±5 to 10 percent or better, except for the rare isotopes ^{3}He, ^{21}Ne, ^{78}Kr, and $^{124,126}Xe$, where this accuracy may not be attainable. A reasonably quantitative identification of other species in the Titan atmosphere also requires measurement of abundances of hydrocarbons/organic compounds up to C_3 or heavier with an uncertainty of a factor 2 or less.

Questions concerning the global atmospheric structure can be approached with the same types of multiple orbital passes that are attractive for surface studies. Radio occultation and infrared soundings of the neutral atmosphere of Titan, unlike Venus, can probe to the surface. Given the detailed composition from an entry probe, repeated occultations can provide temperature profiles to absolute accuracies of about one percent or better at the surface over most of the sphere. Detailed comparisons between profiles at different locations are meaningful at about the 0.2 percent level, based on Voyager experience. First priority should be given to the poles of Titan, which were not well observed by Voyager, and then to mid-latitudes. One may hope to detect global atmospheric temperature and pressure gradients, small-scale waves and turbulence, and possibly evidence of precipitation. The ionosphere can also be studied simultaneously if the electron concentrations exceed about 100 per cubic centimeter.

Questions concerning the interaction of Titan with Saturn's magnetosphere and with the solar wind can be addressed by a Saturn orbiter that regularly encounters Titan. The ionosphere and upper atmosphere also can be studied from orbit. One would also like to measure any small intrinsic magnetic field as well as the higher-order structure of the gravity field, particularly J_2 and J_4. Such measurements could best be made from a low-altitude Titan orbiter. Whether they could be made from a Saturn orbiter that encounters Titan awaits detailed study.

Once it is known whether the surface of Titan is solid or liquid, rock or ice, rough or smooth, and whether the atmosphere near the surface is calm or windy, cloudy or clear, one can envisage an advanced phase of exploration. Even the questions one might ask can only be guessed at: How deep is the Titan ocean? Or if there is no ocean, how thick is the hydrocarbon layer, and what is its composition? Is Titan seismically active? Are there diurnal or seasonal weather changes at the surface? If Titan's rotation is locked to its orbit around Saturn, how large are the librations?

Such detailed questions can be addressed by a variety of balloons, floating buoys, landers, and surface penetrators. Some of these devices will have been tested and used elsewhere in the solar system before they are used at Titan. Other devices may be unique for Titan and will have to be developed. Obviously, a first-order characterization of the surface must precede the use of such advanced techniques.

3. Other Saturnian Satellites

The Voyager flybys of Saturn revealed that the larger satellites form a group of geologically complex objects that have had a long history of surface modification by both impact craters and internal processes such as volcanism and tectonism. Of the 17 currently known satellites, 6 were discovered in 1980. Very little is known about these small satellites (none are larger than 100 km in diameter) except for their sizes, shapes, albedos, orbits, and the intricate roles they play in the dynamics of the Saturnian ring system. Titan, the largest Saturnian satellite, is treated in the previous section.

The Voyager mission produced improved estimates of the radii and masses of the larger satellites of Saturn. These estimates allowed better determinations of the densities and hence the ice to rock ratios of these bodies. Unlike the Jovian satellite system, or the solar system as a whole, there is no evidence for a trend of decreasing density with increasing distance from the planet in the Saturnian system. If confirmed, this would imply that the temperature in the proto-Saturn nebula was low enough for both rock and ice to condense together throughout the region occupied by the satellites. The present level of knowledge is inadequate to distinguish a trend from a random variation.

Nearly all of Saturn's larger satellites, excluding Titan, whose surface is hidden by clouds, show evidence of both impact cratering and internal geologic activity. The cratered surfaces have different proportions of small craters to large ones, and different crater densities. These facts suggest the existence of several populations of bombarding meteoroids or different obliteration mechanisms in the Saturnian system. At least three possible populations have been suggested, one of which is comets. If comet impacts could be distinguished, the size-frequency distribution of comets might be inferred. Each of the satellites has cratered surfaces of different ages, with the youngest surfaces being the least cratered. Enceladus, an extreme case, has one surface unit so young that no craters are recognized at Voyager resolution.

Several of the satellites show different evidence suggestive of internal activity. Tectonic features such as great rifts and valleys appear on Mimas, Enceladus, Tethys, Dione, and Rhea. The dark material on Iapetus is discussed below. Rhea and Dione display bright "wisps" on their surface that may indicate deposits from eruptions and recent internal activity. A large crater on Tethys has clearly relaxed isostatically, hinting at an interior warm enough to flow over geologic time.

Only Phoebe, the outermost satellite (which perhaps is a captured object), Mimas, and Hyperion fail to show evidence of internal modification at Voyager resolution. Higher resolution images will show new details. Mimas, however, is interesting because of its deficiency of large craters other than a single one of 130-km diameter. The predicted impact rate on Mimas, based on gravitational focusing of the observed rate at Enceladus, suggests to some investigators that Mimas has been broken up by impacts and reaccreted one or more times in its history. If correct, not just Mimas' surface, but the entire satellite is geologically "young." Hyperion, measuring about 400 by 200 km, is an object with a highly irregular ("chaotic") rotation; it may be a collisional fragment of an originally larger satellite. Understanding of these collisional processes and interactions of fragments could have profound implications for our understanding of the origin and accretion of the planets themselves.

The study of impact craters on the Saturnian satellites should be a high-priority goal of future missions to the Saturn system. The various crater populations may yield data on the primary fluxes of comets, the fluxes of outer solar system planetesimals, intra-Saturnian meteoroids produced by major impact events on the satellites, and perhaps other, as yet unrecognized, sources of small solid objects in the outer solar system. Crater densities can be used to define geologic units. Crater morphology may add to knowledge of the process of impact cratering on icy bodies, which differs from ordinary impact cratering because the target, and perhaps the projectile as well, is volatile. The detailed form of relaxed craters, such as the large crater on Tethys, indicates how the viscosity decreases with increasing depth in the interior of the satellite.

If Mimas has been broken up and reaccreted one or more times during the history of the solar system, other Saturnian satellites may also have undergone similar episodes of breakup and reconstitution. This interesting hypothesis must be verified or rejected. If this scenario is true, study of Mimas's surface morphology will provide many new facts for investigations of accretion processes, both for planetary satellite systems and for the planets themselves.

The satellites of Saturn, excluding Titan, are small objects—the largest is only about half the diameter of Earth's Moon. They are far smaller than the Galilean satellites of Jupiter. Nevertheless, Voyager found evidence for tectonic and magmatic activity on nearly all of them. Many open questions center on the nature of the heat sources that drive this activity—What is the origin of the heat source? How hot must the interior of these small icy satellites become before "magmatic" (probably liquid water) eruptions begin? How does the "magma" ascend to the surface? Do NH_3-water eutectic mixtures facilitate melting at low temperature? What is the style of eruption and mechanics of "lava" flow movement when the "lava" is water or water-slush and the surface is very cold ice? How recently has this sort of activity occurred on each of the satellites? The answers to these questions and many similar ones bear significantly on our understanding of planetary internal processes.

Some more specific questions concern Enceladus, the large, next-to-innermost satellite, and Iapetus, the large, next-to-outermost satellite. Enceladus is surfaced, in part, by a "ridged plain" unit that is geologically quite youthful—not a single crater has been recognized at Voyager resolution. Both tectonic and volcanic activity can be inferred in very recent time. It has been proposed that the heat source responsible for this activity is tidal flexing, in analogy to the heat that powers the volcanoes of the Jovian satellite Io. However, tidal flexing is expected to be much less important in Enceladus than in Io. But if not tidal flexing, what is the source of Enceladus' heat? The answer is not known. Enceladus is also closely associated with the E-ring of Saturn. It may be the source of the ring particles. But whether the ring particles were ejected from Enceladus by volcanic eruption, meteoritic impact, or some other process, is likewise currently unknown. Evidence for eruptive activity should be sought.

Since its discovery by Cassini in the seventeenth century, Iapetus has been known to be asymmetric in brightness. Its trailing hemisphere is bright, reflecting about 50 percent of the visible light that falls upon it, whereas its leading hemisphere is so dark that Cassini was unable to see Iapetus when it presented this hemisphere to Earth. Although it was originally proposed that the dark material was swept up from space or from dark material knocked off Phoebe, impacting preferentially on the leading hemisphere of the satellite, Voyager images suggest the alternative that the dark material may be extrusive, since it appears to fill low spots on Iapetus' surface. The true nature of this material, the circumstances of its extrusion—if it is extrusive—and its composition are currently unknown.

Orbital dynamics lead to the expectation that the crater densities on the leading and trailing hemispheres of the satellites should differ significantly. No such difference has been definitively demonstrated, however, on either Saturnian or Jovian satellites. The reason for this may be observational—few satellites have been imaged at uniform resolution over more than 50 percent of their surfaces; furthermore, the existence of surface units of different geologic ages complicates the analysis greatly. If crater densities are not asymmetric, however, this fact would have profound implications either for satellite evolution (uniform crater densities could be caused by frequent reorientation of the satellite's rotational axis) or for the population of impacting objects (their mean approach velocity would have exceeded the satellites' orbital velocities). Another possibility, not favored by Voyager scientists, is that both faces are saturated with craters.

Saturn is about twice as far from the Sun as Jupiter and occupies a part of the solar system studied in only a cursory manner. Its satellites probably contain relics of the low-temperature condensates of the solar nebula, including volatile materials that may be unique to the outer solar system. Determination of the compositions of the satellite surfaces coupled with improved measurements of satellite density would further constrain bulk compositions. Particularly important will be understanding the type and proportion of silicates mixed with ices currently found on satellite surfaces. Ultimately, this would contribute to the understanding of chemical trends throughout the solar system.

Many questions thus remain to be answered about Saturn's satellites. The answers to these questions are important to our understanding of the way in which satellite systems and the planets themselves accreted, evolved internally, and interacted with the objects in space around them. No one measurement technique, instrument, or even mission can be expected to address all these questions. Furthermore, the answers to even some of the questions above can be expected to generate new questions. The full exploration and understanding of the Saturnian system will be the work of many years to come.

Many of the questions discussed above can be addressed by remote sensing techniques. More detailed investigations of the satellites to determine geophysical parameters such as heat flow and internal structure are desirable, but probably require more advanced technology than is currently available. These advanced investigations are discussed separately in Chapter VI.

A variety of remote sensing techniques are available to accomplish the outlined goals. Observations by a near-infrared mapping spectrometer would enable the identification of and distinction between mixtures of various silicates and icy surface materials. Infrared measurements obtained at different times of day for given areas of the satellites could allow different ice types to be distinguished based on the observed temperature variations. Measurements with a gamma-ray spectrometer, if feasible, would allow some key radiogenic and other elemental abundances to be determined (e.g., U, Th, K, Fe). Bistatic radar returns from the larger satellites, using the spacecraft radio antenna, could provide information on the surface roughness and dielectric properties.

The major questions about crater populations, crater density distributions, and the relative ages of different geologic units can be answered by imaging of the major part (at least 90 percent) of the satellites' surfaces at a resolution of 1 km or better. This resolution will allow ready recognition of craters exceeding 4 km in diameter. Craters in this size range have, in past studies, proved to be most useful in dating planetary surface units. Approximately 1-km spatial resolution would also be desired for the geochemical mapping using a near-infrared mapping spectrometer mentioned above.

The imaging system and mission plan should contain provision for high-resolution study of small, selected areas on the satellites. A resolution of 100 m or better has proved to be invaluable in the identification of surface processes on the other planets and satellites that have been investigated to date. At this resolution, flow fronts, fault scarps, and details of crater morphology become visible. Volcanic vents and constructs can be seen. A high-resolution mode is thus essential for interpreting the surface manifestations of internal activity and should be included along with the goal of global geological and geochemical mapping at lower resolution. Stereoscopic images at both resolutions and low sun-angle images would also aid in recognition of both geologic units (contact relations) and surface processes. Means should be available to resolve topographic elevations to 50 m. Either stereo photogrammetry or radar altimetry could accomplish this. Such topographic information is needed to address the extent of crater relaxation, measure the heights of flow fronts, and determine the direction and magnitude of surface slopes.

4. Planetary Rings

One of the surprises of the Pioneer and Voyager missions has been the unexpected complexity, variety, and intrinsic interest of the rings of Jupiter and Saturn. Saturn's rings consist of myriad particles, predominantly composed of water ice, which to first order follow Keplerian orbits about Saturn. Spacecraft observations have measured the radial opacity profiles of the rings at two microwave and two optical wavelengths on scales as fine as about 100 m. Some of the outer portions of the middle ring B are so opaque on scales less than about 15 to 20 km that no experiment has been able to penetrate them. Analyses of ring edges, waves, and scattering from the particle ensemble by several experiments give thicknesses normal to the ring plane of less than 100 m.

Approximately two dozen well-established gaps are known, with widths greater than about 10 km and opacity essentially zero. However, thousands of observable fluctuations in brightness or opacity occur within the ring system. Some of these have been established as dynamic structures associated with gravitational perturbations by satellites and possibly the gravitational field of Saturn itself.

Direct searches by Voyager for 5- to 100-km-scale moonlets within the rings were unsuccessful. However, the very sharp edges of some rings, and features such as wavy edges associated with the Encke gap, make it likely that at least a few kilometer-scale or larger moonlets exist within the rings. A recent dynamical model predicts that the particles will occasionally aggregate into short-lived moonlets. Thus continued searches to determine the sizes of the largest particles within the rings remain important (e.g., by direct imaging or occultation searches for narrow gaps swept out by them).

Particle size distributions over the size range of 0.01- to about 50-m radius have been obtained from radio occultation, and extended to micron sizes by comparison of microwave and visible opacities. Such data are available only for the outer and inner rings A and C. In this size range, the particle sizes are distributed in rough accordance with an inverse-cubic power law with a cutoff at maximum detected sizes of about 2 m in ring C and 5 m in ring A. We have less information about the particle size distribution in the size range of about 50 m to 1 km, which needs further study.

Little detailed information on the particle composition is available. Spacecraft observations show slight color differences between various ring components, indicating some variation in composition with location; quantitative analysis is lacking. Studies of microwave emission by the ring particles limit their silicate content to a few percent at most.

Saturn's rings are the only active collisional disk that we can study in detail first-hand. The early solar system, after its initial collapse, spent much of its history as a flat disk. Further study of the rings can constrain related theories of the evolving disk in several ways in that many of the interactions among the original planetesimals are similar to those now occurring in Saturn's rings. The confrontation of data and theory can give new insights: currently unsuspected processes may be discovered and proved to be important. Detailed observations require detailed theory for their explanation, thus refining our understanding. Already, explanation of current Voyager observations has depended heavily on the nonlinear aspects of the dynamics. Although such studies could have been made before Voyager, it seems unlikely that the difficult efforts required would have been undertaken in the absence of data. Study of Saturn's rings can also provide a general comparison, as well as special technical details not in current models for planetary evolution. Numerical simulations of particulate disks are unsatisfactory and will remain difficult; one of the best hopes for advance in this area is from study of this natural laboratory.

Dynamical interactions in the rings are also similar to those in galaxies and in the accretion disks surrounding collapsed stars. Typical recent studies include those of orbital resonances, stability of ring systems, transfer of angular momentum in disks, and waves in disk systems. These results have begun to affect models of preplanetary disks and wave phenomena in galaxies. Again, planetary rings provide a unique laboratory for studies of thin disks.

Among the dynamical processes that continue in Saturn's rings are satellite-disk interactions, transfer of torques through resonances, bending and kinking of ringlets, confinement of material at ring edges, opening of gaps, winnowing of the particles through interparticle collisions, possible temporary aggregation, and sorting of material by size. Sporadic injection of new material off Enceladus may add to the dynamic nature of the E-ring. However, the problems of modeling such processes are formidable. The ability to study an extant ring system close at hand and over long durations is a valuable resource for the testing of models and the evolution of these phenomena. As an example of a problem of this type, density waves are proposed as important processes in galactic evolution as well as a mechanism for clearing gaps in ring systems, but are not well understood. Large amplitude density waves—even to the point of nonlinearity—have been observed at numerous locations in Saturn's rings (see Figure 1), but do not appear to have any particular correlation with gaps or edges. The present theory of density waves does not predict under what circumstances a density wave will occur; observationally there is poor correlation between the strength of the driving resonance and the occurrence of the wave. In addition to density waves, dynamical processes now under study include bending waves, dynamical instabilities, and the resulting vertical structure of the ring system (are the rings one, several, or many particles thick?). Solution of these and similar problems will undoubtedly improve the understanding of important mechanisms of wide applicability in disk formation and evolution.

Long-duration monitoring of ring structure is clearly required. Even during the short time interval of the Voyager flights, changes in fine-scale ring structures were detected. Similar changes of much larger scale over longer time intervals cannot be ruled out, and their confirmation or refutation would affect theories of ring dynamics.

The information with the highest spatial resolution (the Voyager occultations of Saturn's rings) is limited currently to a few linear cuts (occultation paths) through the rings. Multiple occultations from a future orbiter would give temporal, azimuthal, and particle size information now lacking. This in turn would allow us to see the dynamic processes evolve in both time and space. Similarly, the strongest particle size information from the Voyager radio occultation is limited to the optically thinner parts of Saturn's rings because of the low opening angle of the rings. Even so, the two Voyager wavelengths reveal distinct structure associated with different particle size regimes throughout the rings.

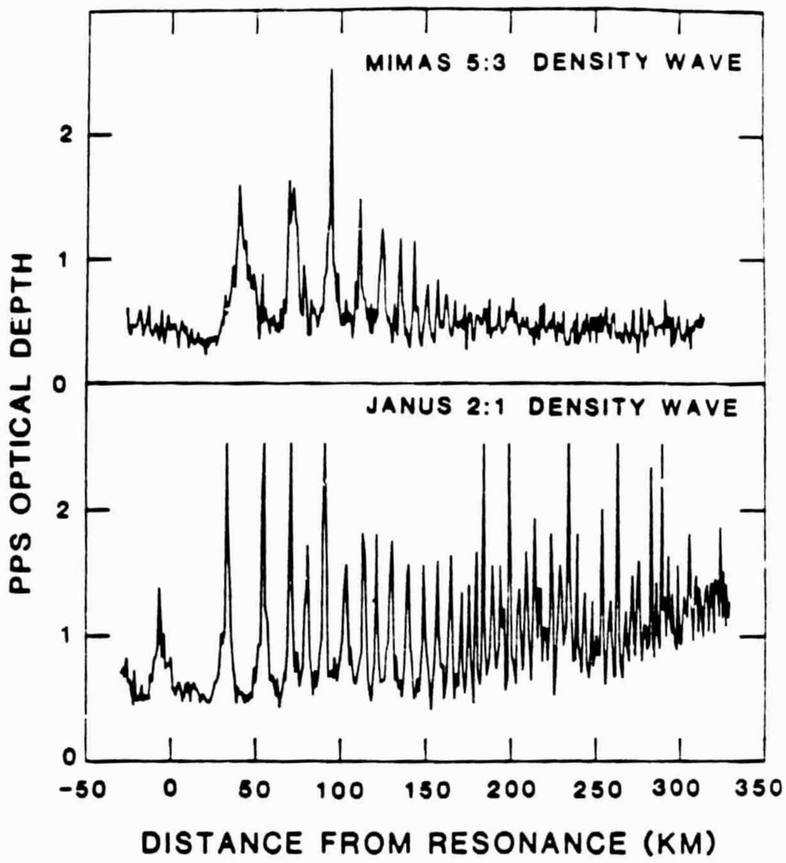

FIGURE 1 Two of the strongly nonlinear density waves observed in Saturn's rings by the Voyager 2 photopolarimeter subsystem (PPS) during the occultation of δ Scorpii by Saturn's rings (from L.W. Esposito, "Structure and Evolution of Saturn's Rings," *Icarus*, volume 67, pp. 345-357, 1986). The differences in distance of propagation for the two waves show differences in local viscosity within the rings.

Saturn's rings have an atmosphere containing atomic hydrogen, undoubtedly derived from water. A future measure of H_2O loss from the rings could give a determination of the current evolution of the ring particle composition.

Collisional processes determine the particle size distribution. This distribution is partially constrained by the Voyager radio occultation for some locations within the rings, but needs to be extended to the entire ring system and particle sizes up to about 10 km. The nature of the size distribution (e.g., a power law typical of fragmentation, truncations at the large or small end, etc.) may shed light on the evolution of the ring particles. Ring compositions that might be measured by a near-infrared imaging system could give new information on the processes of fractionation and accretion in the Saturnian system.

Saturn, Jupiter, and Uranus all have ring systems that may be compared to each other. Occultation results now show that Neptune lacks complete rings like those of Jupiter, Saturn, and Uranus. With recent results from the Voyager encounters, we see that all these ring systems are remarkably diverse. Jupiter's ring consists primarily of a narrow, diffuse annulus of micron-size dark particles (possibly silicates?) spiraling inward toward the planet. Associated with the ring is a halo of material extending some distance from the equatorial plane of Jupiter. Apparently, it must be continuously renewed from a source near its outer edge. In contrast, the Saturnian rings are a broad, extremely flat, thin system completely dominated by centimeter-size and larger pieces of ice in complex dynamical relationships. The Uranian rings are composed of nine distinct, very narrow loops of material with some transient dust between. In terms of scale the individual Uranian rings resemble Saturn's F-ring, or the "embedded" features of Saturn's C-ring, but are made of extremely dark (possibly hydrocarbon?) material of meter or larger size. The overall question of confining mechanisms, disruptive forces, dominant evolutionary processes, and modes of formation can best be attacked by study of all three known systems. However, the study of Saturn's rings alone could set the stage for some progress of a comparative nature with respect to either Jupiter or Uranus because of the wide variety of phenomena in the Saturnian ring system.

Spacecraft investigations of Saturn's rings are likely to provide a significant return in the study of dynamical processes in rings of all kinds. This will have important application to our understanding of the early solar system—the rings provide a unique laboratory. Examples of specific types of recommended measurements include the following:

Composition. Infrared reflectance spectroscopy with photometric accuracy of 1 percent, wavelength resolution of 1 percent, and angular resolution of 0.5 mrad. This technique should be used to map local variations in ring composition.

Physical particle structure. Upper limits on the polarization of scattered light from the rings are already as low as a few percent from Pioneer Saturn and Voyager data. Improvements require visible and microwave polarimetry to measure Stokes parameters to 0.5 percent.

Fractional volume density of ring particles. Extended visible photometry with precision of 1 percent for phase angles of less than 10°.

Radial structure and morphology of rings. Wave structures and other features are seen in Voyager occultation data with sizes smaller than 1 km. Knowledge of the gravitational moment of Saturn allows the prediction of the location of satellite resonances in the rings to an accuracy of better than 5 km. Therefore, to observe small-scale structure and to locate it relative to important dynamical positions require repeated occultation measurements in the extended visible and microwave region, with resolution of <1 km and radial position accuracy of <5 km.

Particle size distribution. Multiple wavelength occultations plus forward and near-forward scatter phase observation.

Out-of-plane distribution of ring material. High time resolution ring-plane-crossing observations, along with forward scattering phase observations.

Ring particle atmosphere. Observation of solar photo-dissociation products to a precision of 20 percent or better using ultraviolet spectra.

5. Magnetosphere

With the Pioneer 11 and Voyager 1 and 2 flybys of Saturn, the reconnaissance phase of the investigation of Saturn's magnetosphere is now complete. The existence of a magnetosphere and the primary characteristics of its particles and fields have been established. The magnetosphere of Saturn has some features in common with the magnetospheres of Earth and Jupiter, and others that are unique to Saturn, including charged-particle interactions with the rings and spoke-like structures in the rings apparently caused by plasma effects.

Saturn's magnetic field has a dipole moment of about 0.2 Gauss $R_S{}^3$ (R_S = Saturn radius). For typical solar wind conditions, the upstream magnetopause position varies from about 18 to 24 R_S. The magnetosphere of Saturn is therefore smaller than that of Jupiter, but still much larger than that of Earth. The magnetic field has a high degree of axial symmetry, with the dipole axis aligned to within 1° of the rotational axis. Despite the near symmetry of the magnetic field, kilometric radio emissions from Saturn's polar regions have a strong modulation at a period of 10 h 39.4 m. The origin of this modulation, which presumably indicates an asymmetry in the magnetic field near the planet, is one of the main unresolved questions concerning the magnetic field of Saturn. The rotational modulation of Saturn's radio emissions has also been linked to the occurrence of spokes in Saturn's rings, thereby providing further evidence of an asymmetry in Saturn's magnetic field. The formation of spokes in the rings is almost universally regarded as being due to electromagnetic and electrostatic forces associated with plasma in the inner regions of the magnetosphere, but the mechanism has not been established. Interactions between dust and plasma are also believed to be important for the tenuous, outermost E-ring. Magnetospheric electric and magnetic fields can cause radial diffusion of small charged dust particles. Such dispersal of particles may appreciably modify the spatial distribution of dust particles, and may be an important factor determining the large-scale structure of the E-ring.

Earth's magnetosphere is dominated by solar wind interactions, with the rotation of the magnetosphere playing only a minor role. Jupiter's magnetosphere, on the other hand, is dominated by rotational interactions with the moon Io, which injects plasma into the magnetosphere from volcanic eruptions. The rapid rotation of Jupiter's magnetosphere causes the plasma to be driven outward by centrifugal force, forming a thin disk of plasma near the equatorial plane. It is believed that the primary magnetospheric interaction at Saturn is with the solar wind, similar to the situation at Earth. The evidence comes mainly from the aurora, which is observed at high latitudes, about 10° from the poles, very near the boundary between open and closed magnetic field lines. The aurora is therefore probably driven by the interaction with the solar wind, as at Earth. This situation is markedly different from Jupiter, where the aurora occurs at the foot of the field lines associated with the Io plasma torus and is driven by the rotational interaction between Jupiter and the torus. The magnetosphere of Saturn appears to be more like that of Earth than of Jupiter.

Although the primary magnetospheric interaction at Saturn is with the solar wind, the plasma distribution inside the magnetosphere is more Jupiter-like. The interpretation of the plasma measurements is complicated by the fact that the dipole axis of Saturn is aligned within 1° with the rotational axis, which eliminates the periodic scanning of magnetic latitudes that occurs when a substantial tilt is present, such as at Jupiter. Consequently, the details of the plasma distribution at Saturn are not as well determined as at Jupiter. The plasma density distribution as currently understood is shown in Figure 2. These data show that the density peaks near the orbits of Tethys and Dione, and tends to be concentrated near the equatorial plane, forming a plasma torus similar to the plasma torus at Jupiter, but less dense and not confined to a thin equatorial disk.

The origin and loss of plasma is a central question. The spatial distribution strongly suggests that the source could be either the inner moons of Saturn—Enceladus, Tethys, or Dione—or the rings, possibly the G- or E-rings. The ions in the plasma are believed to be H^+ and either O^+ or N^+. If they are H^+ and O^+, then the composition is consistent with sputtering from ice-covered surfaces. No moons have been found in the Saturn system that could provide a plasma source comparable to the volcanic activity of Io. The best candidate is Enceladus, although there is little or no evidence that it produces sufficient outgassing. In the outer regions of the magnetosphere, Titan is known to be a source of plasma, both from impact ionization in the exosphere of Titan, and from ionization of neutral hydrogen escaping from Titan and populating a torus. The relative importance of Titan as a plasma source, compared to a centrifugally driven radial outflow from the inner regions of the torus, is not known. Both plasma and plasma wave measurements suggest that sharp density gradients and boundaries may exist in the inner magnetosphere, possibly associated with the orbits of various moons.

Large temporal variations in the magnetosphere of Saturn are suggested. Energetic particle measurements on Voyager 2 show substantial differences between the inbound and outbound trajectories, suggesting a disruption of axial symmetry due to temporal variations. Also, radio and plasma wave measurements on Voyager 1 suggest that Dione modulates the intensity of the

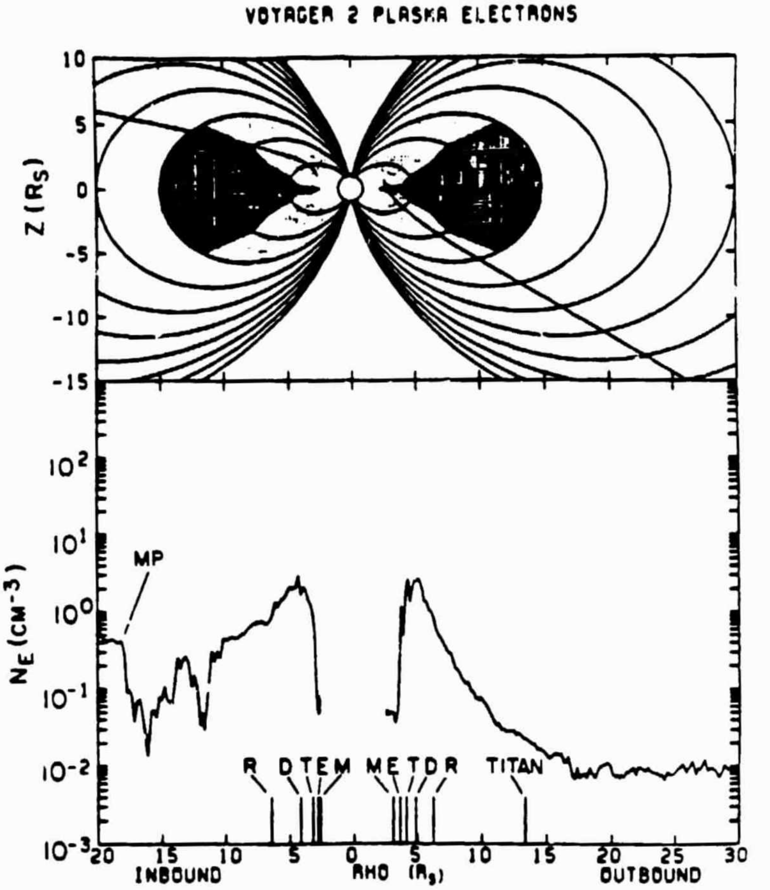

FIGURE 2 The qualitative distribution of plasma in Saturn's magnetosphere based on the Pioneer 11, Voyager 1, and Voyager 2 measurements (from Bridge et al., *Science*, volume 215, page 565, 1982). The lower panel shows the Voyager 2 plasma density profile, illustrating that the peak plasma density occurs in the inner region of the magnetosphere, near the orbits of Tethys and Dione.

kilometric radio emissions. These temporal variations can only be resolved by obtaining measurements in the magnetosphere over periods of months to years, much longer than can be obtained by a single flyby.

The following scientific objectives, and the types of measurements needed to fulfill them, are identified for future magnetospheric investigations at Saturn.

Determine the origin of the 10 h 39.4 m kilometric radio emission modulation. The azimuthally asymmetric feature of the Saturnian magnetic field must be identified, and the mechanism by which this asymmetry acts to control the radio emission and spoke formation must be established. A Galileo-type magnetometer is adequate for this purpose. To map the planetary magnetic field as accurately as possible, periapsis should be as close to the planet as possible, consistent with spacecraft safety in Saturn's ring environment. Direction-finding by the radio wave analyzer and repeated occultations of the source region by Saturn should locate the source, determine its shape and variability, and fix the magnetic longitude of the active sector.

Determine the sources and sinks of plasma in the plasma torus. The spatial distribution and composition of the plasma torus must be determined with substantially better resolution than is available from Pioneer 11 and Voyagers 1 and 2, particularly in the vicinity of Enceladus, Tethys, and Dione, and as close as possible to the rings. Repeated passes are required through the inner regions of the magnetosphere at a variety of latitudes. The relative importance of wave-particle, plasma-satellite, and plasma-dust interactions must also be investigated to establish how each contributes to the torus ion and neutral particle budgets. The fluxes and species of orbiting and charge-exchange neutrals* should be measured to specify directly the parent population of the ions and to determine the neutral resupply rate. Ion and electron fluxes should be measured from 1 eV to 1 MeV with 4π steradian coverage.* Multiple instruments will be necessary to cover the energy range. The mass range should be 1 to 44 AMU with a mass discrimination of 1 AMU.* Doubly ionized species are expected and should be measured.* Time resolution sufficient to resolve the features in Titan's wake is necessary.* In regions not probed in situ, the plasma and gas composition, density, and temperature can be determined with an ultraviolet spectrophotometer. Similarly, the locations and rates of energy deposition of precipitation ions and electrons can be established with an X-ray or an ultraviolet spectrophotometric mapper.* A plasma wave analyzer is needed to

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* Instrument development required, see Chapter VI.

determine the local rate of ions and electrons that are lost through scattering onto precipitation trajectories.

Establish the nature and origin of temporal variations in the magnetosphere. The relative importance of variations caused by solar wind fluctuations, internal configurational instabilities (substorms), and plasma source variations—e.g., possible modulation due to Titan's position in the magnetosphere, and geologic activity of inner moons such as Enceladus—must be determined. Long-term observations, of the order of months, are required in the vicinity of the planets with adequate remote sensing by optical imaging, auroral ultraviolet or X-ray emissions, and radio emissions to monitor global temporal variations. In situ particle, field, and wave measurements are also needed. Instruments already specified are sufficient to achieve this goal.

Characterize the Titan-magnetosphere interaction. Is the Saturnian neutral hydrogen torus supplied by particles from Titan's or Saturn's atmosphere? Determining the spatial distribution of the hydrogen atoms, their loss rates, and their trajectories should isolate the source. Remote sensing by an imaging ultraviolet photospectrometer, in situ measurements by a neutral particle detector, and measurements of the ion and electron populations through the torus are required. A measurement of the H_2 torus through its ultraviolet emissions may also bear on this question. The Titan wake is scientifically highly interesting. It is analogous to the Venus wake, and study of it therefore contributes to comparative planetology. Also it is the direct product of the magnetospheric interaction, and therefore characterizes it both qualitatively and quantitatively. As complete a mapping as possible is desired of the wake magnetic field structure, its ion features with their compositions and velocities, and its plasma wave signatures. Upstream parameters also should be measured to characterize the interaction fully and as inputs to Titan's aeronomic processes.

Determine the physical mechanism involved in the formation of spokes in the B-ring. Measuring spoke parameters in situ is not feasible. Instead, the cause of ring spokes must be sought in remote sensing data and in correlations between spoke behavior and other phenomena. The spatial and size distributions of spoke dust particles can be found through their light scattering properties. The plasma density, temperature and composition, the magnetic field strength and direction, and the radio and plasma wave spectra and intensities near the rings can be correlated with spoke occurrence and duration. A long data gathering interval is desirable to search for correlations.

Determine the charge-to-mass ratio of ring dust. An instrument that can measure dust with radii up to 1 μm and with surface potentials of ±10 V would cover the range thought to be most important in transport processes involving charged dust.

B. URANUS AND NEPTUNE SYSTEMS

The two planets Uranus and Neptune constitute a different class of bodies than that represented by Jupiter and Saturn. Although their atmospheres are hydrogen-rich, the planetary bulk compositions are inferred to be ice-dominated. Consequently, their atmospheric compositions are expected to deviate markedly from cosmic abundances in ways that have implications for the formation, evolution, and structure of the solar system. Their satellite and ring systems and magnetospheres are also different from those previously encountered. For these and other reasons elaborated below, both orbital and atmospheric probe missions to Uranus and Neptune are an essential part of the long-term goals of outer solar system exploration to help us understand why these two planets are so radically different from Jupiter and Saturn. Explaining this difference is one of the most challenging issues in the theory of solar system formation.

Uranus and Neptune each consist of roughly 10 Earth masses of ice (H_2O, CH_4, NH_3) a few Earth masses of rock, and a comparable mass of gas (hydrogen, helium), probably arranged internally in accordance to density (rock core, ice mantle, gas envelope), but with at least partial mixing of the ice and gas components. Both planets have predominantly hydrogen in their upper atmospheres. However, the low temperatures imply that most of the constituents other than hydrogen and helium are condensed or frozen out as cloud layers, usually at great depth in the atmosphere. CH_4 is known to be enriched relative to cosmic abundance by a factor that is very uncertain but could be more than an order of magnitude. In contrast, radio observations of Uranus indicate a strong (but space- or time-variable) depletion of NH_3 by a factor of about 50 relative to cosmic. Deuterium has been detected in approximately cosmic abundance in Uranus. Uranus' thermal structure was measured by Voyager. The thermal structure of Neptune's atmosphere is very uncertain at present, in part because of the large uncertainties in atmospheric composition. The energy balances of these two planets are also uncertain: Neptune has an internal energy source comparable to insolation, whereas Uranus has no detectable internal energy source. However, this result for Uranus may be due to measurement uncertainty rather than the absence of an intrinsic heat source. The latest Voyager results may improve this situation.

Radii of the five largest Uranian satellites are in the 250- to 800-km range, with water ice on their surfaces but with significantly lower albedo than comparably sized Saturnian satellites. The Uranian rings consist of at least nine narrowly confined rings of low albedo particles. The satellite and ring orbits are all very close to the equatorial plane, which probably means that they formed after the event(s) responsible for the 98° obliquity of Uranus. Neptune's satellite system is very different and is dominated by Triton, which is in a retrograde and highly inclined orbit. Triton is the largest solid body in the solar system that has not yet been visited and has methane ice and possibly liquid or solid nitrogen on its surface; at least a small amount of atmosphere is implied.

Fundamental issues for Uranus and Neptune include the origin, structure, and evolution of the interiors and atmospheres. What is the composition and nature of layering within these planets? What is the internal heat flow, and how is it transported from the interior? Although the presence of a magnetic field has been established for Uranus, this question is still open for Neptune: does Neptune have an active, dynamo-generated magnetic field? What is the relationship between the observable atmosphere and the deep interior: does the atmosphere merge smoothly with an interior that is ice rich, or is it bounded below by a compositional (ice surface) discontinuity? Convective mixing is likely to enrich the deep atmosphere with a variety of molecular species, including not only hydrogen-bearing molecules, but possibly significant abundances of CO and N_2 if the thermodynamic conditions at high temperatures and kinetic inhibitions at low temperatures favor these species. What are the molecular abundances deep in these atmospheres? This is relevant to understanding both the primordial state and the present dynamics. Are the atmospheres primarily remnants of the primordial solar nebula, or are they at least partly a consequence of outgassing from the rock and ice core? How effective is convective mixing?

The Uranian satellites have had a very different formation and history than the Jovian and Saturnian satellite systems. Is it possible that the Uranian satellite and ring system formed by the spin-out of a gaseous disk resulting from a huge impact that tilted the rotation axis of Uranus? What are the bulk compositions of these satellites? Why do they have low albedo? We know that these satellites exhibit endogenic features. Number densities and morphologies of craters have also been measured. What do they tell us about the primordial planetesimal population and early thermal state of these satellites? Triton is likely to be a unique body. Where did it form? Was it captured? Why does it have much less atmosphere than Titan, and in what other ways does it differ from Titan?

The Uranian rings are very different from the Saturnian rings. Why? Are small moons maintaining the narrow rings in a way similar to the confinement of Saturn's F-ring? What is the composition of the ring particles? How does the oblique magnetic field of Uranus affect the magnetosphere's morphology and magnetospheric particle distribution? Does Neptune have rings comparable to those of Jupiter? New satellites of Uranus were revealed by Voyager, and we await the Voyager images of the Neptune system.

The outstanding issues are not exhausted by the list of questions above: the Voyager encounter with Uranus has provided additional questions to be addressed. One expects that this will be repeated by the Neptune flyby of 1989. Although identification of some relevant scientific objectives must await analysis of the Voyager results, it is already apparent that future exploration must include both in situ sampling of the atmospheres and orbital missions designed to characterize the satellite and ring systems and near-planet environments. The in situ atmospheric probing should measure the temperature profile and the abundances of major species (hydrogen, helium, CH_4, NH_3, H_2O, CO, N_2) as well as noble gases (diagnostic of atmospheric origin), and should characterize major cloud layers. Since the water clouds may be at the 0.5 to 1-kbar level, in situ sampling should reach or approach this level in order to address the important scientific issues. This may require major technological development.

The internal structures of Uranus and Neptune are constrained by accurate measurements of the gravitational moments, J_2 and J_4. Although the values for Uranus are quite well constrained by accurate determinations of the precession of elliptical rings, it is expected that further significant improvement can be obtained from an orbiter. It is also expected that orbiters with instrument complements comparable to Galileo will be needed to answer many of the important issues posed by the satellites, rings, and magnetospheres, since the brief, first looks by Voyager cannot be expected to provide sufficient data. A more specific definition of measurement strategy must await the Voyager Neptune reconnaissance.

Future exploration of the Uranian and Neptunian systems is an essential part of the primary goals of understanding the origin, evolution, and structure of the solar system. This exploration should include both in situ sampling of the deep atmospheres, to at least several hundred bars pressure if technically feasible, and orbital missions designed to characterize the satellite and ring systems and near-planet environments.

C. CRUISE SCIENCE AND TARGETS OF OPPORTUNITY

The instrumentation used for planetary exploration can often be utilized to perform valuable scientific investigations during the cruise phase between, and often after, planetary encounters and to take advantage of other opportunities. All of the heliosphere, including the region between the planets, is permeated by a wide variety of particles and fields of solar, interstellar, and galactic origin. These include the solar plasma, solar and galactic cosmic rays, interstellar gas, comets, asteroids, meteoroids, and dust. The solar wind flows radially outward from the Sun in all directions and is accelerated to supersonic velocities within a few solar radii. As a result of dissipative interactions with the interstellar medium, the outward expansion of the solar wind is expected to terminate at a boundary called the heliopause. The location of this boundary, both in the plane of the ecliptic and away from it, is of considerable interest. Current estimates place the heliopause at 50 to 100 astronomical units. The expansion of the solar wind involves many basic processes of plasma astrophysics, such as magnetohydrodynamic shock interactions, merging of magnetic fields, angular momentum transfer, and interactions between plasma and neutral gas. The solar wind expansion and its associated magnetic turbulence act to scatter galactic cosmic rays and thus prevent low-energy cosmic rays from reaching the inner regions of the solar system. Understanding of the entry of galactic cosmic rays into the solar system remains one of the central problems of cosmic ray physics. Direct measurements of low-energy ($\leq$ 300 MeV/nucleon) galactic cosmic radiation intensities can only be obtained in the outer regions of the heliosphere, where the influence of the solar wind is small.

The investigation of these important processes requires in situ measurements from spacecraft at large heliocentric radii. At present four spacecraft, Pioneers 10 and 11 and Voyagers 1 and 2, are on their way to the outer regions of the heliosphere. Of particular interest is Voyager 1 because its trajectory is significantly out of the ecliptic plane. Because of the importance of studying the solar wind at large distances from the Sun, and eventually making measurements in the interstellar medium, it is essential that the operation and analysis of data from these spacecraft be continued on a long-term basis. Because no similar missions are likely in the near future, *COMPLEX recommends that NASA undertake a long-term commitment to assure the continued operation, reception, and analysis of data from Pioneers 10 and 11 and Voyagers 1 and 2 to the end of this century.*

During the cruise phase of planetary missions, various opportunities occasionally occur, such as flybys of asteroids or comets. Since the study of these objects is a high-priority objective of solar system exploration, it is important that these targets of opportunity be identified and that appropriate measures be taken to optimize the science return. For example, by making small trajectory corrections it may be possible to fly much closer to such objects than otherwise would be possible. Because of the potential importance of these encounters, *COMPLEX recommends that NASA undertake a detailed study of possible targets of opportunity for all missions to the outer solar system and that every effort be made to maximize the science return when such targets of opportunity are identified, consistent with the overall objectives of the missions involved.*

D. LONGER TERM GOALS

1. Intensive Study of Jovian and Saturnian Satellites

As Galileo first recognized, the satellites of Jupiter constitute a miniature analog of the solar system. It is commonly believed that the satellites accreted out of material condensed from a Jovian nebula, which, like the solar nebula, had a radial temperature gradient. The satellites exhibit differences in composition and possibly in their degrees of differentiation as a function of distance from Jupiter. The Galilean satellites are four separate worlds with different heat budgets and markedly different geologic histories. Knowledge of how planets form, differentiate, and generate and lose their heat may thus be greatly advanced by an understanding of the Jovian satellites, especially Io, Europa, Ganymede, and Callisto. The Saturnian satellites do not conform to the same pattern as the Galilean satellites: there is only one large satellite, Titan, and no clear density decrease as a function of distance from Saturn. The resolution of this puzzling difference is required for our understanding of planetary formation and evolution processes, and will be aided by intensive and comparative study of these satellite systems. Titan deserves special emphasis as a unique body which, because of its dense atmosphere, may greatly advance our understanding of the origin and evolution of atmospheres.

The atmospheres of the Galilean satellites are also scientifically interesting because they differ from any previously encountered. On Io, possible large-scale supersonic flows of SO_2 from day to night may constitute a new phenomenon in atmospheric science, and deposition of SO_2 frost and dust may be a major geologic process in the modification of the surface. Escape of atmospheric gases may affect the bulk chemical properties of Io. The atmospheres of Europa, Ganymede, and Callisto are not known except for an upper bound on Ganymede's atmosphere (10^{-11} bar). They could have thin atmospheres consisting mostly of O_2 (10^{-12} bar), produced by ultraviolet light striking water molecules. Water ice has been detected on these objects from their infrared spectra. Io's atmosphere may also include O_2 derived from SO_2. Europa may have other species if it is volcanically active.

The regoliths of icy bodies such as Ganymede, Callisto, and most of the Saturnian satellites are of particular interest because of the small but appreciable volatility of the fragmental debris. Sintering, formation of hoarfrost, and the resulting alteration of thermal conductivity make such regoliths unusually important in regulating the thermal state of the body's interior. This is in contrast to regoliths on silicate bodies such as the Moon, which simply add an insulating blanket to the surface. A slightly volatile regolith may impose a constant temperature condition at the bottom of the fragmental debris layer, regardless of the surface temperature.

This situation could have profound effects on internal temperatures to depths of tens or even hundreds of kilometers. Variations of thermal conductivity and strength with depth in the upper few tens of meters of Europa, Ganymede, and Callisto should be measured if technically feasible. Penetrators seem most suitable.

Intensive study of the Galilean and Saturnian satellites must involve high-resolution images, seismic measurements to elucidate internal structure, heat flow determination, if feasible, radioactive element measurements, and chemical analysis of surface materials. Other measurements such as global geochemical mapping, conductivity sounding, surface scattering, and magnetic field studies also provide a means of delineating geologic provinces, near-surface stratigraphy, and information on the satellites' interior properties. Returns of samples may be desirable in the more distant future, but are not considered in this strategy.

a. Io

Io the innermost Galilean satellite, is a world of active, sulfur-rich volcanoes. Nine active volcanoes were observed during the Voyagers' brief passes, and Earth-based telescopic observation suggests continuing activity. The internal heat of Io appears to be derived from tidal flexing of its solid crust, making Io a highly interesting geophysical target; while other planetary objects derive internal heat from tidal dissipation, the heat budget of Io is dominated by this mechanism. Although the surface of Io is covered by sulfur and SO_2 there are numerous mountains that are probably composed predominantly of silicate materials.

Sulfur dioxide gas is supplied by volcanoes, which derive their energy from tidal heating of Io's interior. Somehow the SO_2 frost that condenses on the surface is recycled into the volcanoes. Only a small fraction (10^{-3}) of the molecules escape, but these are enough to populate the magnetosphere of Jupiter with sulfur and oxygen ions. Some of the SO_2 is dissociated by ultraviolet light into sulfur, which condenses on the surface, and O_2, which remains in the atmosphere as a minor constituent. This picture has emerged from Earth-based observations of SO_2 surface frost, from Voyager observations of SO_2 gas in the atmosphere and ions of sulfur and oxygen in the magnetosphere, and from Pioneer observations of an ionosphere above the surface.

Io occupies a unique place in the spectrum of planetary objects that have atmospheres. On the sunlit side and close to the volcanoes, the SO_2 gas is dense enough to behave as a fluid and has pressures ranging up to 10^{-7} bar. On the dark side, most of the SO_2 is frozen to the surface; a few molecules follow ballistic trajectories in the near-vacuum (10^{-20} to 10^{-10} bar, with the larger figure representing possible O_2). The flow from day to night sides of Io, powered by this enormous relative change in pressure, may exceed supersonic velocity over much of the surface. Thus, Io spans the range of objects with thin gaseous atmospheres to those with near-vacuum, ballistic atmospheres.

This remarkable atmosphere is difficult to study because of its inaccessibility, deep in Jupiter's radiation belts. Important measurements are still feasible from a great distance, as demonstrated by the Pioneer 10 radio occultation, which should be repeated. Far-ultraviolet occultations of the Sun and stars, as carried out by the Voyagers, also have great potential, as illustrated by the 10^{-11}-bar upper limit set for Ganymede's atmosphere. Stellar events are particularly important since they can probe the night side. Airglow emissions can give still better sensitivities for certain gases and may be observable by the Galileo spacecraft.

The most useful geophysical measurements that could be made on Io relate to its internal structure and heat flow. If feasible, a seismic network of at least four to six stations well distributed about the planet would indicate the locations and extent of internal activity. Measurement of tidal phase can determine the dissipation factor near the tidal flexing frequency and thus be used to relate tidal dissipation to heat flow. Seismic attenuation measurements would also enable assessment of regions that are solid or partially molten. Gravimeters could measure Io's response to tidal forcing.

The global heat budget of Io is of prime importance in understanding its internal geologic activity. A combination of Earth-based and remote (flyby or, preferably, orbital) infrared detectors would allow estimates of heat output of volcanic "hot-spots" on the surface. An important but perhaps lower priority goal is to measure by in situ methods the thermal gradient in selected areas of the crust not immediately affected by volcanic activity.

Although technologically difficult, landers would enable measurement of many critical parameters on Io. Penetrators seem logical probes for Io study. Buried beneath the surface, they also partially avoid the radiation problem that plagues any close-up study of Io. A penetrator mission should also include magnetometers, if technically possible, and other instruments to study the interaction of Io with Jupiter's magnetic field and an in situ measurement of chemical composition. If the radiation problem can be overcome, an orbiter with imaging capability, spectrometers and radio experiments for atmospheric studies, a gravity experiment, and global geochemical mapping instruments would be desirable.

Io affords the opportunity to study volcanic processes involving magma compositions and heat sources that are poorly understood. Obtaining information on the style(s) of volcanism exhibited on Io would expand our knowledge of volcanism in general and place constraints on models of eruptive mechanisms.

b. Europa

Europa, next farthest of the Galilean satellites from Jupiter, has a smooth, bright, uncratered surface (at Voyager image resolution) criss-crossed by linear albedo markings. Estimates of the SO_2 layer thickness on the trailing side of Europa are far less than expected for deposition from Io sources, suggesting that Europa's surface is somehow renewed over geologic time. The paucity of craters and unusually high albedo also suggest that the surface is geologically young and may be covered by thin, frozen flows of water "magma," derived from a possible zone of liquid water beneath a solid crust. Some of the linear markings may be due to fracture of Europa's lithosphere under tidal stresses. Others seem to be related to stresses generated in the interior acting on the lithosphere. Some of Europa's internal heat is probably derived from tidal flexing, as for Io.

Although nearly featureless at Voyager image resolution, the surface of Europa may be heterogeneous and have a wide variety of surface types and ages. High-resolution imaging under low to moderate lighting would enable the nature and timing of various surface units to be discriminated. Detection of small craters is important for dating the surface. If this is not performed by the Galileo mission, higher resolution will be necessary. Like Io, Europa may experience active volcanism as well as deformation by tectonic processes. The most useful geophysical measurements include seismometry and heat flow. A gravimeter to measure the tidal response of the planet would also reveal information about Europa's interior. Voyager images show the surface of Europa to have areas of slightly different colors and reflectivities. Chemical composition measurements would enable assessment of whether the surface is composed of nearly pure water ice or includes other components; porosity would be indicated by thermal analysis. The presence and concentration of radioactive elements should also be determined.

c. Ganymede

Ganymede is of particular interest to geophysicists concerned with plate tectonics. Planetary exploration has shown that among the terrestrial planets, only Earth has experienced plate tectonics, although Venus remains open to question in this regard. Thus, Ganymede may be the best analog for this important process on Earth. The bands in the young, bright terrain are interpreted as regions of extension, interspersed between older, darker crustal blocks. Although plate subduction apparently never occurred on Ganymede (there is no sign of the subduction zones needed to conserve surface area), horizontal shear of crustal plates has deformed substantial parts of the surface. Knowledge of the internal structure and heat budget of Ganymede would aid in understanding the conditions under which plate tectonics occurs. Again, measurements of seismicity and heat flow would address these topics.

Ganymede exhibits a range of surface textures, reflectivities, and ages. Chemical composition and the crustal complement of radioactive elements should be determined on both bright and dark terrains. Global geochemical mapping would be particularly useful because of the varying surface composition. For example, the old, dark terrain may record compositions derived from the infall of debris since the time of heavy impact cratering in the final stages of accretion. Studies of volatile transport near the surface and the nature of Ganymede's polar caps would add to our understanding of the stability and mobility of volatiles on the airless satellites of the outer solar system. The extremely low temperature at the poles (about 40°K) allows for the condensation of highly volatile species.

d. Callisto

Callisto appears to be the least active of the Galilean satellites. All surface features identified by the Voyagers seem to be related to impact cratering. It has been suggested that the striking differences between Ganymede and Callisto arise because Ganymede differentiated, whereas Callisto has remained an undifferentiated ice-rock mixture. For this reason it would be especially useful to obtain information on Callisto's internal structure and heat budget as a complement to similar measurements on Ganymede and other Galilean satellites, to define the conditions under which surface tectonic activity ceases. Instruments to attain this goal would include seismometers, heat flow sensors, and devices to determine chemical composition and abundances of radioactive elements.

e. Smaller Jovian Satellites

The small outer satellites are probably captured bodies and have dark surfaces, similar to Trojan asteroids. Remote sensing of these bodies, as targets of opportunity, is valuable because it will help establish their origin and nature. The inner satellite, Amalthea, has an unknown composition and origin, and also deserves further study in this exploration phase because it may shed light on the environment of satellite formation.

f. Titan

Titan is the least well characterized of the large bodies discussed in this subsection and the development of a strategy for intensive study must await the reconnaissance and exploration described in section IV.A.2. It is likely that the techniques will be specially tailored to Titan's unique environment. Intensive study will probably include some form of geochemical mapping (on dry land or ocean floor) and measurement of seismic or volcanic activity, if any.

g. Other Saturnian Satellites

Other Saturnian satellites have unknown internal structures and compositions (other than water ice), and a diversity of surface morphologies such as variations in crater densities, troughs, a large chasm, and grooved terrain. Enceladus is especially interesting because of the evidence for recent geologic activity. The identification and ordering of goals for intensive study must await the results of the exploration phase described in section IV.A.3.

However, this study is likely to include high-resolution imaging, geochemical mapping, and active seismology and heat flow determination if feasible.

Intensive study of the satellites of Jupiter and Saturn will involve a variety of geophysical and geochemical measurements best performed by arrays of instruments on the surface. The development and deployment of a reliable method of heat flow measurement are of prime importance in this study. Orbiters capable of global geochemical mapping would also yield critical measurements for all the satellites, although radiation hazards are a serious technical problem for Io and Europa. In all cases, a detailed rationale and identification of scientific objectives must await information from as-yet-unflown missions. Future intensive study of the unique satellite Titan may require the development of special techniques.

2. Io's Torus

The inner Jovian magnetosphere is dominated by Io's torus. This region is rich in planetary, magnetospheric, and astrophysical processes. Some of these are unique to the Jovian system; others are uniquely intense. A region of space within a sphere roughly enclosing Europa's orbit is a solar system laboratory for magnetospheric and astrophysical plasma processes (Figure 3).

Io's torus consists mainly of sulfur and oxygen ions in various charge states. This material is undoubtedly the dissociation and ionization product of Io's volcanic effluvia, possibly fractionated. By some not-well-understood process, probably involving sputtering by impacting torus ions, volcanic effluvia are blasted from Io's surface, or from its atmosphere, with sufficient energy to escape Io and orbit Jupiter. The total mass involved is roughly 1000 kg/s. Evidently, most of the ejecta are not ionized. Emissions from a neutral oxygen cloud and a neutral sulfur cloud in the torus have been detected. Electron impact ionization of the neutrals creates the Io plasma torus.

Jupiter's magnetic field grips the torus, causing planet and plasma to rotate together. Ions corotating at Io's distance move at 74 km/s, nearly 57 km/s faster than orbiting neutrals. The resulting centrifugal force acts to transport plasma radially out of the region. It is controversial whether the motion is organized into large-scale convection or small-scale diffusion. The high plasma density of the torus ($\sim 2 \times 10^3$ ions/cm^3) may result from partial

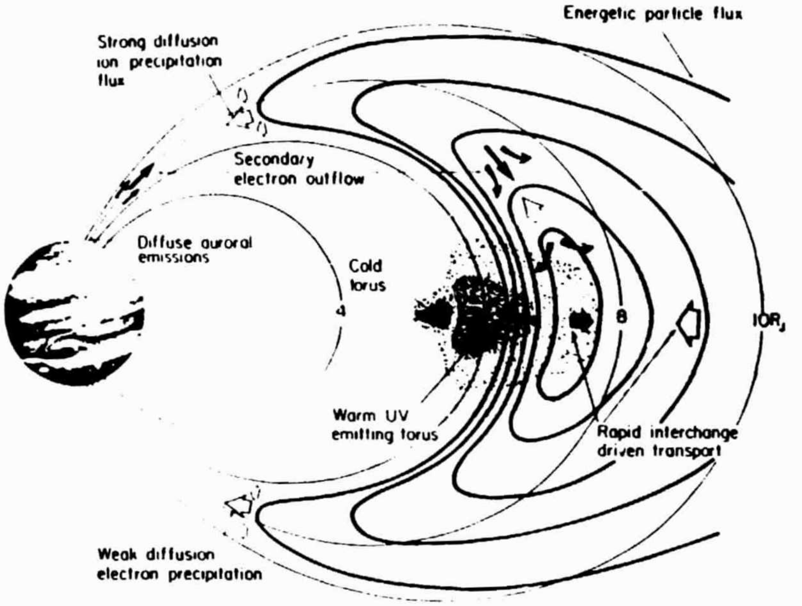

FIGURE 3 The inner Jovian system contains the Io torus, the energetic particle population, and the Jovian aurora as shown here (from R.M. Thorne, "Microscopic Plasma Processes in the Jovian Magnetosphere," in *Physics of the Jovian Magnetosphere,* A.J. Dessler (ed.), Cambridge University Press, 1983). It also contains the satellites Io, Europa, and Amalthea, the Jovian ring, and the neutral gas cloud out of which the Io torus forms.

impoundment of exciting plasma by a wall of energetic ions between Io and Europa. The energetic ions themselves appear to be a second generation of Io ions that have first undergone charge exchange in the torus, thereby becoming fast neutrals on escape trajectories, then ionization in the outer magnetosphere followed by diffusion back toward Io. Inward transport greatly increases an ion's energy. The inner edge of the energetic ion formation (the impoundment wall) marks the location of ion loss to Jupiter's atmosphere by precipitation along the magnetic field. This precipitation produces the Jovian aurora—the most intensely radiating magnetospheric feature in the solar system. The interaction of the low-energy and high-energy ion formations at the impoundment wall is even more interesting because inward transport in the one, and outward transport in the other, are driven by a common, centrifugally generated electric field. Beyond the energetic ion barrier, the low-energy formation extends into a plasma disk stretching past the orbit of Callisto. Because Jupiter's magnetic axis tilts 10° from its rotation axis, the disk's rotation resembles a warped phonograph record.

The continual acceleration-to-corotation of new ions in the Io torus extracts energy from Jupiter's rotation. This energy drives many plasma processes: the outflow of torus plasma, the inflow of energetic ions (and thus, ultimately, the Jovian aurora), the ultraviolet emissions of sulfur and oxygen by which the torus was discovered and mapped with Voyager's ultraviolet spectrometer, and a variety of interesting plasma and radio waves, including the decametric emissions that have been observed from Earth since 1964. To extract rotational energy, the torus must slip in relation to Jupiter. Corotation lag induces a motional electric field between the torus and Jupiter that drives electrical currents linking the torus with Jupiter's ionosphere. These linking currents, which bridge the intervening space by flowing along magnetic field lines, apply a force to the torus that acts to compel corotation. As this force reduces the corotating lag, the motional electric field is reduced, and so also are the linking currents. A steady state is reached when the residual lag induces linking currents just strong enough to impose the lagged corotation speed on new ions. A 5 percent corotation lag of the torus has been reported.

Io itself is coupled electrically to Jupiter's ionosphere by the magnetic field. Linking currents attempt to force Io to corotate with Jupiter. While the force is too feeble actually to affect Io's motion, the linking currents may be sufficiently strong to excite some of the intense radio emissions that are observed. These linking currents extend north and south from Io as Alfven waves (called Alfven wings), propagating obliquely to magnetic field lines and possibly partially reflecting off the density discontinuity that marks the north and south limits of the Io torus.

The torus exhibits puzzling time dependence and longitudinal structure. On a long time scale, the torus sampled by the Pioneer spacecraft was evidently much subdued compared to the torus Voyager 1 encountered five years later. However, in the five years since the Voyager encounter, torus emissions monitored from Earth have varied little (factor of 2). Seen from Earth, the part of the torus astronomically west of Jupiter radiates substantially more than the eastern part. This is a permanent asymmetry.

There is evidence also for temporary, corotating, longitudinal inhomogeneities in the torus.

How does matter gravitationally bound to Io escape to form the Io torus? The answer involves other major questions: Is Io's atmosphere thick or thin? What is its composition? What is the composition and distribution of surface material? Is Io magnetic? What fraction escapes as neutrals and what fraction as ions? What is the composition and distribution of escaped neutral material? High-resolution and more sensitive photospectrometer data are needed. In situ measurements of orbiting and fast charge-exchange neutrals would be exceedingly helpful.

How does plasma move through the torus? Is the main transport by large-scale or small-scale eddies? Are there secular variations? If so, are they regular or irregular? Progress toward answering these questions requires a more detailed and accurate three-dimensional map than Voyager provided of the density, composition, and charge states of the ions in the torus. A similar map of the thermal distributions of ions and electrons would greatly aid the interpretation of remote sensing data.

How do Io's low- and high-energy plasma formations interact? Is impoundment operating to elevate the torus plasma density appreciably above the density in the surrounding plasma disk? Or does the elevated density result from increased conductivity in the Jovian auroral ionosphere, which also would slow outward transport of torus plasma at the contact between the two formations? A proper determination of the impoundment force of the high-energy ion formation requires measuring the particles in it with energies in the range 5 keV to 50 keV, a range to which Voyager was insensitive. Similarly, a proper calculation of the auroral ionospheric conductivity requires measurements of the composition and the full energy spectrum of the energetic particles, and of the intensities of the plasma waves that scatter them onto precipitation trajectories.

What is the creation rate of ions in the torus? How large is the corotation lag? How does it change with distance? How are the linking currents distributed in space? Are there Alfven wings attached to Io and, if so, do they generate some of the observed Io-related radio emissions? Answers to these questions require in situ magnetic field observation on magnetic field lines linking the torus and the region around Io, and radio observations from many phase angles relative to Io together with occultations by Jupiter and Io. High-precision in situ measurements of the plasma velocity could determine corotation lags directly.

These questions can be addressed particularly well by orbiters with high-inclination orbits. The orbits should be selected to achieve some optimum between minimizing the power required to achieve the orbit, minimizing the size of the orbit to maximize sample frequency, and minimizing the effort to harden the spacecraft against radiation. A high-inclination orbit permits measuring field-aligned currents, and provides many phase angles and occultations for radio observations. The plasma waves that scatter energetic particles onto precipitation trajectories are expected to occur off the equatorial plane, out of the region of high-density torus plasma. Energetic ions can be measured directly at all latitudes. The charge-exchange neutral efflux could also be measured directly.

The main disadvantage of a high-inclination orbit is the loss of in situ measurements of torus plasma and orbiting neutrals. Remote optical sensing by onboard instruments can carry out many of the required measurements on these populations. Two spacecraft at opposite phases of a common orbit could probe the plasma directly by transmitting and receiving radio waves through the torus. Additionally or alternatively, a third spacecraft or the second spacecraft of a dual mission could be placed in an equatorial orbit that penetrates the torus. Dual spacecraft radio probes could be used in occultation opportunities to measure electron densities in the atmospheres of Jupiter and Io. T[illegible]ter would bear directly on the question of the amount of [illegible]here. It is evident that a mission of reasonable length wi[illegible]olve many of the puzzles about the spatial structure and temporal behavior of the torus.

The first orbit of the Galileo mission will provide one Io pass. Its subsequent orbits lie well outside the relevant region. It will not measure field-aligned currents nor neutral particle fluxes. Its imaging and spectrophotometry are not optimized for Io torus studies. It may, however, provide valuable data on the spatial and temporal behavior of the torus. The flyby trajectory of Ulysses (the International Solar Polar Mission) makes a single north-south sweep through the inner Jovian magnetosphere. Its findings will be interesting, but will not begin to respond to the systematic investigation needed to address Io torus questions seriously.

A dedicated mission to the inner Jovian magnetosphere is necessary. A study phase to determine the feasibility of such a mission, the optimum mission design, and the instrument complement is a desired first step.

3. Study of Other Bodies

a. Pluto and Charon

Pluto's satellite Charon was discovered in 1978 at a distance of 20,000 km (0.9 ± 0.05 arc sec). From the brightness difference and the 6.3867-day period, the masses of Pluto and Charon are estimated to be 0.0022 and 0.0002 Earth masses, respectively. The densities are around 1.8 g/cm^3 and the radii are 1800 and 1100 km. A possible composition is 21 percent rock, 74 percent H_2O ice, and 5 percent CH_4 ice. Charon's orbit plane is inclined by 120 ± 5° to Pluto's orbit plane. The orbital angular momentum and presumably Pluto's spin are pointing below the plane of the orbit like the spin of Uranus. Fortuitously, the orbital inclination leads to mutual eclipses, which were first detected in 1985. Precise values of both radii and better constraints on the densities are being obtained through observations by ground-based and orbiting telescopes.

A CH_4 abundance of 17 meter-amagats (4.6×10^{22} molecules/cm^2) in a Pluto atmosphere has been determined spectroscopically, yielding a surface pressure of about 1.5×10^{-4} bar. It has been suggested that Pluto is unable to keep such an atmosphere from blowing off and that a heavier gas such as argon is necessary to slow down the loss of CH_4. This conclusion is, however, very sensitive to the temperature assumed for the upper atmosphere, which is drastically cooled if there is rapid escape. When this cooling is taken into account, an acceptable loss rate is found; it could be supplied by the evaporation of about 3 km of CH_4 ice over the age of the solar system.

After the Voyager encounter of Neptune, Pluto will be the only unvisited planet in the solar system, and will continue to be an important target for Earth-orbital and Earth-based studies. As a goal for the long term, a Pluto flyby or orbiter is clearly of great interest. A mission to such a distant body would be an ideal application for a low-thrust propulsion system.

b. Chiron

Little is known about this small body in orbit between Saturn and Uranus. Chiron appears to be much bigger than any known comet but may or may not be an asteroid. Because of its unique orbit it may possibly be a lost satellite, but more probably is a leftover planetesimal. There is no reason to believe that Chiron is the only body of its kind in the outer solar system. Chiron-type objects may form a continuum of moderate-size, orbit-crossing bodies that possibly includes Pluto and even larger bodies. They are important to understand in terms of their relation to comets and primitive planetesimals scattered by the giant planets. Although they do not justify a special mission, Chiron and similar bodies yet to be discovered are significant targets of opportunity in outer planet missions.

V
Support Activities

Sending instruments to observe and probe planetary systems is only the most visible component of a strategy to achieve planetary science objectives. Vigorous experimental and theoretical programs are required during mission planning and ultimately to transform the data returned from the spacecraft into scientific knowledge. Earth-based and Earth-orbital observations are likewise necessary to complement the data obtained by planetary spacecraft.

A. LABORATORY AND THEORETICAL RESEARCH

Laboratory and theoretical work can be separated into four broad overlapping areas:

1. Determination of physical and chemical constants.
2. Calibration and characterization of observational techniques.
3. Laboratory simulation of the physical processes operating on the planets, satellites, and rings.
4. Theoretical modeling of planetary processes.

The physical and chemical constants characterize atomic and molecular structure, liquid and solid bodies, and the numerous processes governing their interactions and physical state. This knowledge is obtained by both laboratory studies and theoretical calculations, and it is relevant to all phases of mission development. The responsibility for broad and continuous progress in this area resides in the wider scientific community, but NASA must ensure the performance of problem-oriented studies directed, for example, at obtaining chemical rate coefficients and identifying spectral lines. For example, proper interpretation of the Voyager ultraviolet spectra of the Io torus was delayed more than a year by the absence of definitive spectra of ionized sulfur and oxygen. Good measurements of sputtering rates are necessary for detailed theoretical modeling of changes in satellite-ring surface chemistry and magnetospheric plasma injection rates.

Calibration relates an instrument signal to the underlying physical process or state that is the objective. This is, however, a broader activity than simply relating the output signal from an instrument to the input signal. Rather, calibration entails a detailed characterization of the measurement technique and its strengths and weaknesses. Spacecraft instrumentation is constrained by weight, power, temperature, and reliability considerations. This, in turn, leads to compromises in resolution and sensitivity to false signals in addition to those problems already inherent in the techniques. Thus, an ultraviolet spectrometer signal may be plagued with scattered light from the strong Lyman-alpha line of hydrogen, or a mass spectrometer may have difficulty ensuring that the measured constituents in a sample are representative of the atmosphere. A related set of problems concerns the inversion transformations required to change radio and solar occultation data to altitude profiles. To ensure that the best instruments are designed and developed, such activities should be conducted over a long time rather than the brief period during which a particular spacecraft instrument is constructed. It is essential that this calibration and characterization of the measurement techniques receive emphasis in mission planning and development stages to ensure that proposed experiments are fully capable of delivering their intended scientific payoff, and that valid reduction and analysis tools will be in place when data are received. Because space missions are such conspicuous engineering efforts, it is tempting to equate instrument signals with scientific success. More critical attention is needed to define the actual scientific information content in data and to improve and validate strategies to extract it.

Laboratory simulations of processes such as impact cratering and particle accretion shed light on complex planetary processes and place constraints on theoretical models. Laboratory conditions enable at least partial simulation of different planetary environments and afford the opportunity to isolate individual parameters in order to assess their role in the overall process. For example, most existing knowledge of cratering processes applies to impacts into silicate objects, yet outer planet satellites are predominantly ice. What are the effects of icy targets on impact cratering mechanics? How are the morphologies of craters formed in ice-rich materials different from those of craters formed in silicate materials? These and other related questions can be addressed, at least in part, through laboratory experiments. Similar arguments can be made for other planetary processes, and include simulations of ion-sputtering and ultraviolet-darkening of volatile-rich surfaces and experiments involving the collision of particles in order to model aspects of ring dynamics.

Some aspects of planetary processes cannot be simulated in laboratories on Earth, but could be carried out in Earth-orbiting facilities such as a shuttle or a space station. For example, collisional accretion and destruction processes, so important for planetesimal and ring particle physics, cannot be adequately studied experimentally in the large gravity field of Earth. Given the very low gravity environments of the outer planet satellites, impact cratering experiments conducted in an Earth-orbital environment may yield new insights into the cratering process. ***Continued support of laboratory simulations of planetary processes and expansion of capabilities into a wide range of conditions—especially as appropriate to the outer solar system—are strongly encouraged.***

One mark of scientific understanding is the ability to predict and then interpret the outcome of new observations through theoretical modeling. This is especially true in the earth and planetary sciences, where complex, nonlinear geophysical processes are involved. Models are the testbeds of progress on planetary problems and are essential to mission success. Strong programmatic support is needed to maintain a flow of vigorous, high-quality theoretical contributions to planetary science, to encourage new theoretical researchers, and to supply the necessary support, especially high-performance computers and scientific programmers. Examples relevant to future outer solar system investigation where support for theoretical modeling should be continued and augmented include the following: studies of the origin and evolution of the solar system, and planetary systems generally; studies of the dynamics of the atmospheres of the giant planets; studies of the dynamics of ring systems; models of the structure, composition, and dynamics of the atmospheres of the satellites of the giant planets, for example, Io and Titan; studies of the aeronomy of the upper atmospheres of Jupiter, Saturn, and Titan; models of the interiors of the giant planets and their satellites; studies of surface processes, such as the volcanoes on Io (volcanism on Io is one spectacular example of a successful theoretical prediction); and studies of magnetospheric transport and energization processes, and of the mutual interactions between satellites, their ejecta, and magnetospheric ions.

Proper support of laboratory and theoretical studies is an integral part of any program of planetary exploration. The support must be sufficiently stable to maintain these activities at a professional level and to encourage participation of young investigators.

B. EARTH-BASED AND EARTH-ORBITAL OBSERVATIONS

Observations of the solar system from Earth and from orbit have always been important and will remain so. Remote observations are complementary to and supportive of those obtained from planetary spacecraft. Prime examples include the following:

1. Discovery of new phenomena and processes.
2. Study of seasonal and secular variations over a time base not accessible to planetary spacecraft.
3. Study of transient events, whose occurrence cannot be anticipated with the rigid schedule of spacecraft missions. Examples are Io's volcanic eruptions and Martian dust storms.
4. Support of spacecraft mission encounters by observing planetary conditions during spacecraft approach, planning observation sequences, determining the state of a planetary atmosphere in the context of historical observations, and making observations simultaneous with a mission encounter but of a nature not within the spacecraft capability (e.g., at other wavelengths).
5. Observations that are not easily made from a spacecraft or that do not benefit from being particularly close to a planet; these include searches for dim objects (e.g., new Chiron-class or Pluto-class objects, or near-Earth asteroids), astrometric observation of satellites for the determination of mass and gravity harmonics, and occultations, including those in the Pluto system.

6. Instruments can be designed and flown in Earth orbit (especially on a shuttle) much more quickly than they can be sent to another planet, and can be used to follow up unexpected discoveries such as the Io plasma torus.

Ground-based observations must contend with the Earth's atmosphere. Observations at wavelengths short of microwave are limited by atmospheric transparency and stability (typically 1 arc sec). Ground-based observations will likely be largely superseded by Earth-orbital observations as instruments with various spectral and spatial resolution are flown. Two notable exceptions for the near future are very-high spectral resolution observations and radio observations, which are little affected by the atmosphere.

Observations by the Space Telescope will bring about a major advance in the capability of near-Earth observations of planets. The 2.4-m telescope itself is essentially diffraction-limited from 200 nm to 1 mm; at 633 nm, 70 percent of the energy will be contained within a 0.1 arc sec radius. Pointing stability is intended to be 0.007 arc sec. Operational constraints will normally restrict the Space Telescope from pointing within 50° of the Sun.

The first generation of Space Telescope science instruments will allow imaging with resolution elements as small as 0.007 arc sec, detection of twenty-seventh magnitude objects in 4 hours with a signal-to-noise ratio of 10, spectra of planetary objects with a resolving power of about 10^5 from 110 to 320 nm, 0.3-nm resolution spectra of objects to twenty-second magnitude, and two-channel occultation measurements with 0.01-ms time resolution. These capabilities could make a major improvement in our knowledge of the outer planets in terms of atmospheric composition and temperature, small satellites, and ring observations.

For example, the resolution of the Wide Field/Planetary Camera (at f/30, in terms of pixels across the equatorial diameter at mean opposition) for Jupiter, Io, Saturn, Titan, Uranus, Neptune, and Pluto is, respectively, 1073, 27, 446, 21, 83, 49, and 3. Images can be obtained through 48 filters, including narrow spectral bands of specific atoms or molecules (e.g., sodium in the Io torus, or CH_4-band images of Uranus or Neptune).

The International Ultraviolet Explorer has already been highly productive in observing solar system objects and will continue as long as it operates. Planning and development are in various stages for other observatory facilities, such as SIRTF (the Space Infrared

Telescope Facility), AXAF (the Advanced X-ray Astrophysics Facility), and FUSE (the Far-Ultraviolet Spectroscopic Explorer, for the 100-A to 1200-A region). SIRTF and FUSE will be applicable to many solar system studies. It is important that planetary scientists examine the best way to utilize this instrumentation and help plan those features that would significantly enhance the use of these observatories for planetary research. We are now entering the era of shuttle-borne instruments in both facility and principal-investigator classes. The latter include Spacelab instruments, simple attached instruments, and free-flyers that are placed in orbit for the duration of a shuttle mission and then returned to Earth. In the future, some of these shuttle-borne instruments are likely to be operated from unmanned or manned space stations. The virtues of quick reaction will be most valuable in using shuttle-borne instruments to study planetary objects.

In summary, adequate Earth-based and Earth-orbital synoptic observations should continue to be made of the outer planets to record seasonal, secular, and, where possible, transient changes. Observations of seasonal changes on Uranus will be of great interest in terms of atmospheric dynamics and cannot be obtained by spacecraft. Studies of the composition and nature of the Pluto system are particularly important as they will provide the only new information about these objects during this century.

Advantage should be taken of opportunities to fly planetary remote-sensing instruments on the shuttle and, in the future, on space stations. The planetary observation capabilities of the Space Telescope should be utilized to the fullest extent possible in determining the nature of the outer planets in advance of defining spacecraft science instruments. Improved information on atmospheric composition and scale height would be particularly valuable for planning of entry probes. Discovery and orbit determination of additional satellites would allow planning for detailed observations by planetary spacecraft.

VI
Hardware Development

A. INSTRUMENTATION

A recent COMPLEX study has considered the general problem of instrument development for planetary exploration (*Development of Instruments for Planetary Exploration Spacecraft*, Space Science Board, in press). This section summarizes recommendations relevant to the exploration of the outer solar system, with emphasis on the Saturn system.

It is clear from the discussion in the remainder of the present document that the general type of instrumentation utilized for the Galileo Jupiter orbiter-probe mission would also be suitable for the Saturn system. Nevertheless, as a matter of general philosophy, Saturn system exploration should use at least upgraded instruments in terms of such matters as accuracy, sensitivity, efficiency, and reliability. Moreover, there are important differences between the Jovian and Saturnian systems, the presence of Titan being the outstanding example. The following discussion summarizes instrument requirements only in areas where development is needed beyond what is currently available.

A general requirement for future spacecraft instrumentation is for more efficient and more standardized data transmission and processing techniques, e.g., by onboard data compression or processing. Modern developments in microprocessor technology hold promise for considerable onboard processing of instrument data, with the result that significant reductions in the downlink telemetry requirements could be effected. It seems likely that "smart" instruments, acting on the results of measurements, might greatly improve experimental returns, especially for instruments operating at great distances from the Earth. But the problems of radiation hardening, device reliability, and software control are formidable, and development is needed.

1. Atmospheric Studies with Probes

a. Instrumentation Common to Saturn and Titan

Measurements of the atmospheric composition and structure for Titan and Saturn are high-priority objectives. As the major atmospheric gaseous constituents are already identified, quantitative information on the isotopic compositions and on minor and trace constituents are the important objectives. Development of a combined gas chromatograph-mass spectrometer seems to be the best way to meet these objectives. A mass spectrometer is required for isotopic measurements, but results may be ambiguous in situations where different molecules or atoms have the same mass numbers, e.g., N_2 and CO or hydrocarbon isomers. The gas chromatograph chemically separates the different gases and permits individual analysis. Chemically active gases such as H_2O or NH_3 present special problems because they are difficult to remove as contaminants from mass spectrometer sources. These constituents are important, especially for Saturn, and development of spectrophotometric instruments for their analyses would be warranted. A deuterated water (HDO) channel in the H_2O detector would be especially important. Present instrumentation for cloud physical properties is adequate, but no instruments for cloud composition are available. In many cases, however, the vapors can be measured in the gas phase.

b. Instruments Unique to a Titan Probe

A problem occurs in a Saturn orbiter-Titan probe mission due to the relatively short communication time available between orbiter and probe. Rapid data acquisition and transmission may be required, or long-lived probes (balloons, boats, etc.) may be needed. It is now known that the lowest atmosphere of Titan is free of CH_4 or nitrogen clouds; consequently, a Titan probe should contain instruments for surface imaging. Because of the low visible light levels and, possibly, restricted data transmission time, instrument development is probably needed. Infrared or even radar imaging might be considered. Since CO and CO_2 are trace gases in the Titan atmosphere, a special instrument for their analysis might be justified. In general, instrument operation in the smoggy Titan atmosphere will be difficult. (Section 10 below discusses related matters for Titan lander instrumentation.)

2. Atmospheric Studies from Orbiters

Unlike atmospheric composition measurements, which are best done with probes, meteorological studies are well carried out from orbiting spacecraft. However, greatly improved compositional and structural data might be obtained by the further development of instrumentation for radio occultation studies with a spacecraft receiver detecting a signal transmitted from Earth. As on Voyager, observation of solar occultations can produce occultation spectra for many atmospheric constituents with very high sensitivity. Improved meteorological instruments, especially multispectral imaging devices, are also needed to distinguish cloud structure. Imaging infrared and ultraviolet spectrographs are necessary for mapping the abundances of atmospheric constituents Instruments for direct wind velocity measurements with high spatial resolution, such as LIDAR, are also needed. Since Titan has no cloud features to track, such instruments are especially critical.

3. Internal Structure

Detailed knowledge of the Saturn gravitational field (higher gravitational moments) can yield improved knowledge of the interior structure, addressing important issues such as the extent of differential rotation in the deep atmosphere and interior. More advanced instrumentation in this area, including a gravity gradiometer, is required.

4. Saturn's Rings

The composition of the ring particles is a major unknown. In this area, instrument development efforts are essentially nonexistent. A high-spatial-resolution imaging spectrometer could address the issue of surficial compositional differences among different rings and variations within a given ring. Such differences are strongly suggested by color variations reported throughout the rings by Voyager.

Improved radio occultation experiments, with a receiver on the spacecraft and a transmitter on Earth, would be valuable for complete probing of ring structure and size distributions. LIDAR development or in situ measurements are required for direct measurement of ring thickness. Development of a trackable subsatellite for injection into the rings—an artificial ring particle—is an exciting possibility that could contribute experimental data on ring particle-particle interactions and the "viscous" properties of the ring structure.

5. Saturn's Satellites

The primary instrument development requirements for the Saturnian satellites other than Titan concern substantial upgrading of instruments that obtain information on surface composition. Improvements of two key instruments currently in intermediate stages of development would substantially increase the science return: (1) Gamma-ray spectrometers require high sensitivity and spectral resolution. Continued development is needed for active cooling and in preventing degradation from cosmic rays. (2) Visible and near-infrared mapping spectrometers require further development in detector technology (infrared arrays), optimized optical design, and onboard preprocessing and data compression. In addition, since the full complement of moderate- to high-resolution images is data intensive, improvements in data compression and transmission will be essential.

6. Saturn's Magnetosphere

Development of instruments is required for the following: (1) higher mass resolution and mass range ion composition measurements, capable, for example, of distinguishing between ^{14}N and ^{16}O; (2) 4 π steradian plasma ion detection; (3) flux measurements of the kiloelectron volt ions important for sputtering, and of orbiting and charge-exchange neutral atoms; (4) detection of charged dust particles; (5) multispectral imaging capable of revealing the spatial distribution of ultraviolet and possibly X-ray emissions from Saturnian tori, the Titan airglow, and auroral precipitation; and (6) radio wave analysis with direction-finding capability.

7. Planetology of Large Jovian Satellites

Key objectives in understanding the satellites include determination of surface compositions, physical properties of the surfaces, and characterization of the interiors. Remote sensing techniques developed for the Saturnian satellites described above can also be applied to the Jovian satellites. Two additional areas of development are directly applicable to intensive study of the large Jovian satellites: development of appropriate hard or soft landers to deliver science packages to the surface or subsurface of the satellite, and development of instruments for such landers that acquire science information in situ.

Technology for flight vehicles that emplace soft landers on solid surfaces is fairly well developed. Alternative hard landers, and penetrators in particular, require further development and are discussed in section VI.B. The most extensive instrument development requirements concern techniques and instruments to characterize chemical properties of near-surface material and interior properties of the satellites.

The state of development of all but a few instruments for in situ chemical analysis is extremely low. Studies of major element chemistry, trace element chemistry, volatile abundances, isotopic analysis, and mineralogy all require extensive instrument development. Specific areas include X-ray spectrometry, neutron interaction techniques, alpha-particle scattering, mass spectrometry and gas chromatography, and scanning electron microscopy. Particular attention needs to be paid to problems associated with techniques of sample collection and preparation. The icy satellites present particular problems where small, dense, solid particles probably reside as grains, sparsely disseminated through a matrix of up to 90 percent H_2O ice.

Physical properties of Galilean satellites, such as density, porosity, and strength, are important, since they bear on the presence of "regoliths" (of pulverized ice) and layering caused by resurfacing. Intensive studies are likely to involve penetrators, which measure these properties by accelerometry, as already demonstrated on Earth. Thus, the need for physical property instrument development for penetrator-class reconnaissance appears minimal, although instruments to measure additional physical properties, such as thermal and electrical conductivity in the dirty ices, will be desirable and compatible with penetrators.

Characterization of interior properties of the satellites includes determining the following: (1) thermal structure and heat sources, (2) state of the interior (e.g., are liquid zones present?), and (3) internal dynamics (e.g., are seismically active zones present?). Although measurement techniques exist for some of these topics, devices to measure heat flow and seismometers suitable for deployment on the Jovian satellites must be developed. In situ measurement of heat flow is particularly difficult because most mechanisms to emplace suitable instruments disrupt the thermal regime and invalidate the measurement. Nonetheless, heat flow is a sufficiently important parameter, especially on Io and Europa, to warrant the resources necessary to develop techniques for its measurement.

It should be noted that development of instrument packages for hard and soft landers has a double benefit. These devices not only are promising for Galilean satellite studies, but also have universal potential for intensive studies of many other bodies, including other satellites of various sizes, Trojan asteroids, comet nuclei, and Mars.

8. Inner Jovian System

The inner Jovian system is defined operationally as the region within which the Galileo mission will not make systematic in situ measurements. It is roughly a Jupiter-centered sphere enclosing the orbit of Europa. To make systematic measurements in the inner Jovian system, the problem posed by the severe radiation environment must be solved. Radiation hardening of the spacecraft and instruments may enable a mission of sufficient duration to achieve major scientific goals for the investigation of this region. Novel orbits and spacecraft configurations should a. be explored. Eccentric high-inclination orbits reduce the radiation fluence but miss the heart of the Io torus. Dual spacecraft can probe the torus from high-inclination orbits with radio signals sent through the region. The hardware to perform such measurements must be designed, but requires no new technology. The instrument development specified for Saturn's magnetosphere will be needed to investigate the inner Jovian system. The mass range for ions should be increased to 64 AMU. An X-ray spectrophotometric imager is highly desirable here. The neutral particle detector should measure orbiting neutrals with masses up to 64 AMU and charge-exchange neutrals up to 32 AMU. Magnetometer sensitivity to 0.1 nT is desirable to measure distributed field-aligned currents.

9. Spacecraft Radios and Tracking Systems

Spacecraft radios and tracking systems have the primary function of providing command and control of the spacecraft, relay of data to the Earth, and the observational data necessary for navigation. These same systems have been employed on numerous missions for scientific purposes directly relevant to important planetary issues, including occultation studies of planetary atmospheres, ionospheres, and rings, and the study of planetary interiors through determination of the gravity fields. The relevance of the radio data to central issues in planetary missions warrants continued consideration of the spacecraft and ground radio system as a scientific instrument, in addition to its service role.

Improvements to the spacecraft radio are best incorporated at the time of the initial engineering design. At each later stage they become more difficult and more costly. The ground system, which is the necessary adjunct to the spacecraft system, is under continual improvement, so that considerations of radio science ground instrumentation need to be a part of an ongoing process. Voyager has demonstrated that early consideration of the scientific uses of the radio system can greatly enhance the value of the returned data. NASA design studies should consider at an early stage the scientific uses of the radio systems.

For most cases in the past, occultation measurements have been based on the use of 10 to 20 W of power emitted by the spacecraft transmitter, with signal reception on the ground. An exception is Mariner 5, where special dekameter and meter wavelength equipment was placed onboard to receive much stronger signals (400 kW) sent from Earth. There exists the possibility of dramatic gains in future radio experiments by a reversal of the propagation direction, as was done for Mariner V. NASA Deep Space Network (DSN) ground-based transmitters are from 4 to 5 orders of magnitude more powerful, depending on the frequency, than the spacecraft transmitters. Radio experiments utilizing DSN transmitters with reception on spacecraft would gain more than a factor of 1000 in signal-to-noise ratio in the worst case and could share some equipment with the onboard command receivers. Such a large gain in sensitivity would greatly improve occultation measurements of atmospheres, ionospheres, and rings, and could make fundamentally new observations possible as well. As an example, a thousandfold increase in sensitivity would have made bistatic-radar scattering observations of Titan's surface feasible for the Voyager flyby, thus permitting determinations of the dielectric constant, small-scale surface roughness, and large-scale variations in relief; it would also have permitted full radio probing of Saturn's B-ring.

10. Titan Lander Instruments

Rational design of instrumentation for in situ measurement of chemical and physical properties and processes on Titan's surface must await a first characterization of the nature of this surface. But it seems probable, from what is now known from Voyager, that lander or "floater" instruments will have to function on or immersed in a surface of hydrocarbons and organic compounds, possibly subject to wave and wind motions, at ambient temperatures of ~95°K and pressures of 1.5 bars or greater, and in conditions of poor optical visibility. If a floater is utilized, development of technology to maintain a radio link from an irregularly moving platform may be required.

If a solid ("blacktop") surface exists on Titan, with sufficient strength to support a soft lander or emplaced penetrator, then seismometers and whatever heat flow instrumentation is eventually developed for automated in situ measurements on planetary surfaces would be appropriate. It is likely that no major Titan-specific development of geophysical instruments, except for protection of critical components from the environment, would be required. Seismic measurements could be carried out from a platform deployed on a liquid surface, and valuable data on wave spectra and tidal flows would be obtained from tiltmeters. Tracking of surface packages would allow a determination of the Lagrangian circulation of a Titan "ocean."

The instrument of choice for in situ compositional measurements on either a solid or liquid surface is a combined gas chromatograph-mass spectrometer (GCMS), similar to that specified for a Titan probe in section VI.A.1. Here significant development is needed for both probe and surface applications, not only of existing GCMS systems themselves to ensure accurate analysis of trace constituents (e.g., the heavy noble gases Kr, Xe) in the presence of enormously larger amounts of hydrocarbon and organic molecules, but also of techniques for preanalysis sampling and processing of ambient environments containing high-pressure gases, liquids with or without suspended particulate matter, or brittle to tarry carbonaceous solids. In addition, "wet" chemical techniques may be required for measurement of important nonvolatile element abundances (e.g., silicon, potassium, rare earth elements). These techniques are totally undeveloped for automated in situ application.

If Titan has a planet-wide ocean, one option may be to sink the instrument platform to the seafloor if the liquid is sufficiently radio transparent, which it may be at 10 to 20 cm. This could allow deployment of geophysical instruments on or in the seafloor, and geochemical sampling on both sides of the liquid-solid (sediment) interface. Emplacement of a penetrator-type instrument package into the Titan ocean floor may be feasible by a technique similar to oceanographic gravity coring. High ambient liquid pressures are an obvious consequence of deep submersion, and would require additional development for instrument protection and sample selection and collection. Imaging capability would be lost. Oceanographic instruments and observations would replace meteorological ones.

11. Instruments for Penetrators

The potential value of penetrators has been widely recognized and is further discussed in section B of this chapter. But this potential will not be realized until a suite of suitable instruments has actually been built and demonstrated. The closest to reality are seismometers and accelerometers for measuring physical properties of the medium encountered. Samplers for chemical analysis, and the analytical instruments themselves, exist only as concepts. Heat flow, high on the list of important measurements, does not even have a viable concept. Studies and the building of prototypes should be pursued.

B. FLIGHT VEHICLES

1. Deep Atmospheric Probes

The deep atmospheres of the giant planets may contain the critical information needed to deduce the bulk composition and understand the meteorology. On Venus, probes have relayed information from a depth where the temperature is 750°K and the pressure is 90 bars. They can, in principle, be used at the giant planets. Absorption of radio signals is a severe problem when NH_3 and H_2O are present. The probe will have to fall rapidly if it is to stay in radio contact with the parent satellite overhead. Other relay stations, such as a balloon floating near cloud-top levels (if feasible in a hydrogen atmosphere), might also receive data from a deep probe. An acoustic link to the balloon is also conceivable.

The time to study the feasibility of deep atmospheric probes is after the Galileo mission, when the Galileo probe will have reached below the 10-bar level on Jupiter, and will have provided an estimate of the H_2O and NH_3 abundances, and information on radio propagation. An altitude profile of wind, temperature, and cloud opacity will be available for this altitude range. An extrapolation to deeper levels can be made, and the difficulties and potential rewards of a deep probe mission can be assessed.

2. Penetrators or Other Hard Landers and Associated Instrumentation for Airless Bodies

The basic tool for study of the interior of a planetary body is a network of instruments, especially seismometers but not limited to them. A relatively inexpensive landing technique is therefore essential. On the few bodies with dense atmospheres, parachutes are a possible solution, but even the Martian atmosphere is not quite dense enough and there are many bodies with much lower atmospheric densities than Mars. The classic solution has been the soft lander (Surveyor, Apollo, Viking), which requires retropropulsion, attitude jets, and a complex guidance system. Although there may be ways to reduce the cost of this technology, it seems more likely that some form of "hard lander" can be much cheaper. Many techniques have been suggested, often involving a bumper of crushable material such as balsa wood or plastic foam, and some have been used in the Soviet program. It is important to find some method to reduce costs and increase opportunities, and to bring some such technology to the point where it can be seriously proposed for future missions. Penetrators, which seem to have several attractive features, have had the most study in recent years and are the focus of the rest of this section. However, other vehicles that perform the same functions should also be considered.

A surface penetrator is a missile-shaped vehicle designed to bury itself and the instruments it carries into the surface of a planetary body. Current designs envisage a steel forebody a few meters long and roughly 10 cm in diameter connected by an umbilical cable to an afterbody that remains on the surface. The total mass of the penetrator is about 35 kg. The forebody buries itself a few meters to tens of meters deep in the target planet's surface and is thus ideal for implantation of instrumentation for measurement of seismicity and subsurface physical and chemical properties. The value of penetrators would be enormously enhanced if a method for measuring heat flow could be developed.

Penetrators must be emplaced at a nominal velocity of 150 m/s and with no more than a small angular deviation between the long axis of the penetrator and its entry direction. This alignment must be accurate to 3° for hard rock targets and to 11° for softer targets such as loess. Very cold ice is presumably similar to hard rocks in alignment requirements.

For bodies that have escape velocities greater than 150 m/s, penetrator emplacement requires some kind of retrorocket system. The necessity of aligning the penetrator with the flight direction also requires a lightweight guidance system and radar altimeter. Penetrator missions to airless bodies thus require more supporting hardware than the well-studied penetrator mission to Mars, whose atmosphere can be used to both brake and align the penetrator before emplacement. Nevertheless, preliminary design studies show that penetrator missions are feasible for airless bodies even with current technology. The main difficulty is in deployment of the umbilical cable linking the forebody to the afterbody on the surface. *The advantages of a planet-wide seismic and (if possible) heat flow network are so great that development of penetrator technology for airless bodies should be given a high priority.*

Penetrators can carry a variety of instruments. Surprisingly, many existing instrument designs can successfully withstand the ~2000-g accelerations experienced by the forebody and the ~20,000-g accelerations in the afterbody. (The entry shock for an atmosphere probe is ~400 g.) The most appropriate instruments for penetrator implantation are those that form parts of global array experiments: seismometers and heat flow devices. Chemical compositions can be measured by gamma-backscatter techniques, X-ray fluorescence, gamma-ray spectrometers, or possibly other techniques.

Each type of instrument places some constraints on penetrator design. Current seismometers, if not on gimbals, require near-vertical emplacement to function properly. Heat flow measurements suffer interference from engineering constraints on penetrator internal temperatures, the heat generated by the emplacement, and the disruption of the local material. Composition measurements adjacent to the penetrator may be contaminated by penetrator material scraped off during emplacement. None of these difficulties appear insurmountable, however, and further development is strongly recommended.

Stratigraphic horizons and mechanical impedance of the target planet can be inferred from deceleration of the forebody during implantation. Other instruments such as geophones or long-period seismometers (e.g., tiltmeters), gravimeters, or magnetic sensors may also be feasible. Further development of instrumentation should be undertaken before any penetrator missions are actually flown: it is possible that other types of planetary data (for example, rare-earth element compositions) might be acquired by more sophisticated instrument systems.

C. ELECTRIC PROPULSION SYSTEMS

Electric propulsion systems show considerable promise for substantially decreasing trip times and increasing the usable payloads for targets in the outer solar system. They also have many potential uses after encounter in changing orbits for rendezvous with various satellites. *The value of electric propulsion systems for missions to bodies such as comets and asteroids is immense.*

In this section, the various systems that have been proposed are described, the advantages and disadvantages of each are discussed, and the state of development of each is given. Since the power required for the acceleration of the propellant is derived from external sources, the propellant material can be accelerated to velocities far greater than those typical in chemical systems. A large total impulse can therefore be obtained from a relatively modest amount of propellant mass. The advantages for outer solar system exploration are obvious.

Generally, the propulsion systems can be considered separately from their primary power sources, since all that is required is electric power regardless of its ultimate source. The two power sources proposed so far are solar cells and a nuclear reactor. The former has a long history of development and use in space, albeit not on the scale necessary for powering a propulsion system, whereas within NASA the latter has proceeded only as far as technological studies. The acronyms SEPS (Solar Electric Propulsion System) and NEPS (Nuclear Electric Propulsion System) refer to the two power sources, which so far have involved only one type of propulsion—electrostatically accelerated ions.

Besides the electrostatic thrusters, several thrusters use electromagnetic forces for the acceleration. These are generally simpler in design and operation in that they accelerate the propellant in a single process by ionizing the propellant and driving high currents through the resulting plasma. The Teflon-pulsed plasma thruster, the magnetoplasmadynamic (MPD) thruster, and the inductive-pulsed plasma thruster are three forms of this latter type of thruster. The operation of all the thrusters is described below.

1. Electrostatic Thrusters

The ion accelerators proposed for use in the SEPS and NEPS vaporize mercury, ionize it either in a DC electric discharge or in a radiofrequency field, and accelerate the ions through an electrostatic potential difference of the order of 3000 V. The resulting ion beam is neutralized, and a charge is prevented from building up on the thruster by a hot wire electron emitter located in the beam. Other propellants can be used, but heavy ions yield the highest thrust for a given power expenditure.

There has been sufficient development of these thrusters in the last decade that flight models can be easily designed. In fact, the thrusters have been flight-tested on two satellites, SERT I and SERT II (Space Electric Rocket Test). On SERT II, two 15-cm thrusters were operated for several thousand hours with frequent on-off sequences with no apparent deterioration. Both thrusters were retested in 1979, after 9 years in orbit, with no degradation in performance. A 30-cm thruster has been developed and thoroughly tested. The power consumption of this thruster is 2.75 kW, the thrust is 0.14 N, the exhaust velocity is 30,000 m/s, the overall efficiency is 73 percent, and the lifetime is 15,000 hours. The lifetime is determined by erosion of various grids by ion sputtering—both the accelerating electrode and grids in the discharge ionization chamber. With full development, one could expect the lifetimes to be increased. Unfortunately, the U.S. project in these thrusters was terminated in 1980.

In Europe, an ion thruster has been developed that differs from the American design by using a radiofrequency field for the ionization of the mercury propellant. A 35-cm-diameter thruster was proposed in 1979 with a 73 percent efficiency and a thrust of 0.2 N. The power consumption is 4.8 kW, the mass flow rate is 5.6 mg/s, and the exhaust velocity is 34,000 m/s.

The maximum thrust per thrust module is relatively low, 5 mN to 1 N, because of space-charge limitations on ion currents. The development has proceeded sufficiently for these ion thrusters that higher thrust systems could be assembled using components that have a substantial history of ground testing. Matching of power source and thrusters can be achieved with state-of-the-art, high-efficiency circuits and components.

For many potential applications to the exploration of the outer solar system, the thrusters should have lifetimes exceeding the currently realized 15,000 hours (1.7 years of continuous use). Another concern is the reliability of components under continued high voltage stress (~1000 V). Finally, the thruster system is very complex, with many parts whose continued function is necessary for extended operation. Both the reliability question and the limited lifetime could be compensated by redundancy at a cost of added mass.

Several environmental factors associated with the use of ion thrusters will compromise the function of instruments without special tactics or procedures. There is a magnetic field contamination from the thrusters as well as radiated electric fields. If a high-power solar array is the power source, magnetic field contamination is increased. There is also optical and ultraviolet line radiation from the excited mercury ions in the beam. Perhaps the greatest concern is the plasma cloud that completely surrounds the spacecraft when the thrusters are on. This follows from the fact that 10 percent of the mercury leaves the ion optics unionized. Charge exchange between high-energy ions and neutrals produces low-energy ions, which, together with their neutralizing electrons, diffuse around the spacecraft. Some molybdenum ions are sputtered from the accelerating grid by the charge-exchange ions attracted by its negative potential and can contaminate spacecraft surfaces on line-of-sight trajectories. Mercury will condense on those spacecraft surfaces that are sufficiently cold. This is an especially serious problem for those instruments requiring radiative coolers, which are likely to be at low temperatures, and thus will allow the mercury to condense. The resulting loss of radiator emissivity could destroy the function of the instrument. Some instruments have their interiors exposed directly to space without protective covers or lenses, and their function could be destroyed by the entering mercury plasma. The electrons in the plasma will be attracted to any positively biased solar array, causing a power drain, although the estimated drain is small.

There are several countermeasures that can be adopted to make the instrumentation compatible with the thruster environment, such as the use of shields or heaters, and using the instruments only when the thrusters are off. Detailed engineering study is required to establish the significance of the mercury hazards and how much relief can be obtained by waiting for some time after termination of thrust. A different propellant such as argon or xenon would eliminate mercury contamination, but at the expense of a loss of thrust. These problems with the use of the ion thrusters are substantial, but they do not appear insurmountable and the ion thruster seems to be an attractive alternative for low-thrust, long-duration propulsion for journeys to the outer solar system.

2. Electromagnetic Thrusters

The Teflon-pulsed plasma thruster is fully developed and flight-tested for low-thrust applications such as stationkeeping of synchronous satellites. The device works by discharging a bank of capacitors across the face of a Teflon block. The discharge vaporizes and ionizes a small amount of Teflon, and the high current j through the plasma interacts with its own magnetic field B to create a strong $\vec{j} \times \vec{B}$ body force, which, together with the gas dynamic pressure, propels the plasma from the discharge chamber. The system has several attractive features: no propellant valves are required, it can provide an accurately timed pulse, and it is an extremely simple design requiring only two power sources. However, there are also major technological challenges to using the system for long-term propulsion. These include low efficiency, scaling to higher thrust or power levels, deposition of carbon on sensitive spacecraft surfaces, limited capacitor lifetime, and electromagnetic interference arising from high voltage and current pulses. This thruster concept is therefore not competitive with the ion thruster for outer planet missions—at least not in its present state of development.

The self-field magnetoplasmadynamic (MPD) thruster operates by passing a gas, typically argon, through an electrical discharge from a cylindrical cathode to a coaxial anode located downstream in the flow. The discharge ionizes the argon gas and the resulting plasma is accelerated in the axial direction and confined in the radial direction by $\vec{j} \times \vec{B}$ body forces. Here $\vec{j}$ is the current density along trajectories from the cylindrical anode to the central coaxial cathode and B is the azimuthal field due to this current.

The efficiency of these thrusters increases with total discharge current. For reasonable values of thrust efficiency, currents of the order of tens of kiloamperes and powers of the order of megawatts are necessary. With argon, thrusts to 200 N and specific impulses to 3300 s (pound-seconds of thrust per pound-mass of fuel) are possible. The goal for the development of these thrusters in 1979 was a 50 percent efficiency at a specific impulse of 3700 s. As the necessary megawatt power levels will not be available on any spacecraft in the foreseeable future, operation of the thruster in a pulsed mode is proposed. Pulse lengths of about 1 ms at megawatt power levels and repetition rates of one per second were proposed in 1979. Energy storage would be accomplished by slow charging of a capacitor bank. All of these numbers were projected from existing laboratory data obtained from less ambitious devices, and as yet no hardware has been constructed. Technological studies with laboratory prototypes are proceeding, however.

The MPD thruster has the advantage of being much simpler than the ion thruster. Since it accelerates a neutral plasma, there is no need for a beam neutralizer. It can provide relatively high thrusts if the repetition rate in the pulsed mode can be made sufficiently high. The thrust could be produced with a wide variety of gases. Technological challenges remain nontrivial, however. A pulse-forming network would have to be designed to work into a 0.01-ohm load. The voltage must be high enough to ignite the plasma arc and must sustain the current for about 1 ms so that the thruster operates in a quasi-steady mode. A space-qualified fast valve would have to be developed for gas control that would be capable of 10^7 to 10^8 cycles. Electrode lifetimes at high power levels may be too limited. Finally, the efficiency is low compared with that of ion thrusters, and that efficiency is highest at exhaust velocities of only 10,000 to 20,000 m/s, which necessitates a larger total propellant mass than that for ion thrusters with the same total impulse.

The inductive-pulsed plasma thruster works by pulsing a large current through a flat coil. The closed loop electric field in a gas above the flat coil ionizes the gas and generates a large closed loop current in the plasma. Interaction of this current with the coil field and its own field propels the plasma away from the coil at high velocity. The design has several advantages. The plasma discharge is electrodeless. Impedance matching of the energy source and inductance coil are straightforward. It could be operated continuously with an appropriate energy source and propellant injection system. The principal disadvantage is the necessity of high currents in the coil to achieve efficient acceleration, which means high losses unless the coil were superconducting.

In spite of their inherent simplicity, electromagnetic thrusters face technological problems that seem sufficiently formidable that ion thrusters, flight-tested and in an advanced state of development, must be preferred at the present time to meet the long-term, low-thrust needs of outer planet exploration.

3. Power Sources

Solar arrays for powering ion thrusters are currently projected in the 25- to 30-kW range with two "wings" of order 4 × 32 m in size. Technology is available to support the development of 66 W/kg solar arrays and planar arrays with specific power of up to 200 W/kg appear feasible. Although direct funding of SEPS technology studies terminated in 1980, the mechanical design of the large arrays is also important for the shuttle and the space station. SEPS will benefit from the information gained. Other than this, there are no plans for the development of a working model of a large solar array. Solar arrays have limited use for powering ion thrusters in exploring the outer solar system because of the $1/r^2$ decrease in power output. For this reason, nuclear power is a preferred option for this application. Given the uncertainties attached to the development of a space nuclear reactor, a working example of SEPS would solve many of the technological problems sure to be encountered in the development of the complete NEPS system. On the other hand, work on SEPS has stopped, and it may make sense to abandon it altogether and concentrate on NEPS as the low-thrust capability for all NASA missions that can benefit by it.

Technology studies for a space nuclear reactor have been going on for a number of years, and they are currently continuing under a project called SP 100 (Space Propulsion 100 kW), which is funded jointly by NASA, DOE, and DARPA. Current design centers on a 1.2-MW reactor cooled by heat pipes with thermionic or thermoelectric conversion to electrical power at about a 10 percent efficiency. There is the possibility of more efficient conversion and simultaneous elimination of the heat pipes with the use of alkali metal thermoelectric converters (AMTEC), which work by forcing liquid sodium through porous molybdenum electrodes. These converters have efficiencies of 15 to 40 percent, no moving parts, and power densities of 0.7 W/cm^2. The advantages gained in exploring the outer solar system with NEPS are so great that it should be considered carefully.

4. Mission Advantages with Electric Propulsion

The discussion here will center on orbiter missions to the outer planets, although advantages of electric propulsion for flyby-probe missions are comparable. Jupiter can already be reached with reasonable payloads in flight times of about 2 years using only chemical propulsion. Although some advantage, such as very large payloads, could be gained by the use of electric propulsion, Jupiter missions probably will not drive the development of these low-thrust systems. Orbiters can be placed around Saturn with direct ballistic trajectories, and with Earth gravity assists (EGA), or, in certain time windows, Jupiter gravity assists (JGA). A variation of the EGA is SEEGA, where solar electric propulsion is employed between launch and the return Earth encounter, and perhaps for some time afterward before the SEPS is jettisoned. Use of SEEGA reduces the trip time from 8 to 5 years for a 1500-kg orbited payload in one mission option studied by Science Applications, Inc. The advantage of NEPS in this latter case is that there is power for deceleration upon approach to Saturn, thereby reducing the retrorocket requirements. In fact, with NEPS the trajectory can be direct with a spiral Earth escape and spiral into Saturn capture where 1500 kg is delivered into orbit in about 5 years. A further advantage is that with NEPS the missions can deliver 2000 kg into Titan orbit in 5 years as well. This mission can also be accomplished by a Jupiter swingby, but only when Jupiter is in the right place.

In a study of orbiter-probe missions to Uranus and Neptune, and an orbiter mission to Pluto with the constraint that the mission be completed within 8 years, Science Applications, Inc. chose the NEPS option over various alternatives, including use of aerocapture and Jupiter swingbys. The independence from unique launch opportunities and greater flexibility in trajectory design, failure mode recovery, and orbital maneuvers were key factors in this choice. With NEPS 900 kg could be orbited around Uranus, Neptune, or Pluto, and a 300-kg probe dropped into the two gaseous planets in 6 years from launch for Uranus and in 7 years from launch for Neptune or Pluto. The assumptions were a 100-kW electrical power output into 5 ion thrusters whose properties were a reasonable extrapolation from those of the existing 30-cm thruster. Thruster lifetime was increased from the existing 15,000 hours to 20,000 hours, and thrust per system to about 0.5 N from the existing 0.14 N. The limited life of a given thruster was compensated for by incorporating extra thrusters into the design. A chemical thruster launch from Earth orbit was also assumed with initial C_3 near 60 $(\mathrm{km/s})^2$. Additional study should be directed toward the use of NEPS during the orbiting mission and a comparison with Titan gravity assists in terms of ease and precision of control, flexibility, and scientific return.

The shorter trip times, increased payloads, and vastly greater flexibility in mission design and scientific potential make NEPS an extremely valuable tool for exploring the outer solar system. Although development of the necessary space reactor will be limited in the short term by current budgetary constraints, its capabilities in defining and implementing scientific objectives for outer solar system exploration for the next 20 to 30 years are obvious. *COMPLEX recommends continued support for reactor technology projects such as SP 100, and for studies of the role of nuclear electric propulsion in planetary missions, with the objective of developing NEPS to the point where it can be realistically used as a propulsion option in constructing outer planet exploration strategies for the decade 1996-2006.*

VII
Recommended Strategy

At the time that the previous COMPLEX report on the outer planets was written (1975), the only encounter that had taken place was that of Pioneer 10 with Jupiter; the Pioneer 11 encounter occurred while the report was being published. The recommendations for Jupiter could be based on the Pioneer reconnaissance, but for Saturn and Titan only Earth-based information was available. Since then, both planets and their satellites have been explored by Voyagers 1 and 2, in addition to the Saturn encounter of Pioneer 11, and, in large part, these systems have passed through the phases of reconnaissance and exploration. Detailed study of the Jupiter system will begin with the Galileo orbiter-probe mission. The studies that led to the present report naturally gave much more attention to the Saturn system than would have been possible in 1975. Our knowledge of systems beyond Saturn has been greatly augmented by the 1986 Uranus encounter by Voyager 2, and by Earth-based studies. Even though much more can be said about Uranus and Neptune than was possible a decade ago, detailed planning for further study of these systems must await full analysis of the 1986 encounter data, and the 1989 Voyager 2 Neptune encounter. Because trip times to the outer planets are so long, it is inevitable that the pace of their investigation will be slow.

Since 1976, COMPLEX has issued two other strategy reports, dealing with the inner planets (1978) and primitive solar-system bodies (1980). The theme for the inner planets is comparative planetology of Venus, Earth, and Mars, with the Moon and Mercury regarded as complementary bodies of high scientific interest.

The only inner planet missions since 1976 have been to Venus: The U.S. Pioneer Venus Multiprobe and Orbiter had their encounters in late 1978, and the U.S.S.R. has had several successful lander and flyby missions and a pair of radar imaging orbiters arriving in 1983. These investigations have yielded an enormous harvest of information about the surface, atmosphere, and clouds of Venus and its interaction with the solar wind. Many fruitful comparisons with the Earth have been made, but comparison with Mars has suffered because there has been no mission since Viking in 1976. A totally unexpected discovery was the very different abundances and ratios of noble gases on the three planets, as well as a great enrichment of deuterium on Venus, implying a great abundance of water in the past. The Venus Radar Mapper is being developed for a launch in the late 1980s. Its primary purpose is to obtain a global radar map, as recommended by COMPLEX in its 1978 report. Exploration and intensive study of Venus have therefore been proceeding at a steady pace.

Plans for the intensive study of Mars have also been initiated with the 1986 new start for the Mars Observer mission. This spacecraft is being developed to obtain global and temporal information on the surface chemistry and climate of Mars. This extended exploration mission in the early 1990s is in direct response to recommendations of the 1978 COMPLEX report, as is current planning for a later Mars Aeronomy Observer mission. An active Soviet program is also under way.

Spacecraft investigation of primitive bodies began with the ICE flyby of the Giacobini-Zinner Comet in 1985, and the 1986 encounters of Halley's Comet by the spacecraft of several other nations. NASA hopes to proceed with a comet rendezvous mission in the 1990s. The Galileo mission is expected to fly near one or more asteroids, as well.

The results of the Voyager encounters with Jupiter, Saturn, and Uranus have given a broad range of information raising many important questions for further intensive studies. Such studies of the Jupiter system will be undertaken by the Galileo probe and orbiter. On this mission, the probe and its instruments will make detailed measurements along a single vertical path; in addition to their intrinsic importance, these results will provide "ground truth" for the remote sensing instruments on the orbiter. Conversely, the orbiter results will give a global perspective that is lacking in the probe data alone. The Jovian magnetosphere and plasma torus have major effects on Io and other satellites, and cannot themselves be understood without consideration of these objects as sources of ions. Precipitation of particles into Jupiter's upper atmosphere provides major sources of heat, and optical and X-ray emissions. Any series of focused spacecraft concentrating on individual areas would be much less scientifically effective, and their total cost would probably exceed that of the single, interdisciplinary Galileo mission. Saturn, its rings, and its remarkable satellite Titan offer an equally fascinating opportunity, and intensive study of this system is the next step for the outer solar system.

The high degree of interrelationship among phenomena in each of the Jupiter and Saturn systems has been noted above. As emphasized in the next section, intensive study of the Saturn system as an interacting whole is therefore the highest priority for outer solar system missions in the next decade, on the assumption that Voyager 2 and Galileo succeed in their planned missions. Fulfillment of other objectives, also of high priority, is better deferred until the analysis of results of current missions, or technical developments, makes them timely. They include study of the Uranus and Neptune systems, small satellites, and the inner Jovian system.

The integrated approach is already being followed in the Galileo mission and is equally natural for the Saturn system. The 1976 document was already moving toward the systems approach for study of Jupiter, and the arguments for Saturn are equally forceful. Ions in the magnetosphere are derived from gas emitted by Titan and probably other satellites, and interact with them. The system is pervaded by microscopic dust, derived from both rings and satellites. The rings absorb magnetospheric particles; the ring shadow has major effects on the atmosphere and ionosphere of Saturn. These and other time-dependent effects make it almost mandatory to study many phenomena at the same time. Nevertheless, budgetary concerns may force the program into smaller missions addressing fewer objectives. A list of individual areas is presented in the next section. Any restricted mission should still be planned as far as possible to address the interrelationships, and should include a reconnaissance of Titan's surface for guidance of future exploration.

Although direct studies of the atmospheres of Uranus and Neptune could be undertaken at any time, the guidance of understanding provided by the Voyager encounters will almost certainly be available by the time they could be seriously planned. More ambitious missions, taking the systems approach, certainly need such guidance. The outer solar system is a rich area for comparative planetology, and the variety of rings, magnetospheres and satellites immediately comes to mind in this context. Icy satellites, particularly the Galilean satellites of Jupiter, are of particular interest. The inner Jovian system, comprising the magnetosphere and the satellites, has very high scientific priority but suffers from a special technical difficulty--the enormous radiation doses that quickly accumulate in any spacecraft. Given this difficulty, *COMPLEX urges further development of radiation-hardened systems, consideration of highly inclined orbits, and careful study of the relevant information from Galileo.*

All these recommendations are based on the assumptions that Voyager 2 will have a successful encounter with Neptune and that the major parts of the primary Galileo mission will succeed. An extended mission for Galileo will give valuable information, particularly further coverage of the magnetospheric tail and of the surfaces of the satellites. However, information from an extended mission is not required for the planning of future missions to Jupiter or Saturn. If any of the major Galileo objectives is not realized (for example, by failure of the probe), the implementation of this strategy would have to be reconsidered.

The pace of solar system exploration is controlled almost entirely by political and budgetary considerations, which are subject at times to rapid change. Technically, the controlling factor is the development of the Mariner Mark II spacecraft, for which approval was first requested, unsuccessfully, for 1987. A Saturn system mission started as early as 1988 could still arrive several years after the conclusion of the Galileo mission at Jupiter. A 1989 or later start for Uranus and Neptune would be able to take advantage of all the Voyager results.

The rest of this chapter is in two sections. The major scientific objectives appear in section A. Additional recommendations, principally for development of instruments and techniques, follow in section B.

A. SCIENTIFIC OBJECTIVES FOR OUTER PLANET EXPLORATION, 1986-1996

1. The Saturn System

The highest priority for outer planet exploration in the next decade is intensive study of Saturn—the planet, satellites, rings, and magnetosphere—as a system. In this context, the scientifically most valuable implementation of the strategy would address several broad areas of study and their cross-comparison. Important scientific goals are as follows: understanding of the composition and structure of the atmospheres of Titan and Saturn; detailed, long-term studies of Saturn's rings, of Saturn's small satellites, and of Saturn's magnetosphere; and a first characterization of the physical state of Titan's surface.

Exploration and intensive study of the Saturn system should include the following scientific objectives:

- *Titan's atmosphere—measure the composition, structure, and circulation of Titan's atmosphere, and characterize the atmosphere-surface interaction.*
- *Titan's surface—carry out a reconnaissance of the physical properties and geographical variability of Titan's surface: solid or liquid, rough or smooth. Emphasis should be given to any information needed to guide the design of a lander vehicle.*
- *Saturn's atmosphere—determine the elemental composition, dynamics, and cloud composition and structure, to a level well below the H_2O cloud base.*
- *Saturn's rings—measure particle composition and its variety, spatial distribution of particles, and determine the evolution of dynamic structures.*
- *Saturn's small satellites—make comparative determinations of surface composition, density, geologic history, and geomorphological processes*
- *Saturn's magnetosphere—specify the structure, dynamics, and processes, and the mutual interactions of the magnetosphere with Saturn's atmosphere, rings, icy satellites, Titan, and the solar wind.*

The primary consideration in choosing these objectives is scientific return, tempered by assessment of technical feasibility with an expected measuring accuracy adequate for substantial progress. The preferred strategy is to address most of the major objectives in a single mission: the physical characterization of Titan's surface, detailed determination of the atmospheric composition of Titan and Saturn, and further study of the Saturnian atmosphere, rings, magnetosphere, and satellites. Such an intensive, multidisciplinary study of the Saturn system is the top priority. It is expected to provide major scientific returns in broad areas of planetary science. A less desirable alternative implementation is to pursue these objectives in a series of smaller missions designed to study the individual phenomena and, to the extent possible, their interrelationships. However, no matter what the primary objective, the first such mission should include a reconnaissance of Titan's surface for guidance of future exploration, as well as for its scientific importance.

The major goals of planetary science include the following: (1) *understanding the origin and evolution of the planets*, (2) *understanding processes, and* (3) *comparison of the operation of fundamental processes in different planetary environments.* These goals are well served by a broad, interdisciplinary approach to study of the Saturn system.

The compositions of Titan and Saturn will provide important information on the origin and evolution of all the planets. Titan provides an example of an evolving atmosphere. Primordial solar system material may be preserved in the regolith of Saturnian satellites and the particles in Saturn's rings. The bulk composition of Saturn's atmosphere helps in understanding the planet's internal history.

The strong dynamical interactions within the Saturnian rings and with the inner satellites are of great interest for the light they cast on analogous processes in the early solar system and in other objects such as galaxies. The magnetosphere exhibits processes of great interest to planetary scientists and astrophysicists. Many of the phenomena are of the same kind as at Jupiter, but are much more accessible to study because of the lower intensities of dangerous charged particles. Dust-plasma interactions are a new feature. The atmosphere of Saturn, like that of Jupiter, is a gigantic fluid dynamics laboratory for study of meteorological processes. On satellite surfaces, a wide variety of geologic processes have been revealed by Voyager, and they merit detailed study with better image coverage and resolution, and with remote sensing of surface composition.

With regard to the third major goal, the meteorology of Saturn and Titan may be compared with weather on Venus, Earth, Mars, and Jupiter. Saturn's magnetosphere may be compared with those of Earth, Jupiter, and Uranus, and Saturn's rings and satellites with those of Jupiter and Uranus. More generally, physical processes occurring on the Saturnian, Jovian, and Uranian satellites will provide insight to analogous processes on the terrestrial planets and on other satellites.

2. Longer-term (post-1996) Strategy for the Outer Solar System

The strategy for outer planet investigation after the Saturn system comprises general objectives that await specific definition from the results of near-term missions (Voyager and Galileo), developments in instrumentation, and demonstrations of technical feasibility. *These longer-term objectives include exploration and intensive study of the following:*

- *Uranus and Neptune systems—(1) elemental composition, cloud structure, and meteorology of the planetary atmospheres; (2) rings, and satellites (especially Triton); and (3) structure and dynamics of magnetospheres.*
- *Planetology of the Galilean satellites and Titan—surface composition and physical properties, seismic activity, heat flow, and, where applicable, atmospheric composition and meteorology.*
- *Inner Jovian system—density, composition, and energy of magnetospheric particles; large-scale structure, rotation, and time-dependent phenomena in the Io torus, and relation to Io and other satellites, orbiting gas and plasma, auroral activity on Jupiter, and electromagnetic emissions.*

From a purely scientific point of view, these objectives for the longer term are of high priority. The post-1996 goal for all four giant planets is to know their composition, physical state, and meteorology. Such knowledge would allow one to separate effects that are specific to each planet, in order to understand giant planet formation, evolution, structure, and basic processes in general. However, further investigation of Uranus and Neptune building on the reconnaissance of these objects by Voyager should follow intensive studies of Jupiter by Galileo, and of Saturn, to make use of the technical and scientific experience of such missions.

Similarly, intensive study of the surfaces of Titan, Io, Europa, Ganymede, and Enceladus, for example, would greatly aid our understanding of satellite and, by inference, solar system formation, of surface composition and history of planetary-sized bodies, and of internal processes. Yet such studies must await technical developments. Titan's surface composition may hold the key to the evolution of its atmosphere. This surface may be solid or liquid, or some of each; a first-order reconnaissance must precede intensive study.

The Jovian magnetosphere is important as a laboratory for magnetospheric physics in which to study processes that affect the formation and evolution of solar system bodies. The environment of the inner magnetosphere is a serious hazard to the electronics and detectors of spacecraft and instruments. Close-in studies of the Galilean satellites and in situ studies of the inner magnetosphere may be impossible until these problems are solved. Remote sensing instruments on a magnetosphere-intensive spacecraft, perhaps in a high-inclination orbit, might provide the knowledge necessary to understand this physical system. The feasibility of such measurements must, however, first be demonstrated.

B. SUPPORT ACTIVITIES

A scientifically balanced strategy for exploration of the outer solar system includes not only building and flying deep space probes with existing technologies, but also developing new enabling technologies, expanding laboratory facilities, and promoting excellence in data analysis, theoretical interpretation, and modeling. These issues are discussed in Chapters V and VI. Accordingly, the following recommendations are made to meet the near-term (1986-1996) and long-term (post-1996) objectives for exploration of the outer solar system. Recommendations 1, 2, and 3 refer not only to outer planet exploration, but also to essential elements of all planetary studies. As such, they are of intrinsically high priority, and should be implemented throughout any and all of the specific COMPLEX decadal strategies, in support of both near-term and long-term science objectives. Other recommendations concern instrument and/or spacecraft development activities. Of these, recommendations 4(c,d,f,g) and 5 are highest priority for near-term outer planet exploration because they involve instruments and data handling techniques that relate to scientific objectives of the Saturn system study. The remaining recommendations address objectives that are specific to long-term outer planet strategy (4a and 7), or are generally applicable in both near-term and long-term to all areas of planetary exploration, including not only the outer planets, but also the inner planets and primitive bodies (4(b,e,h), 6, and 8). Because of the long lead times inherent in development, utilization of these components in addressing long-term science objectives demands viable development support during the present decade.

1. *Increased support of laboratory and theoretical studies (section V.A.).* The studies provide the basic physical data necessary for interpreting the spacecraft measurements, a better understanding of the relationship between the measured instrumental signal and the underlying planetary processes, and the experimental and theoretical modeling needed to predict and interpret the spacecraft measurements. Support of laboratory and theoretical studies is an important part of a program of planetary exploration. The support must be sufficiently stable to maintain these activities and to encourage the participation of young investigators.

2. *Pursuit of Earth-based and Earth-orbital observations (section V.B.).* These studies are needed as a complement to exploration by planetary spacecraft. For example, missions to Pluto are not likely before the end of this century, yet observations—such as could be made from Space Telescope—could refine measurements of the radii, densities, and compositions of Pluto and its satellite. Other important applications are premission planning, the study of seasonal and secular variations over a long time, and the utilization of specialized instrumentation. The unique capabilities of the Space Telescope for planetary research should be optimized and utilized to the fullest extent possible. Likewise, the specialized instrumentation available on SIRTF (Space Infrared Telescope Facility) and other observatory missions should be utilized for planetary studies. Advantage should be taken of opportunities to fly planetary remote sensing instruments on the shuttle (e.g., Spacelab and Spartan missions) and, in the future, on space stations.

3. *Commitment to continued operation of productive spacecraft (section IV.C.).* Reception and analysis of data from Pioneers 10 and 11 and Voyagers 1 and 2, as well as future outer planet missions, should continue as long as useful data can be transmitted.

Targets of opportunity and cruise science should be assessed for these missions as well as for all other planetary missions, and efforts should be made to maximize the science return when opportunities occur.

4. *Implementation of the instrument development plan (section VI.A.) as appropriate for the outer solar system. The following areas are particularly relevant*:

a. Development of radiation-hardening techniques for instruments and spacecraft components (see recommendation 7 below).
b. Development of techniques for in situ sampling of solid surface objects for compositional and isotopic measurements.
c. Development of large-angle (4 π steradian), low-energy ion detectors, adequate species discrimination (e.g., O^+, N^+), determination of charge state and charge-to-mass ratio of ring dust particles. Development of neutral particle detectors for measuring flux, velocity, and species of ambient and charge-exchanged neutrals.
d. Development of X-ray and ultraviolet spectrophotometric imagers for auroral zones and torus emissions.
e. Analysis of low-temperature electronics versus heaters for various instruments and spacecraft design.
f. Development of array detectors for remote sensing utilizing gamma rays, X-rays, and imaging the full infrared spectrum.
g. Development of efficient onboard data handling techniques such as data compression.
h. Development of techniques to measure heat flow on satellites.

5. *Studies of deep atmospheric probes (section VI.B.)*. The Galileo probe will reach pressures of 10, and possibly 15 or 20 bars. Current models suggest that this is below the base of the water cloud for both Jupiter and Saturn, but not for Uranus and Neptune. The problem is not only the high pressure, but also attenuation of radio signals and the passing of the orbiter, which serves as a relay to Earth, over the horizon of the probe. Further studies of deep probes should be pursued.

6. *Development of penetrators or other hard landers (section VI.B.)*. In recognition of the wide range of satellite science that could be addressed using penetrators, studies should be completed

to determine the feasibility of sending penetrators or other hard landers to outer planet satellites and to determine the kind of instruments that could be carried on penetrators.

7. *Development of radiation-hardened spacecraft (section IV.D.2.).* Operations in the Jovian magnetosphere are currently limited by radiation. Yet understanding the satellite Io and its environment is an important objective. Work on radiation-hardened components, subsystems, and detectors should be continued. Use of polar orbits of Jupiter to minimize radiation dosage should be studied.

8. *Development of low-thrust propulsion systems (section VI.C.).* It may not be too much to say that electric propulsion is the key to exploration and intensive study of the outer solar system, as well as comets and asteroids. Long trip times are always a concern when missions to these regions are considered; they can be drastically shortened, and payloads increased, by use of electric propulsion. Increased maneuverability is valuable for many reasons, such as permitting close encounters with small satellites, as well as asteroids and comets. In particular, nuclear electric propulsion systems (NEPS) deserve further development; however, the currently preferred propellant—mercury—requires engineering study to establish whether mercury is hazardous to instruments, and how much time may be needed from the termination of thrust to the initiation of instrument measurements. With regard to the possible application to a Saturn orbiter, an engineering study should compare NEPS with satellite or planetary gravity assists in terms of ease and precision of control, flexibility, and science return.