A Program for Exploration

Report of a Study by the
Space Science Board

NATIONAL ACADEMY OF SCIENCES

THE OUTER SOLAR SYSTEM

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PHYSICS OF THE OUTER SOLAR SYSTEM STUDY

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PREFACE

This is the report of a study convened by the Space Science Board in cooperation with the Lunar and Planetary Missions Board of the National Aeronautics and Space Administration to consider the exploration of the outer solar system in the period from 1972 to 1980. The report complements the Space Science Board's 1968 study, Planetary Exploration: 1968-1975.

The study was conducted during the week of June 8, 1969, under the cochairmanship of James A. Van Allen and Gordon J. F. MacDonald and involved twenty-three scientists, representing a broad range of scientific interests in outer solar system studies. The recommendations of the group were presented to NASA management on the afternoon of June 14 and endorsed by the Space Science Board at its meeting on June 21 and 22, 1969.

The Space Science Board is grateful to those who participated in this study, to Bruce N. Gregory of the Space Science Board staff, who ably served as Staff Director of the study, and to Mrs. Jacqueline Boraks, also of the staff, for her contributions to the report's publication. The Board acknowledges with appreciation the support of the National Aeronautics and Space Administration, which helped to make this study possible.

H. H. Hess, Chairman
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3. We recommend eight prime scientific objectives of the exploration of the outer solar system (page 8).

4. We recommend the continuation of the Pioneer capability for outer-solar-system studies and the development of a new spacecraft of flexible capability and increased payload capacity (page 14).

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6. We recommend immediate start on detailed design studies of possible probes for the atmospheres of the major planets (page 16).

7. We recommend development of a hybrid spinning spacecraft, design studies leading to a data system that can handle both cruise mode and encounter operation, and that special attention be devoted to design of a spacecraft that can survive and remain magnetically clean after passing through the Jovian environment (page 17).

8. We recommend that design studies be made of mass spectrometers for deep-entry probes and of several types of imaging systems (page 19).

9. We make several recommendations with regard to radio links, bistatic radar, and ground-based radar (page 20).

10. We make several recommendations with regard to ground-based studies and earth-orbital observations (page 22).

11. We recommend that NASA proceed with the development of advanced methods of propulsion useful for exploration of the solar system (page 24).

SUMMARY OF PRINCIPAL FINDINGS

1. Study of the outer solar system offers a rich field for the discovery of new phenomena, for the development of new concepts, and for definitive solution of long-recognized problems in physics, astronomy, and chemistry.

2. *In situ* observations by deep-space missions offer great advantages in directness, sensitivity, and resolution.

3. In many areas such as planetary magnetism, physics of the interplanetary medium, physics of nonthermal radio sources, and composition of deep planetary atmospheres, there is no known alternative to the techniques of direct observation near, or within, the object of investigation.

4. Considerable advances in our knowledge of the outer solar system can also be made by use of earth-based radio, radar, and optical telescopes, and of equipment flown on rockets, balloons, aircraft, and earth-orbiting satellites.

5. The successful conduct of flight missions during the next two decades to all the outer planets and, indeed, to heliocentric radial distances of the order of 100 astronomical units is well within the technological capabilities of the United States.

6. Chemical propulsion systems, such as the Titan IIID/Centaur/Burner II launch vehicles, and radioisotope thermal generators are adequate for a large variety of flyby, orbiting, and probe missions, as well as missions involving solar-captive orbits in planes at inclinations up to 90° to the ecliptic and trajectories that escape the solar system. Advanced propulsion schemes, ion propulsion, for example, may be important for certain specialized missions such as prolonged flight within the asteroid belt.

7. Exceptionally favorable astronomical opportunities occur in the late 1970's for multiplanet missions. Equally favorable opportunities will not recur for approximately 180 years, although there will be some multiplanet opportunities in the period 1989 to 1996.

8. Professional resources for full utilization of the outer-solar-system mission opportunities in the 1970's and 1980's are amply available within the scientific community,

and there is a widespread eagerness to participate in such missions.

9. A vigorous national program of exploration of the outer solar system can be mounted for a small fraction of the total cost of the program of the National Aeronautics and Space Administration.

Chapter I

INTRODUCTION

In the Summer of 1968 the Space Science Board convened a group to recommend a planetary exploration program for the years 1968-1975. The emphasis of the study was on the earth's near neighbors -- Venus, Mercury, and Mars. This emphasis resulted in part from technological considerations, since boosters were available in this time period that would permit substantial scientific exploration of the inner planets. In addition, the strong interest in possible life forms on Mars made the exploration of that planet a goal with high priority. The present report proposes a program for the exploration of the outer reaches of the solar system in the years 1974 to 1980. The stress on the giant planets and their surroundings does not imply that we do not support a continuing program in the study of the smaller planets. We believe, however, that there are compelling reasons for directing attention to the outer solar system. First, existing knowledge suggests that *in situ* study of the solar system may provide answers to some of the great scientific problems of our day. Second, an unusual configuration of the great planets in the late 1970's makes possible missions in which several planets can be visited on a single operation -- the "grand tour" concept discussed in the 1968 report. An equally favorable opportunity will not be available for 180 years, although subsidiary opportunities for multiple planet missions will recur in the period 1989-1996. Third, rapid developments in chemical booster technology and in particular the Titan IIID-Centaur combination make it possible to place, in the vicinity of the giant planets, scientifically meaningful payloads. Finally, with the approaching end of the Apollo program it is essential that the scientific community examine opportunities for the advancement of science making use of the technology of space developed during the past ten years. In proposing a program for the exploration of the outer solar system we recognize that the technological requirements of the many-year missions and the vast distances represent new and difficult challenges in many technological areas such as communication, reliability, and miniaturization.

This report examines the nature of the program for the exploration of the outer parts of the solar system. We present a substantive account of the major scientific objectives of flight missions to the outer planets, and we discuss the technical requirements in typical missions. We note that for certain missions, in particular those probing the planetary atmospheres, engineering studies have not been completed; therefore, final statements cannot be made at this time.

Chapter 2

MAJOR RECOMMENDATIONS

A NATIONAL PROGRAM

The 1965 study of the Space Science Board identified three goals for the nation's planetary program. The total planetary program should be designed to provide for progress in our understanding of: (1) the origin and evolution of the solar system, (2) the origin and evolution of life, and (3) the dynamic processes that shape man's terrestrial environment. We believe that these goals remain valid with regard to the study of the outer solar system, and that all three should be recognized in the development of the program for the study of the outer solar system. The major emphasis of the program should be the study of the planets and their near environments. However, spacecraft will spend many years in interplanetary space en route to the planets, and there will be the opportunity for the observation of particles and fields of the interplanetary medium during these times. We wish to emphasize that a study of the interplanetary medium contributes both to an understanding of the origin and evolution of the solar system and to the processes that shape the space environment near the earth. Furthermore, flyby missions offer the possibility of out-of-the-ecliptic and even interstellar trajectories, and such flights will greatly enhance the understanding of how our solar system interacts with the rest of the galaxy. The program for investigation of the outer parts of the solar system should not, in our view, be concentrated on a single goal or a single mission. Rather there should be an emphasis on those experiments and missions that contribute to the understanding of the solar system, the origin of life, and terrestrial processes.

The rare opportunities for planetary voyages, the length of these voyages, their cost, and the long times required for preparing spacecraft and experiments all imply that planning for exploration of the outer solar system must take place years in advance of the actual missions. It is imperative that a decision be arrived at determining the character and scope of the program for the exploration of the solar system.

We recommend that NASA in its 1971 congressional budgetary presentation bring to the Congress a long-term plan for the exploration of the outer parts of the solar system. In addition, NASA should ask Congress for initial funding for a major Jupiter mission, to be discussed in greater detail below, with a target date of 1974.

LEVEL OF SUPPORT FOR PLANETARY EXPLORATION

The Space Science Board 1968 study repeated the recommendation of the 1965 study that an increasing fraction of the space programs be devoted to planetary exploration. It is our judgment that the current funding for planetary exploration is totally inadequate to take advantage of the opportunities available to us. Technology to place scientifically meaningful payloads near or on the planets is at hand, and the technology required for the long lifetimes and communication can be developed. The configuration of the planets in the 1970's presents a unique opportunity for studying several planets on a single mission, thus substantially reducing the cost of exploration of this part of the solar system. We believe that we must take advantage of this situation. Therefore, we fully endorse the statements with regard to funding of the previous studies and recommend that a substantially increased fraction of the total NASA budget be devoted to planetary exploration.

SCIENTIFIC OBJECTIVES IN THE EXPLORATION OF THE OUTER SOLAR SYSTEM

In this section we present our views on the prime scientific objectives in the exploration of the outer part of the solar system. These objectives should guide the choice of missions and experiments. In presenting the scientific objectives we recognize that missions to the outer planets provide major values other than scientific. The requirements of the missions on technology will undoubtedly stimulate advances with far-reaching consequences. We are not competent to discuss in detail either the technological consequences of voyages to the distant planets or the problems of national prestige but do note that it is important to take these considerations into account in any over-all decision.

We recommend that the prime scientific objectives of the exploration of the outer solar system be:

1. to conduct exploratory investigations of the appearance, size, mass, magnetic properties, and dynamics of each of the outer planets and their major satellites;
2. to determine the chemical and isotopic composition of the atmospheres of the outer planets;
3. to determine whether biologically important organic substances exist in these atmospheres and to characterize the lower atmospheric environments in terms of biologically significant parameters;
4. to describe the motions of the atmospheres of the major planets and to characterize their temperature-density-composition structure;
5. to make a detailed study for each of the outer planets of the external magnetic field and respective particle population, associated radio emissions, and magnetospheric particle-wave interactions;
6. to determine the mode of interaction of the solar wind with the outer planets including the interaction of the satellites with the planets' magnetospheres;
7. to investigate the properties of the solar wind and the interplanetary magnetic field at great distances from the sun at both low and high solar latitudes, and to search for the outer boundary of the solar-wind flow;
8. to attempt to obtain the composition, energy spectra, and fluxes of cosmic rays in interstellar space, free of the modulating effects of the solar wind.

Chemical and Isotopic Composition

A major problem facing all theories of the origin of the solar system is the determination of chemical composition of the material out of which the sun and the planets formed. Today the evidence is derived from spectroscopic observations of the composition of the sun, from observations of the rocks on the surface of the earth, and from the determination of the composition of meteorites. The compositions do not agree. Further, it is known that the inner planets have lost their lighter elements during their formation and subsequent evolution. Presently available evidence suggests that Jupiter and perhaps Saturn may have retained all elements in the same relative abundance and be much more like the primitive solar system in composition. It would appear that Uranus and Neptune differ since they are deficient in hydrogen with respect to the sun and may be deficient in helium as well. In order to identify the variations in chemical abundance, which must obviously be intimately related to the processes involved in the origin and evolution of the solar system, it is essential to have more quantitative data on the abundances of the elements of those planets that dominate by mass the planetary system.

It is important to emphasize that the ratio of hydrogen to helium in Jupiter and possibly Saturn has significance that goes beyond the problems associated with understanding the origin of the solar system. Rival theories for the origin of the universe have suggested that different amounts of helium will be produced. In the "big bang" model, hydrogen and helium are produced almost immediately as part of the initial expansion, whereas in other cosmologies, the helium is produced by later nuclear synthesis. There is some question about whether the amount of helium observed in the sun is accurate. The values currently quoted have a large uncertainty but appear to be distinctly higher than the values obtained from the observations of old stars, a result that would be unacceptable to the big bang cosmology. Thus the determination of the hydrogen and helium concentration within the atmosphere of Jupiter would be of great significance to cosmology.

Abundance ratios of isotopes are of great value for an understanding of the problem of element formation, a key question in cosmology. The carbon-12 to carbon-13 ratio is one of great interest; but other isotopic ratios less subject to change by neutron capture would be even more revealing in view of the probability that solar surface electromagnetic effects may have modified materials exterior to the sun during the early stages of solar system development.

In view of these considerations, we identify as a prime objective for missions to the outer planets the determination of the relative abundance and isotopic ratios of hydrogen, helium, carbon, and heavy elements up to mass 40 in the atmospheres of all the outer planets.

Origin and Evolution of Life

It is commonly assumed that conditions on the primitive earth were very different from those presently obtained. There is some disagreement over the details, but it is generally supposed that during this early period the terrestrial atmosphere was highly reducing, consisting primarily of methane and ammonia. Chemical reactions in this atmosphere were stimulated by solar ultraviolet radiation, electrical discharges, and local sources of planetary thermal energy. The initial result of these reactions is assumed to be complex organic molecules such as amino acids that are necessary precursors to life itself. Under conditions that developed on earth, the progression of complexity continued to the level of formation of limited living organisms and ultimately the wide diffusion of life we now observe.

It is already known that conditions in the atmosphere of Jupiter are very similar to this hypothetical model for the primitive earth. A logical first step in the investigation of the outer planets from the biological point of view would be further investigation of the atmospheres to determine how favorable conditions are for the abiogenic formation of organic compounds. Are there warm regions in the lower atmospheres? Are electrical discharges present? What solvents are available? What chemical reactions are occurring in the upper atmosphere?

The next step in sophistication is a search for the complex organic substances themselves. It has already been suggested that some of the coloring matter observed in the Jovian atmosphere could be organic polymers dissolved in the cloud material. Laboratory experiments using mixtures of methane and ammonia, subjected to electrical discharges, have produced colored substances, thereby lending support to this interpretation. An unequivocal identification has not yet been achieved. To finally resolve these ambiguities it is essential to probe the atmosphere of these planets and make *in situ* measurements. A prime objective of outer planetary exploration is, therefore, the characterization of lower atmospheric environments in terms of biologically significant parameters and a search for and an identification of organic substances of importance to life.

Atmospheric Circulation

We would like to understand the terrestrial atmosphere much better than we do. The usual way of acquiring an understanding of a physical system is to do experiments on it. We cannot do large-scale experiment on the earth's atmosphere. If it were unique, we would be stuck. But fortunately, there are other planets around, in fact at least three others that are reasonably accessible, so we have at least four examples of atmospheres to work with. While we still cannot do experiments, we can do the next best thing, which is to observe several atmospheres of different scale, structure, and composition, and thus acquire a deeper understanding of atmospheres in general, and ours in particular.

Studies of motions in the atmosphere of Jupiter have recently begun to achieve a quantitative status and are leading to new ideas about the behavior of rapidly rotating atmospheres and the interaction of clouds and planetary motions. Recent developments in the study of the atmosphere of Venus have led to a new understanding of the circulation originally proposed many years ago by Hadley for the earth; current work on the diurnal circulations on Mars is leading to a fresh appreciation of diurnal effects in terrestrial boundary layers. We may anticipate benefits of a similar nature to meteorology and to other branches of atmospheric physics from the studies of the atmosphere of Jupiter and the other outer planets. An objective of the exploration program should be the study of the dynamics of the atmospheres of the major planets.

Magnetic Fields and the Radiation Belts of the Giant Planets

The earth's magnetic field is due to motions in an electrically conducting core. The energy source driving the motions is unknown. They may be due to internal thermal sources or to the external torques due to the moon. The moon, Venus, and Mars do not possess a magnetic field of internal origin. It is not clear whether the absence of a magnetic field on Venus is due to the lack of rotation or lack of a satellite, while the absence of electrically conducting materials in the interior of the moon and Mars is generally thought to explain the lack of a magnetic field on these bodies. Jupiter has a very strong magnetic field as is evidenced by radio emissions from high-energy particles trapped by the field. The source of the field on Jupiter is not known; it could be in the deep interior or in an electrically conducting outer shell.

Jupiter is the only planet, other than the earth, known to have belts of electrically charged particles temporarily trapped by the external magnetic field of the planet. Radiation belts were discovered by in situ observations with a Geiger-Müller tube flown on the first American satellite, Explorer I. Those of Jupiter were identified shortly thereafter by the analysis of the nonthermal decimetric radio noise of that planet. The moon, Venus, and Mars do not have radiation belts. It is not known whether the other major planets have magnetic fields or trapped radiation since nonthermal radio emissions from these planets have not been observed. Detailed observation of the magnetic fields and radiation belts at the planets will provide information vital to the understanding of these planetary phenomena. Because of this, a prime objective of the exploration of the outer solar system should be a detailed study of the external magnetic field and charged-particle populations in the vicinity of the major planets. This information will be most valuable if concomitant observations of the nonthermal radio emissions originating through cooperative phenomena are made in situ.

Interaction of the Solar Wind with the Outer Planets and of Their Satellites with Their Magnetospheres

Three examples of flow of magnetized solar plasma past a dense body in the solar system have been studied. In the case of the earth, the external magnetic field dominates the situation and the solar wind is held off at a great distance from the earth by its magnetic field. In the case of the moon, which has no intrinsic field, no ionosphere, and a very low conductivity, the solar wind flows unimpeded into the surface leaving a nearly empty cavity behind the moon. In the case of Venus, which has little if any magnetic field but does have a highly conducting ionosphere, the magnetic field of the solar wind cannot quickly penetrate the ionosphere and the solar wind does not flow unimpeded into the atmosphere. The solar wind flows around Venus, and there is evidence for a wake on the downstream side of that planet.

It is of great interest to learn whether the solar-wind flow past other planets and their satellites can be classified as one of those three types or whether there are new and surprising modes of interaction. Observations of the solar-wind interaction will not only lead to a better understanding of the earth's near-space environment, but they will also shed further light on the behavior of collisionless plasmas, a subject that lies at the heart of many problems in astrophysics.

The Nature of the Solar Wind and Magnetic Fields at Great Distances

The solar wind cannot continue to flow outward from the sun to indefinite distances. Somewhere it must merge into the interstellar gas and the galactic magnetic field. This transition zone joining the solar system with the rest of the galaxy is of great interest. The zone should not be regular in its plasma properties and magnetic fields, and there may be substantial fluxes of energetic particles covering a great range of energies.

In the direction parallel to the sun's pole of rotation (out of the ecliptic) the magnetic field may be more nearly radial, and perhaps interstellar particles of a variety of energies more closely approach the sun than in the plane of the ecliptic. The interaction of the solar wind and the sun's magnetic field with the interstellar particles and fields along this direction will be of great interest. The study of these interactions can lead to major advances in the understanding of plasma physics.

Further advances in the understanding of plasma physics can be expected from clarification of the role played by large-scale coherence in natural radio emissions from the planets.

Galactic and Solar Cosmic Rays

Knowledge of the composition and energy spectrum of galactic cosmic rays is of considerable importance in the understanding of a wide range of cosmological phenomena, including the origin of the elements. The understanding of galactic cosmic rays will be very much enhanced by observation in a location unaffected by the solar magnetic fields and free of energetic solar particles that are so abundant at 1 AU in the plane of the ecliptic. These kinds of observations are needed if we are to untangle the effects of local magnetic fields on the properties of the cosmic rays.

MISSIONS FOR THE EXPLORATION OF THE OUTER SOLAR SYSTEM

Pioneer F/G scheduled to fly in 1972 and 1973 will provide the first information on conditions existing in the interplanetary media out to the distance of Jupiter. We recommend that spacecraft of this class and capability be maintained and utilized as appropriate for further missions.

Further exploration of the outer solar system will require larger scientific payloads and much more sophisticated instrumentation. We therefore recommend that a new spacecraft of flexible capability and gross weight of ~ 1500 lb be developed and used as the principal working vehicle of the outer solar system program for the next decade.

We recommend the following missions in order of scientific significance:

1. Jupiter deep entry probe and flyby. The target date for this mission would be 1974 or 1975. Purpose of the mission would be to introduce into the atmosphere of Jupiter a probe capable of sounding to an atmospheric pressure of 10 to 100 bars. After depositing the probe, the remaining spacecraft would be swung by Jupiter's gravitational field out of the ecliptic on such a path that it would pass over a high-latitude region of the sun and have a perihelion of ~ 2.5 astronomical units. The entry probe would carry a mass spectrometer to sample the composition of the atmosphere as well as instruments to determine temperature, density, pressure, and physical and chemical properties of the clouds. The instrumentation remaining on the spacecraft would be designed to measure fields and particles over a wide energy range and to detect decametric radio emissions.
2. Jupiter orbiter mission would be designed to place a spacecraft in an orbit having a high inclination (greater than 60°), a perigee of 3 Jupiter radii, and an apogee of about 100 Jupiter radii. The spacecraft would carry instruments to measure the particles, fields, and radio emissions in the near-Jupiter environment and to observe, both visually and in the infrared, motions in the atmosphere of Jupiter. Detailed tracking of the orbit would provide information regarding the high harmonics in Jupiter's gravitational field. The existence of harmonics other than even zonal harmonics would establish either the presence of rigid solid material or of vigorous dynamic processes capable of maintaining large-scale density inhomogeneities. We further recommend that this mission carry a deep-entry probe, similar to that used in mission 1, if the capability is available.
3. Earth-Jupiter-Saturn-Pluto missions are proposed to take advantage of the opportunity to visit three of the outer planets with a launch scheduled in 1977. Particles and fields in interplanetary space, and in the near vicinity of the planets, would be examined. Thermal and visual imaging equipment would be used to study the surface characteristics of the planets and the nature of Saturn's rings. If possible, a radio occultation beacon would be dropped off at Saturn. In this mission, as in other multiplanetary missions, full use

should be made of the radio occultation to determine the characteristics of the upper atmosphere of the planets.

The feasibility of small unshielded entry probes should be considered for upper-atmosphere research on all multiple-planet missions, provided they do not endanger the primary mission objective. These missions provide an early opportunity for rapid escape from the solar system and for a variety of important particles and fields observations at the outer fringes of the solar system and beyond.

4. Earth-Jupiter-Uranus-Neptune missions. Two launches are proposed in 1979 to take advantage of this multiplanet opportunity. The instrumentation carried aboard the spacecraft would be similar to that for the Earth-Jupiter-Saturn-Pluto missions. An investigation of Neptune with an unshielded probe is particularly important on this mission.

5. Earth-Jupiter-Uranus mission scheduled for the early 1980's would be designed to deposit an entry probe at Uranus.

In selecting missions we have been guided by the fact that in almost every observable respect the giant planets appear to fall into two fundamentally different classes which we may refer to as Jovian (Jupiter and Saturn) and Uranian (Uranus and Neptune). A knowledge of the composition and structure of both classes is necessary as a preliminary to the formulation of a satisfactory theory of the origin of the solar system.

Missions Requiring Further Study

The smaller bodies of the outer solar system may contain information vital to the understanding of the history and origin of the solar system. In particular, detailed in situ observations of the asteroids may be valuable in tying together the vast array of information that has been secured by observations on meteorites. A soft landing on an asteroid would take the form of a rather simple docking. We do not believe that this kind of mission has been sufficiently studied so that a definite recommendation for it can be made at this time. Similarly, the analysis of cometary material may be extremely valuable in that comets may indeed contain elements not associated with the solar system. The determination of the chemical composition of the comet could be of great cosmological importance. However, we do not believe that there has been sufficient analysis of a cometary mission, in particular with regard to the kind of payloads that would be required to perform a satisfactory chemical analysis of the varying materials making up a comet.

We therefore recommend a detailed analysis of a mission designed to analyze chemically an asteroid or asteroids and a mission designed to determine the physical and chemical properties of a comet.

MAJOR ENGINEERING DEVELOPMENTS

As we have noted earlier, we believe that the propulsion available in the Titan IIID-Centaur combination is sufficient for the preliminary exploration of the outer planets. However, there are several major engineering developments which are essential for the effective exploration of the outer parts of the solar system.

Entry Probe

The determination of the composition of the atmospheres of Jupiter and Uranus, so valuable to the understanding of the solar system, will require entry probes capable of descending to depths equivalent to pressures of 10 to 100 atm. It will require great engineering ingenuity to design and build a lightweight probe capable of withstanding the extraordinary chemical conditions of the atmosphere, the mechanical stresses imposed by the high pressures, and at the same time able to carry out a variety of sophisticated scientific experiments and communicate the results to the mother spacecraft. We recommend an immediate start on detailed design studies of possible probes for the atmospheres of the major planets.

Hybrid Spacecraft

There has been considerable discussion regarding the relative merits of spacecraft which are spinning or are three-axis stabilized. It is recognized that there are advantages to either system both scientifically and technically. In order to conduct studies of energetic particles, plasmas, magnetic fields, and radio emissions in the interplanetary medium, planetary magnetosphere, and radiation belts, it is essential that the detector systems scan directionally. This is mandatory in order to determine uniquely the anisotropies and pitch-angle distributions of the particle and plasma fluxes. A spinning spacecraft offers distinct advantages over an attitude-stabilized one for both magnetic-field and radio-physics experiments. The intrinsic rotation of the spacecraft permits the accurate determination of two of the three components of the local magnetic field somewhat independent of the presence of the contaminating spacecraft magnetic field. Those radio-physics experiments utilizing directionally sensitive antenna systems can properly conduct their studies only by scanning directionally past sources (or targets close by) and thus determining the spatial properties of these objects. On the other hand, it is clear that for definitive measurements of the planetary atmospheres a stabilized platform is desirable and such a platform may facilitate communication with the earth.

The spacecraft would include both a spinning portion suitable for those experiments requiring such motion and a portion which could be despun and accurately pointed, perhaps only during planetary encounter. We recommend that NASA develop a hybrid spinning spacecraft, a portion of which could be despun; the total spacecraft would act as an optimum laboratory bench for the broad classes of experiments contemplated in the exploration of the outer solar system.

Telemetry Data Coverage

An important requirement of the scientific studies to be conducted during interplanetary cruise is effectively continuous data coverage. During the cruise mode, a relatively modest bit rate of 50 to 200 bits per second is sufficient. Continuous coverage can be achieved either by 24-hour ground-antenna coverage scheduled each day or by use of an on-board data storage system to provide for coverage of those time gaps during which ground antenna facilities are not available. The continuous coverage is required because significant transient events such as shock waves and discontinuities in the solar wind occur irregularly and cannot be anticipated. In addition, any space-time correlation between several space probes will require such continuous coverage because of the large time offsets for widely separated probes.

During planetary encounter, the data requirements will be quite distinct with the instruments collecting data at a high rate. It is therefore desirable to design an over-all data system that will provide for continuous coverage during the cruise mode and a higher rate of data storage and subsequent transmission during planetary encounter. We recommend that NASA undertake design studies leading to a data system that can handle the varying requirements for both cruise mode and encounter operation.

Magnetically Clean Spacecraft

The very weak magnetic field expected beyond 3 astronomical units may well prove to be among the most difficult of the parameters to determine with sufficient accuracy. In order to permit such measurements to be made on satellites and space probes, special nonmagnetic fabrication procedures and long sensor booms are required. The presently developed methods, applicable to satellites at distances less than 3 astronomical units may not be appropriate at larger distances. Indeed, the passage of a spacecraft through the expected very strong field of Jupiter may lead to the magnetization of the spacecraft which will contribute a large uncertainty to the data obtained subsequent to the encounter. We recommend that studies be carried out to design a spacecraft that will be magnetically clean even after passing through a strong planetary magnetic field.

Design of Instruments for the Encounter at Jupiter

The environment near Jupiter is very likely to be hostile to sensitive sensors. The high flux of energetic particles, the strong magnetic field, and the possibility of tenuous dust clouds make it essential that the spacecraft be designed to survive in this environment. This is particularly important for the Jupiter orbiter. The value of this mission depends on long-term survival of the spacecraft. We recommend that special attention be devoted to the design of an over-all system that can survive the Jovian environment.

INSTRUMENTATION

The instrumentation for determination of the particles and fields in interplanetary space and near the major planets is well in hand except for the over-all design considerations noted above. On the other hand, the study of the deep atmospheres of the large planets will require very substantial instrument development programs.

Mass Spectrometer

The only reliable way to measure the abundance of the chemical compounds in the atmosphere is by mass spectrometers with suitably chosen sensitivity and sampling inlets; therefore, a mass spectrometer is to be carried aboard the deep-entry probe. The high pressures and possible corrosive chemical atmosphere present unusual design problems. We recommend that NASA initiate design studies for suitable mass spectrometers.

Visual Imaging

The study of cloud motions which in turn will lead to critical information regarding the dynamics of the atmospheres of the major planets requires visual imaging over a broad range of horizontal scales. The visual imaging should begin at a distance at which the camera resolution is comparable with that achievable from earth and continue to a similar distance after closest approach. In addition, the imaging system should be adjustable to provide high resolution on selected features. Resolution of as little as a few kilometers at closest approach is needed for observations that will provide information on aerosol distribution and cloud stratification. The images should be acquired in stereo pairs in order to determine the relative heights and motions of clouds. We recommend the initiation of design studies of such imaging systems.

Thermal Imaging

In nonhomogeneous, convective atmospheres, upward mass motions transport heat from hotter to cooler regions. At a sufficiently high level, this heat is radiated to the outside, and it can be measured remotely by an infrared sensor. If the receiver is sufficiently sensitive, the surface of the planet can be scanned to provide a two-dimensional representation of the temperature prevailing at a depth in the atmosphere determined by its transmission in the wavelength range admitted to the sensor. The temperature field can then be correlated with the visual field to provide further information regarding motions within the atmosphere. We recommend design studies of thermal imaging systems covering the infrared wavelengths likely to be observed in the atmospheres of the major planets.

RADIO LINKS, BISTATIC RADAR, AND GROUND-BASED RADAR

Radio links between deep space probes and the earth have potential for a wide array of scientific experiments. These

include possibilities based on measurements on direct links, and over paths that include intermediate reflections from a planet or satellite (bistatic radar). With improved and new ground-based radars, it should be possible to obtain echoes from the Galilean satellites of Jupiter (and possibly from Jupiter, Saturn, Titan, and the rings of Saturn) for experiments that are independent of any spacecraft. In various sections of this report, the scientific possibilities are outlined in terms of studies of: planetary and satellite atmospheres; solar, interplanetary, and planetary plasmas and magnetic fields; planetary radii, masses, and detailed gravity fields; spin rates, radii, and masses of the larger satellites and Pluto; surfaces and topography of the satellites and Pluto; deep atmospheres and possible surfaces of the Jovian planets; satellite and planetary orbits; ring thickness and sizes, reflectivity, velocity distribution, and number density of the particles in the rings of Saturn; the mass of the asteroid belt and possibly the mass, rotations, and reflectivity of a few large asteroids; and several fundamental relativistic effects.

Dramatic increases in knowledge of our planetary system have come in recent years from radar and radio-propagation experiments. For ground-based radar, further advances and increases in range to Jupiter and Saturn depend on the development of improved and new facilities. Past radio-link and bistatic radar experiments have largely been conducted using the radio system provided for communications and tracking. The experiments were in effect afterthoughts, and while important results were obtained, very great improvements are possible for the future.

A unified view is needed of the potentialities of the various radio and radar experiments, and the interaction of these experiments with communications and tracking facilities, both on the spacecraft and on the earth. Radio links can be improved for communications in a way that could also greatly increase scientific capabilities. The data needed to improve tracking accuracy for mission-support purposes are the same data that would provide scientific information on space plasmas. The wave polarization generally used for communications makes certain experiments impossible, although the communications could be done just as well with a polarization that would provide scientific information. The large spacecraft antenna needed for communications could be used to provide maximum sensitivity for scientific experiments. The transmitting portion of a very powerful ground-based radar system would provide maximum capability for bistatic radar and radio-link experiments which could make measurements to the limits of the solar system, and even beyond.

In order to maximize the scientific return from radio-link and radar studies of the planets:

1. We strongly support the 1968 recommendation number 2 of the NAS-NRC Space Science Board Panel on Planetary Astronomy,* leading to the upgrading of existing radar/radio astronomy facilities and the construction of a major new facility with capability for planetary radar astronomy.

2. We recommend that spacecraft radio systems be designed to accomplish both mission-support (communications and tracking) and maximum scientific purposes. To this end, we recommend that for the missions to the outer planets, a Radio Science and Celestial Mechanics Scientific Team be selected at an early enough date to be able to affect the design of the spacecraft radio systems and the operational capabilities of the ground-based terminals of the Deep Space Net.

3. We recommend that principal investigators and instruments for radio-link and bistatic radar experiments, which may share the use of spacecraft antennas or radio system signals, be chosen sufficiently early that these principal investigators can participate with the radio team in helping to determine spacecraft and ground-based radio-system capabilities.

GROUND-BASED OBSERVATIONS

As has been emphasized in earlier reports, the optimum utilization of probes to the planets will require many supporting observations from ground-based, balloon-borne, aircraft, and earth-orbital observatories. The observations from the near-earth environment of the major planets pose special problems, some of which are noted below.

Southern Hemisphere Telescope

During the next four decades Uranus and Neptune will be at southern declinations, and during the 1980's Saturn will also be in the southern sky. We therefore recommend the construction of a fully instrumented high-optical-quality telescope of the 100-in. class in the southern hemisphere for planetary observations. This telescope together with the three large optical telescopes that NASA has already developed for planetary studies will provide continuing coverage of the major planets during the *in situ* exploration.

Fourier Spectrometers

The study of the atmospheres of the planets will require a determination of the line profile of the compounds existing in the atmosphere. Information gained from such studies will be of great aid in correlating and enhancing the data secured by a spacecraft. We recommend that NASA support further development of Fourier spectrometers and the construction of a large light-gathering aperture in the 15-m class for very-high-resolution spectroscopy of the planets.

Laboratory Programs

A great deal of new laboratory data will be required in order to analyze high-resolution infrared spectra of the outer planets. This is particularly true of the near infrared combination bands of CH_4 and NH_3 for which line strengths, pressure-broadening coefficients, and J identifications are (with very few exceptions) unavailable. We therefore recommend that NASA support a comprehensive laboratory program to measure the properties of the bands of CH_4, NH_3, H_2, and other relevant molecules and a complementary theoretical program to calculate the structure of these bands.

Our understanding of the interiors of the major planets is limited by a lack of knowledge of the equations of state of matter at high pressures and the various transport coefficients. Present-day technology of high pressures has progressed sufficiently to promise important results. We, therefore, recommend that NASA support theoretical and experimental studies of the equations of state of hydrogen and of the hydrogen-helium system.

Use of a Large Radio Antenna Array

Apparently the only ground-based possibility for directly studying the deep atmosphere of the major planets is by means of radio and radar observations at wavelengths between 10 and 100 cm. A large antenna array having a resolution of a few seconds

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*Planetary Astronomy: An Appraisal of Ground-Based Opportunities, NAS Publ. 1688, Nat. Acad. Sci., Washington, D. C. (1968), p. 71.

of arc could observe structural detail in the Jovian atmospheres at pressures greater than 1 atm. Of particular interest would be structures which could be correlated with visible surface features or with magnetic field structure as measured by the flyby spacecraft or orbiters. Although designed primarily for galactic and extragalactic observations, several large antenna arrays now being planned will be capable of making valuable planetary measurements. We recommend that the designs of large radio antenna arrays include provisions for real-time pencil-beam observations of the planets and that NASA support planetary programs that make use of such arrays.

Earth-Orbiting Observations

Ultraviolet spectroscopy from earth-orbiting telescopes can be expected to yield much valuable information on the atmospheres of major planets. The University of Wisconsin OAO-A2 experiment has already made a substantial number of planetary observations, and we encourage them to obtain more. The potential for doing planetary astronomy with OAO's and other earth-orbital telescopes now being planned is great. We urge that the design of these telescopes, which are primarily for stellar and galactic astronomy, be sufficiently flexible to facilitate planetary observations. We recommend the funding of planetary programs that will make use of the capabilities for high-resolution imagery and ultraviolet spectroscopy of the planets from earth-orbiting telescopes.

ADVANCED PROPULSION

As we have noted, chemical propulsion would appear adequate for the study of the outer reaches of the solar system during those times when Jupiter can provide a gravitational assist to spacecraft traveling beyond that planet. During the 1980's the configuration of the planets will not be so advantageous. During the 1980's it may be necessary to use low-thrust engines continuously in order to decrease trip times. We recommend that NASA proceed with the development of advanced methods of propulsion useful for exploration of the solar system.

Chapter 3

PLANETARY ATMOSPHERES

COMPOSITION

Existing knowledge suggests that the compositions of Jupiter and Saturn are essentially the same as that of the sun, although the evidence for this is difficult to obtain from abundances measured in chemically differentiated regions of the planet. It is, however, conceivable that significant results may be obtained from abundance ratios of elements that would not be expected to have been separated by either differential loss or concentration.

Presently available evidence also strongly suggests that Jupiter and probably Saturn have retained all the elements in the same relative abundances as the sun. This is in marked contrast to the inner planets, which have lost the lighter elements during their formation and/or subsequent evolution. Evidently some other fractionation process has been active in the outermost regions of the solar system as well, since Uranus and Neptune are deficient in hydrogen with respect to the cosmic average and may be deficient in helium as well.

In order to identify the causes of these abundance variations, which must obviously be intimately related to the processes involved in the origin and evolution of the solar system, it is essential to have more quantitative data on the abundances of the light and heavy elements in the atmospheres of these planets to complement models giving the bulk composition of their interiors.

It is important to realize that the ratio of hydrogen to helium in these bodies has a significance that goes beyond the problems associated with an understanding of the solar systems. Rival theories for the origin of the universe have suggested that different amounts of helium will be produced. In the "big-bang" model, the abundance of helium relative to hydrogen presently observed in the sun is produced almost immediately as part of the initial expansion, whereas in other cosmologies, the helium is produced by nuclear synthesis in stars. There is some question of whether the amount of helium observed in the sun is accurate. The values currently quoted have a large uncertainty but appear to be distinctly higher than values obtained from observations of old stars, a result that would be unacceptable to the big-bang cosmology. Thus verification is important, and a proper investigation of the Jupiter atmosphere would provide the necessary data.

The abundance of the noble gases, especially neon and argon, which have particular significance, cannot be determined by remote sensing at planetary temperatures. This does not mean that the possibilities for extracting new information from data obtained from ground, balloons, or earth satellites have been exhausted. Indeed, modern instrumentation can provide important new data related to the abundance problem. However, it is related in such an inextricable fashion to the physical state variables, that no hope exists for solving both the abundance and structure problems from such data. There is another aspect of the abundance problem of great importance for understanding the chronology of the solar system -- isotopic abundances, which are virtually unaffected by chemical reactions and are critical tests of astrophysical theories for element formation. A wealth of data related to the abundance of isotopic nuclei in the earth's crust and the meteorites is available, on the basis of which very precise determinations of the time of formation of the elements and of these bodies can be made. The nuclei used for this purpose are relatively heavy and rare and include strontium, rubidium, lead, and even fissionable species. For the sun, isotopic abundances can be estimated for only very few light nuclei, such as $^{13}C/^{12}C$ and $^{2}D/^{1}H$. They are, nevertheless, of great importance, because variations in isotopic ratios among various bodies of the solar system imply the operation, at certain times and places, of high-energy processes capable of producing nuclear reactions in large numbers. Any information on the abundances of these nuclides in the planetary atmospheres may therefore be of great value for an understanding of this activity.

On the basis of theories advanced to explain the observed abundance of certain nuclei in the earth, specific predictions have been made regarding isotopic abundances in other solar-system bodies. It has thus been predicted that the $^{2}D/^{1}H$ abundance ratio in Jupiter should be less than one hundredth that found in seawater. The verification of such a prediction for Jupiter would thus clarify our understanding of the composition of the earth.

Measurements are required of the abundances of the elements, up to argon, with an accuracy of 10 ppm. We also need to know the abundance ratio of isotopes with special interest, such as $^{2}H/^{1}H$, $^{3}He/^{4}He$, $^{36}A/^{40}A$, and $^{13}C/^{12}C$.

The lower atmosphere by definition is well mixed, but it does not follow that it has a uniform composition. The abundance of molecules which may undergo phase changes or are affected by solar radiation will vary with height in the atmosphere and location on the planet.

The only reliable procedure to obtain measurements related to abundances and physical variables is by means of a direct probe--carrying mass spectrometers with suitably chosen sensitivity and sampling inlets, and pressure-temperature transducers. Because of its very nature, a direct probe samples a very small column in the atmosphere. An accurate direct measurement of the abundances, particulate content, and physical variables, at a given location, however, would provide the basis to unravel data obtained from the ground, satellites, and flyby missions. All data obtained through remote sensing have to be interpreted in terms of a model representing the physical conditions in the atmosphere. The verification of a model through direct measurements will provide reliability to results obtained from models applied to other parts of the same atmosphere and even to other planets. It is for this reason that we recommend an early direct probing of the Jupiter atmosphere, for which we have the most extensive knowledge. The results gathered in such a probing will enable us to interpret observations obtained from flyby and orbiting missions, recommended for a later date, to planets other than Jupiter.

The physical structure of the atmospheres of the major planets is directly determined, not by the abundances of the atomic species but rather by the abundance of the molecular compounds they can form. Only H_2, NH_3, and CH_4 have been detected, but, undoubtedly, H_2O and H_2S are also present in large amounts at lower levels of the atmosphere. In addition, other more complex molecules are doubtless present in trace amounts, which are formed through photolytic processes induced by solar light. A manifestation of the presence of such complex molecules is probably the coloration observed in the cloud structures observed in Jupiter and Saturn, for which there is no concrete explanation available. Suggestions have been made that such colors arise by the presence of complex molecules in the ammonia or methane crystals forming the clouds. Their actual nature, however, has been the subject of widely ranging speculation. At one extreme, purely inorganic compounds have been suggested; but at the other, the existence of organic polymers formed through nonequilibrium processes in the basic mixture has been hypothesized on the basis of some laboratory experiments. A special significance has been attached to the possible formation of such complex organic molecules, because this formation is thought to be similar to the spontaneous abiogenic chemistry that took place in the early history of the earth and eventually lead to life.

It is commonly assumed that conditions on the primitive earth were very different from those we presently experience. There is some disagreement over the details, but one school of thought has maintained that during this early period the terrestrial atmosphere was highly reducing, consisting primarily of methane and ammonia. Chemical reactions in this atmosphere were stimulated by solar ultraviolet radiation, electrical discharges, and local sources of planetary thermal energy. The initial results of these reactions are assumed to be the complex organic molecules such as amino acids that are necessary precursers to the origin of life itself. Under the conditions that developed on earth, the progression of complexity continued to the level of the formation of primitive living organisms and ultimately the wide profusion of life we now observe.

It is already known that conditions in the atmosphere of Jupiter are very similar to this hypothetical model for the primitive earth. A logical first step in the investigation of the outer planets from a biological point of view would be further investigation of their atmospheres to determine how favorable conditions are for the abiogenic formation of organic compounds. Are there warm regions in the lower atmospheres? Are electrical discharges present? What solvents are available? What photochemical reactions are occurring in the upper atmosphere?

The next step in sophistication is a search for the complex organic substances themselves. It has already been suggested that some of the coloring matter observed in the Jovian cloud deck could be organic polymers dissolved in the cloud material. Laboratory experiments using mixtures of methane and ammonia subjected to electrical discharge have produced colored substances, thereby lending support to this interpretation. An unequivocal identification has not yet been achieved, however.

To resolve these ambiguities, it is essential to probe the atmosphere of these planets and make in situ measurements. A primary objective of outer planet exploration is, therefore, the characterization of lower atmospheric environments in terms of biologically significant parameters and a search for and identification of abiogenically produced organic substances.

Studies of upper atmospheres play an important role in a balanced program for exploration of planetary atmospheres. The upper atmosphere can be studied rather extensively from a flyby. Such observations have contributed significantly to our present understanding of Mars and Venus and would be expected to be equally important for the outer planets.

The atmospheric experiments which can be performed from a flyby with a suitable geometry are essentially of two basic kinds: radio occultation experiments and airglow observations. Radio occultation provides information on structure of the neutral atmosphere between pressures of 10^{-4} atm and 1 atm. It also provides information on the structure of the ionized component of the atmosphere, corresponding to neutral gas pressures of 10^{-8} atm down to essentially zero background pressure. Interpretation of the ionospheric measurements can elucidate the photochemical processes which modify atmospheric composition at high levels. Thus Mariner IV and Mariner V showed, surprisingly, that CO_2 is not appreciably dissociated by ultraviolet radiation. In the outer planets, methane is expected to be photochemically modified by absorption of ultraviolet radiation. Present knowledge suggests that the detailed chemical processes lead to formation of complicated hydrocarbons, an exciting prospect which may have significant biological overtones. Occultation measurements of the ionosphere may clarify these qualitative ideas. Ionospheric studies can also allow one to infer the temperature in the exosphere of the planet. It is this parameter which in large measure controls the rate of gas escape from the planet and has correspondingly great significance for studies of the time evolution of the atmosphere. We feel that it would be unwise simply to assume that the exospheric temperature is low on all the outer planets as a consequence of the large distance from the sun. For example, recent work suggests that the exospheric temperature of Neptune might be even higher than that of Mars. If so, significant hydrogen escape may be taking place, leading to enhancement in the H/He ratio on this planet. Upper-atmospheric measurements would clarify the role of escape in modifying composition of atmospheres.

The most important airglow experiment is perhaps to measure helium resonance radiation at $\lambda 584$, and we strongly endorse the flight of suitable instrumentation on Pioneers F and G. It should be recognized, however, that the probability that such measurements should provide an unambiguous determination of the H/He ratio in the planetary atmosphere as a whole is not high. Above some level, namely, the turbopause, atmospheric gases are expected to separate gravitationally. A measurement of helium in the separation regime cannot readily be extrapolated to infer the helium mixing ratio in the lower atmosphere unless the location of the turbopause is specified by an independent experiment. Although possible in principle, we view this as unlikely and conclude therefore that a definitive helium measurement would require sophisticated instrumentation on a deep atmospheric entry probe.

We recommend measurements of (1) neutral composition; (2) ion composition; (3) electron densities; (4) temperature profiles, for electrons, ions, and neutrals; and (5) airglow emissions. Recommendations (3) and (5) may be performed from flybys. Recommendation (5) should emphasize the search for possible auroral emissions. Recommendations (1), (2), and (4) require entry probes and could be satisfied by unshielded entry probes or by more versatile probes to lower levels in the atmosphere. We therefore recommend that consideration be given to the development of small and relatively simple unshielded entry probes capable of being carried on all outer-planet missions.

THERMAL STRUCTURE AND DYNAMICS

Studies of motions in the atmosphere of Jupiter have recently begun to achieve a quantitative status and are leading to new ideas about the behavior of rapidly rotating atmospheres and the interaction of cloud and planetary motions. While the atmosphere of Jupiter differs greatly from that of earth, the re-examination of fundamentals needed to embrace a different system should lead to ideas of importance to terrestrial meteorology. Recent developments on Venus have led to a new understanding of the circulation originally proposed by Hadley for the earth and current work on diurnal circulations on Mars is leading to a fresh appreciation of diurnal effects in terrestrial boundary layers. We may anticipate benefits of a similar nature to meteorology and to other branches of atmospheric physics from studies of the atmosphere of Jupiter and the other outer planets.

The interpretation in terms of basic hydrodynamical processes of the horizontal circulation patterns at the visible surfaces of the major planets could lead in due course to information about the interiors of these bodies (e.g., lower atmospheric depths, angular momentum transfer, energy sources) that may be obtainable in no other way. The acquisition of this information is probably as important as the discovery and elucidation of the hydrodynamical motions themselves, which in turn will deepen our understanding of the terrestrial atmosphere.

As these motions are thermally driven, by solar radiation and by internal heat sources, the determination of horizontal and vertical temperature gradients will be of cardinal dynamical importance. The required information will not be obtainable with ground-based observations and requires space missions to the planets.

The central theoretical difficulty in all dynamical studies of the motions of planetary atmsopheres is that of understanding the interaction between motions on different scales. Owing to the great distances of the outer planets, we have (a) no knowledge of the scales of motion on Neptune; (b) indications of planetary-scale banded structure which are vague in the case of Uranus, rather better for Saturn, and pronounced in the case of Jupiter; (c) evidence for strong equatorial jets on Saturn and Jupiter; and (d) a certain amount of information, going back a century or so, about large irregular markings on Jupiter. (Whether Pluto possesses an atmosphere has not yet been ascertained.) These deficiencies in our knowledge of the scales of motions present and of the details of certain conspicuous features (edges of the strong equatorial jets on Jupiter and Saturn, Jupiter's Great Red Spot) will be remedied if high-resolution visual pictures required can be acquired during the contemplated missions to the major planets.

Thermal Mapping and Vertical Temperature Structure

In nonhomogeneous convective atmospheres, such as those of Jupiter and Saturn, upward mass motions occur which transport heat from hotter to cooler regions. At a sufficiently high level, this heat is radiated to the outside, and it can be measured remotely by an infrared sensor. If the receiver is sufficiently sensitive, the surface of the planet can be scanned to provide a two-dimensional representation of the heat or temperature prevailing at a depth in the atmosphere determined by its transmission in the wavelength range admitted to the sensor. Infrared sensors available for deep-space missions are actually hopelessly insensitive for the pupose of obtaining thermal maps, comparable in scale and detail to a visual image. However, over restricted areas or regions and by means of improved detectors and taking advantage of the availability of the light at all thermal wavelengths, one should be able to study the temperature fields and their correlation with details visually observed.

Studies have been made of the thermal emission of Jupiter in the 10-μm atmospheric window. Certain results indicate that at times little or no temperature contrast exists between visual features, such as the Great Red Spot and its surroundings, while at other times the brightness-temperature variations can be pronounced. The Great Red Spot has appeared cooler on two widely separate occasions, once by ~2°. The shadows of satellites in the 8- to 14-μm range have been reported to be tens of degrees brighter than their surroundings; at other times no contrast is detectable.

The average emission in the total range of wavelengths appears to be higher than the absorbed solar energy, indicating the existence of an internal heat source. A similar conclusion has been reached for Saturn.

Near 5 μm, the thermal emission appears to be from lower and warmer levels than that for the 10-μm window. Preliminary, unpublished results indicate that most of the emission comes from tropical regions and that it has a complex structure.

The methane band near 7 μm shows anomalously high emission at the band center. This has been interpreted to suggest the existence of a temperature inversion above the level of the clouds. A similar explanation has been invoked to explain an apparent reversal of lines in the 1.25-cm NH_3 microwave band.

These remarks show that from ground-based observations little progress has been made in understanding the thermal structure of Jupiter, and there is even less progress on the other outer planets. On the theoretical side, a great step forward was made when the importance of pressure-induced hydrogen absorptions in the thermal emission spectrum was

recognized. On this basis, radiative-convective profiles have been computed for all the outer planets.

Recent reassessment of the heat balance on Jupiter has indicated a more complex state of affairs in which thermal radiation mainly influences boundary conditions: The distribution of heat through the lower atmosphere will be dominated by fluid motions on a variety of scales, from that of the general circulation down to small-scale convection.

Flybys and orbiters can be used, not only for thermal imaging, but for radio occultations and infrared and microwave thermal soundings. Radio occultations will give data down to ~1 atm, just above the cloud level. It is unlikely that they can yield vertical temperature gradients of sufficient accuracy for dynamical theories (the required accuracy depends on the closeness of the gradient to adiabatic: if it is close, very high accuracy -- better than $10^{-2}\Gamma$-- is needed). The horizontal resolution from occultation measurements is poor. Nevertheless, this type of measurement is so simple and reliable that it should be performed on all missions to the outer planets, and with the greatest precision possible.

Infrared emission spectra can be obtained from flybys and orbiters. The techniques of temperature sounding from ir emission spectra are now well tested for terrestrial conditions, although further investigation is needed to discover whether a suitable methane band exists (ammonia bands are not so suitable because the gas may not have a constant mixing ratio in the region of the atmosphere under consideration). If a successful technique can be developed, temperature soundings in the two or three scale heights immediately above the cloud tops may be possible with significant spatial resolution. It is important that attention be given to the development of this technique.

The microwave spectrum of ammonia can be used in a similar way to give thermal soundings between the 120 and 180 K temperature levels. This technique has yet to be fully investigated on earth, and it applies to a gas whose mixing ratio will vary in the vertical.

It is difficult to avoid the conclusion that the vertical thermal structure inside the clouds, to the required accuracy for dynamical investigations, can only be discovered from entry probes. This alone might not justify a probe mission, because only one geographical location can be investigated at a time. However, temperature measurements must also be made with accuracy in order to interpret the cloud layers which, in turn, interact thermodynamically with the motions. These measurements add justification to what appears to be the most important single mission concept for outer-planet atmospheric studies.

VISUAL IMAGING

Studying features of the visible surface of dense cloud over a broad range of horizontal scales requires photography of the planet beginning (in the case of a flyby) at a distance where the camera resolution is the same as that achievable from earth and continuing to a comparable distance after the instant of closest approach. In the case of Jupiter, for instance, with a miss distance of a few planetary radii, scales down to as little as a few kilometers would be resolved with a realizable camera system. During the 100 Jovian days occupied by the encounter, typical displacements of planetary-scale features in the equatorial zone relative to nonequatorial regions will be of under 100 deg of longitude (100,000 km); the corresponding relative displacements of features within the nonequatorial regions is about 1000 km.

Resolution of as little as a few kilometers (a fraction of the atmospheric scale height) at closest approach is needed for observations of the limb (including stellar occultations and optical aspects of the earth), which will lead to information on aerosol distribution and cloud stratification. Determinations of the relative heights and motions of clouds could be made stereoscopically and possibly by measuring the evolution of the lengths of shadows cast by some of the clouds.

The camera required must have high resolution, dynamic range, photometric accuracy, metric integrity, and be capable of rapid sequencing and fast movement from one target to another.

CLOUDS

Jupiter

The most striking visual feature of Saturn and Jupiter is their banded and ever-changing appearance: we are clearly observing atmospheric phenomena exclusively, and there is good reason to believe that, in the case of Jupiter, we are observing a vast turbulent cloud layer composed principally of ammonia crystals. Spectroscopic data on the gaseous NH_3 abundance above these clouds show that the amount of NH_3 present is what one would calculate from the vapor-pressure equation of solid NH_3 at the observed cloud-layer temperature, but no direct identification of the composition of the clouds can presently be made from earth-based observations.

The polarization data suggest that micron-sized cloud particles must be abundant in Jupiter's atmosphere but shed no light on the composition problem.

Jupiter's clouds do differ from pure solid NH_3 in respect to one readily observable property: color. Delicate shades of yellow, orange, brown, and even pink and very pale blue have been reported by numerous observers. It is often stated that these colors are due to small traces of intensely colored organic matter, produced by the action of solar ultraviolet light on the methane and ammonia in Jupiter's upper atmosphere.

Finally, there have been some purely theoretical studies of the cloud-condensation process in atmospheres of solar composition. These computations suggest strongly that Jupiter (and Saturn) may be shrouded by several distinct cloud layers of disparate composition. The topmost cloud layer is found to be solid NH_3, then a layer of NH_4HS (ammonium hydrosulfide) clouds containing dissolved NH_3, then NH_4Cl (ammonium chloride) clouds near the 475 K level. The atmospheric pressure near the lowest of these cloud layers is roughly 100 atm.

Whether this specific model is correct for Jupiter and Saturn cannot under any foreseeable circumstances be determined from earth-based observations alone. Given a Jupiter flyby mission (such as Pioneer F and G) or an advanced orbiter, it would be possible to derive certain additional data concerning the clouds. Measurement of the planetary phase function, which is an effect produced by the clouds, gives data useful for other purposes but contributes little to our understanding of the chemistry and physics of the clouds. Photography of the cloud structures near the terminator may help in understanding the scale of motions in the atmosphere near the cloud level. Such imagery could be conducted from either a flyby or an orbiter.

But even combining the data from flyby and orbiter missions with all the ground-based observations deemed possible through the 1980 period, it seems certain that our ignorance about conditions beneath the topmost clouds will still be great.

In order to investigate the structure and composition of the atmosphere and clouds below the very thin region accessible to outside observers, it is essential that an atmospheric entry probe be employed. It is necessary for cloud studies that a Jupiter entry probe capable of withstanding up to 100 atm pressure and instrumented with cloud-physics and cloud-chemistry experiments be developed for launch at the earliest possible opportunity.

One instrument of central importance for analysis of the atmosphere is a mass spectrometer. Since the principal cloud layers on both Jupiter and Saturn are believed to be due to condensation of trace gases from the atmosphere, it appears that mass spectrometric analysis of the atmosphere combined with temperature and cloud-density measurements would permit determination of the cloud composition. At present, it appears that a mass spectrometer of dynamic range 10^5:1 would be capable of effecting a very detailed elemental and isotopic analyses for the elements H, He, O, C, N, Ne, S, Ar, and Cl. It is of great interest to note that, in theoretical studies of the composition of Jupiter's deep atmosphere, these elements, which are the only ones expected to be present in meaningful amount (<1 ppm) above the 500 K level, all have atomic weights less than 40. Thus an exhaustive analysis of the atmsophere and clouds at all points above this level is possible with a mass spectrometer of limited mass range.

An essential complement of this analysis experiment is a direct measurement of the cloud optical density as a function of altitude. This is readily accomplished with a simple nephelometer. In addition, it should be possible to measure the the cloud particle size distribution.

Some essential knowledge of the depth of penetration of sunlight into the atmosphere may be obtained very simply from an omnidirectional solar radiometer. A method of detecting cloud layers and distinguishing hazy and clear regions independent of the nephelometer would be a downward-pointing thermal radiometer.

Finally, there remains the problem of the trace coloring matter in the clouds. The in situ detection and identification of such material by gas chromatography and mass spectrometry might be an extremely difficult and uncertain undertaking if polymeric organic matter is responsible. On the other hand, theoretical studies of the cloud-forming process imply that $(NH_4)_2S$ (ammonium sulfide) may be produced in substantial quantity. This material is a yellow-brown solid of high volatility, and analysis of its vapors would show only NH_4 and H_2S.

Saturn

Our present data on the structure and composition of Saturn show it to be similar to Jupiter in all important respects. Of the four giant planets, the most similar two are Jupiter and Saturn. Our knowledge of Saturn's clouds is severely limited by its smaller size and greater distance: the banded cloud structure is well established as is the presence of micron-sized particles. However, ammonia has not been detected with certainty in Saturn's atmosphere, and the clouds are essentially devoid of color. Occasional reference is made to a "pale-lemon tint" on the planet.

Theoretical models of the clouds and atmosphere of Saturn predict that its atmospheric structure should differ from Jupiter's only with respect to vertical scale. Thus the entire range of experiments detailed under the proposed Jupiter probe mission are directly applicable to Saturn. But herein lies a serious question of priorities: if funding is limited, can we then justify sending probes to the most similar pair of outer planets? A more appealing possibility appears to lie in sending the second such entry probe to Uranus or Neptune.

Uranus and Neptune

Is an entry probe mission to Uranus or Neptune justifiable in fact? From the point of view of atmsopheric and cloud composition and structure, the answer must be a firm "yes."

First, it is clear that, while Jupiter and Saturn do not deviate markedly from solar composition, Uranus and Neptune are strongly enriched in the heavier elements. This situation introduces the possibility of extremely complex multicomponent phase equilibria leading to fluid-fluid immiscibility in the deep interiors, with consequent drastic alteration of the atmospheric composition from the average for the whole planet.

Second, it appears that the uv-visible reflectivity of the disk of Uranus can be explained satisfactorily by a model in which only molecular scattering and absorption by hydrogen is considered: clouds may not be involved above approximately the 10-atm pressure level. Because of the formidable theoretical difficulties in constructing plausible physicochemical models of Uranus and Neptune and the near-complete lack of relevant high-pressure phase equilibrium data, it seems almost easier to probe the atmosphere than to attempt to predict its behavior.

Certain useful contributions to the study of the clouds of Uranus and Neptune may be made by flyby vehicles. Visible and ir imaging of both planets, including study of the horizontal and vertical cloud structure near the terminator, and optical polarization measurements are all experimentally feasible and of potential value in our attempts to understand their cloud and atmospheric structures.

It cannot be stressed sufficiently that earth-based observations of Uranus and Neptune are completely incapable of solving any of these problems.

In almost every observable respect, the giant planets appear to fall into two fundamentally different classes, which we may refer to as Jovian and Uranian. It must be asserted that a knowledge of the composition and structure of both classes is necessary as a preliminary to the formulation of a satisfactory theory of the origin of the solar system. Almost every piece of information essential to the solution of these problems must be derived from the results of entry probe missions. We therefore strongly recommend Jupiter and Uranus entry probe missions at the earliest possible date.

GROUND-BASED OBSERVATIONS

Optimum utilization of probes to the outer planets will require many supporting observations from ground-based, balloon-borne, aircraft, and earth-orbital observatories.

We endorse NASA's sponsorship of the construction of three large optical telescopes for planetary studies (the 107-in. at the McDonald Observatory in Texas, the 88-in. at the Mauna Kea Observatory in Hawaii, and the 61-in. at the Catalina Observatory in Arizona) in addition to several 24-in. planetary patrol telescopes. We urge NASA's continuing support of the construction of large optical telescopes for planetary observations. In particular, we recommend the construction of a high-optical-quality telescope of the 100-in. class in the southern hemisphere (possibly at Cerro Tololo). This telescope will greatly facilitate spectroscopy, photometry, and imagery of Uranus and Neptune during the next four decades when these faint planets will both be at southern declinations. During the 1980's, Saturn will also be in the southern sky.

One aspect of our knowledge of the major planets which could be substantially improved concerns the structure of their clouds. Different cloud models are characterized by different line profiles, and comparison of computed and measured profiles of weak, medium, and strong lines of CH_4 and NH_3 over a range of wavelengths should allow one to establish the gross features of the upper Jovian cloud structure. A resolution of at least 0.1 cm^{-1} will be required. Rotational temperatures and pressures determined from these measurements can be used to improve the initial model atmospheres and, consequently, the cloud models. The same is true of the relative abundances obtained from the measured equivalent widths and curves of growth computed for the cloud model.

The line profiles can be efficiently measured with a Michelson interferometer at the focus of a large light collecting area of 10- to 20-m diameter having a resolution of a few seconds of arc. We therefore recommend that NASA sponsor the construction of a large light-collecting aperture in the 15-m class for very-high-resolution Fourier spectroscopy of the planets. This large light collector should be located at a very dry site and as near to the equator as is practical. At the same time, we recommend that NASA support further development of Fourier spectrometers so that these invaluable instruments may become more generally available and simpler to use. The development of other specialized equipment, e.g., multislit spectrometers, also requires support.

New laboratory data will be required to analyze high-resolution infrared spectra of the outer planets. This is particularly true of the near-infrared combination bands of CH_4 and NH_3 for which line strengths, pressure-broadening coefficients, and J identifications are (with very few exceptions) unavailable. A laboratory investigation of the collision-narrowing phenomena in the H_2 quadrupole lines will also be required. We therefore recommend that a comprehensive laboratory program to measure the properties of the bands of CH_4, NH_3, H_2, and other plausible molecules in the atmospheres of the outer planets be vigorously pursued. At the same time, we recommend that the complementary theoretical calculations of the structure of these bands be pursued with equal vigor. These laboratory and theoretical studies are essential to the understanding of the atmospheres of the major planets.

An important parameter in any cloud model is the value of the continuum single scattering albedo. For a given cloud model, it can be determined from the measured brightness variation over the Jovian disk. Here measurements should be made in wavelength intervals specially selected to be free of absorption lines.

Another important parameter is the scattering phase function of the cloud particles. In principle, it can be deduced from the observed limb darkening if the cloud structure is uniform over the planetary disk. In the case of Jupiter, the cloud structure seems to vary considerably from the equator to the poles. However, measurements of the equatorial limb darkening should provide information on the phase function near the equator. High spatial resolution is important in such measurements since most of the variation occurs near the limb of the planets.

The 24-in. NASA planetary patrol telescopes, operating at f/75, should provide good material for analysis. Also, diffraction-limited photographs of Jupiter should soon be obtained with Stratoscope II, a 36-in. balloon-borne telescope. However, a precise determination of the scattering phase function of Jupiter's clouds will probably only come after analysis of the photometry of Jupiter planned for Pioneers F and G.

It seems certain that detailed models of the Jovian clouds will require a variation in the cloud structure with Jovian latitude. Photographs of Jupiter obtained with an interference filter centered on a relatively strong CH_4 band at 8850 A reveal that the methane absorption in this band is not uniform over the disk but occurs in "bands" at different latitudes. This nonuniform behavior can be surveyed with the aid of monochromatic images taken in other bands of CH_4 and NH_3. Particular attention should be given to identifying time variations. Further studies should be made to determine the variation of the equivalent width of weak spectral lines (or bands) with latitude. These weak bands are probably formed deeper in the clouds than the strong bands and should therefore reflect latitudinal variations of the deeper cloud levels.

Another aspect of our knowledge of the major planets which should be improved before advanced space probes are sent is their energy budget. Although the present evidence strongly suggests that Jupiter has a substantial source of internal energy, several related questions could be answered by further observations (from the ground and from aircraft) of the far-infrared radiation emitted by Jupiter.

First, does the total radiation of Jupiter vary with time? Monitoring the brightness temperature near 20 and 300 μm from the ground and from 10 to 100 μm from aircraft altitudes should settle this question.

Second, does the brightness temperature vary with latitude as suggested by some measurements at 20 μm? Measurements with the 36-in. infrared telescope being constructed for the NASA aircraft should enable us to obtain some spatial resolution for wavelengths up to 40 μm (where the diffraction limit is about 10 sec of arc). Higher spatial resolution is possible in the 20-μm window with large ground-based telescopes. The nearly completed 88-in. telescope on Mauna Kea seems particularly well suited for this measurement. The large light-collecting aperture recommended above would be very advantageous at 300 μm.

Third, how much east-west asymmetry, if any, is present in the emitted radiation? From the east-west asymmetry (or its upper limit), it should be possible to estimate the difference in effective temperature between the day and night sides of Jupiter. Here measurements from the ground at 20 μm will probably provide the best data.

Perhaps the single most important parameter in Jupiter's atmosphere is the H_2/He ratio. Since the absorption coefficient of the He-induced translational and rotational transitions in H_2 has a different wavelength dependence than the self-induced transitions, it should be possible to estimate the He/H_2 ratio by fitting the emission spectrum from 10 to 100 μm with model atmospheres. One drawback to the procedure is the probable variation of effective temperature over the surface. However, the theoretical resolution of a 36-in. telescope is ~25 sec of arc at 100 μm allowing some resolution on Jupiter even at the longer wavelengths.

In consideration of the above discussion, we recommend that the 36-in. NASA aircraft telescope be used extensively to measure the far-infrared emission spectrum of the major planets. We also recommend that the feasibility of operating the 36-in. at altitudes above 50,000 ft. be explored in order to reduce further the atmospheric attenuation in the 100-μm region.

Apparently the only possibility of directly studying the deep atmosphere of the major planets is by means of radio and radar observations at wavelengths between 10 and 100 cm. A large antenna array having a resolution of a few seconds of arc could observe structural detail in the lower (pressure >1 atm) Jovian atmosphere. Of particular interest would be structure, which could be correlated with visibile surface features or with magnetic field structure as measured by the early flyby spacecraft.

Although primarily designed for galactic and extragalactic observations, the large antenna arrays now being planned will be capable of making such planetary measurements. We therefore recommend that the designs of the large radio antenna arrays now being planned include provisions for real-time pencil-beam observations of the planets.

A number of important ground-based radar observations of the outer planets and their satellites will become possible with present radar systems or systems now being planned. It now seems most likely that the radar detection of some or all of the Galilean satellites of Jupiter will be within the capability of several radar systems now in existence when they are improved as planned between now and 1975.

Jupiter occultations of these satellites occur frequently, and in each case the detailed manner of decay or rise of the radio signal can be studied in much the same way as during spacecraft occultation. From this, deductions can be made concerning the density and structure of the ionosphere of Jupiter, as well as the structure of the upper atmosphere and some indication of its chemical composition. This radar information becomes clearer and less ambiguous when results at more than one frequency are available, because of the different frequency dependence of the effects of the ionized and neutral atmospheres. A resolution of better than one scale height is expected for Jupiter.

Although attempts at detection have been made by the major U. S. planetary radar systems, there is no clear evidence that any radar signal from Jupiter has yet been detected. The difficulty of estimating the signal strength to be expected is great, since it is not known whether any surface of discontinuity exists at any level in the atmosphere that the radio waves can reach. Two types of detectable signal might be searched for. First, there is the possibility that a surface representing a phase change or composition change does exist at an accessible level in the atmosphere. This may be an actual liquid or solid surface, or it may represent a well-defined level at which a constituent of the atmosphere changes its phase or concentration. A sharp boundary of clouds would come into this category. For these cases the reflection would occur because of a change in the dielectric constant, and the surface would be required to be normal to the radio beam to be detected. Long wavelengths would be preferable for this type of signal, both because they are expected to suffer less attenuation and scattering before reaching the level in question and because the surface of discontinuity does not need to be so sharp or smooth to give the specular type of return.

The second type of radar echo that may be expected from Jupiter arises from incoherent scatter by cloud particles. Since these particles are almost certain to be small compared with any of the radar wavelengths used, the returned signal strength will depend on λ^{-4}. Thus the high-frequency radar systems would seem to be advantageous although the level at which large droplets or cloud particles exist may be low and atmospheric attenuation will disfavor the high frequencies.

Either type of radar echo detection from Jupiter would give new information concerning the atmosphere: the level of a surface of discontinuity, the amount of change in the value of the dielectric constant, the attenuation above this discontinuity, and the dependence of the attenuation on frequency all would be valuable for creating a model of the atmosphere. In the case of the detection of incoherent scatter from clouds, their height and particle size as well as windspeeds and overlying atmospheric attenuation can be deduced from two-frequency radar observations.

The problems of radar observations of Saturn are similar to those of Jupiter, and the greater distance will require a much higher level of radar performance. The rings of Saturn, if composed of large particles, may, however, be good radar targets, as may the satellites, especially Titan. We expect that the development of radar systems in the next ten years will have the required capability.

Ground-based radar beyond Saturn requires performance levels beyond those that can be discussed realistically at present.

The above discussion on radar studies of the deep atmospheres of Jupiter and Saturn is also applicable to the potentialities of bistatic radar, where the same transmitting system is used on the earth but reception is at the spacecraft. This would provide an increase of sensitivity by several to many orders of magnitude, making it possible to study these atmospheres in more detail and to search for deep atmospheric characteristics of the more distant Uranian planets. Bistatic radar would also be an important method of studying the surfaces of the major satellites of the giant planets and the particles in the rings of Saturn.

In consideration of the above discussion, we recommend that NASA support radar astronomy to the extent necessary to obtain direct measurements of the Jovian atmosphere and with the plan that the same ground-based facilities would be used with spacecraft for bistatic radar investigations.

The rapid rotation of Jupiter plus a substantial magnetic field produce a complex magnetohydrodynamic situation. Some insight into this problem may come from systematic high-resolution imagery of the planet. Such synoptic data are expected from the NASA planetary patrol telescopes. Extraction of quantitative results from these patrol data should be facilitated by the use of image-processing computer programs in searching for significant temporal and spatial correlations.

Since Uranus has an angular diameter of near 4 sec of arc, some spatial resolution should be possible on photographs taken at times of good seeing. The relatively long exposure times on Uranus (compared with Jupiter) makes it much more difficult to catch intervals of superb seeing. Integrating television systems are now becoming available which are about a factor of 10 faster than film after correction for their lower resolving power. Utilizing the reduced exposure time possible in these systems on the NASA planetary patrol telescopes increases the probability of obtaining high-resolution photographs of Uranus. Image-processing techniques could be used to average the best photographs. Also, Stratoscope II is expected to obtain photographs of Uranus with a resolution of 0.1 sec of arc.

Diffraction-limited imagery of the major planets with extended time sequences will be possible from the intermediate size ($\approx$1-m diameter), all-reflecting orbital telescopes planned for the mid-1970's.

Ultraviolet spectroscopy from earth-orbiting telescopes can be expected to yield much valuable information on the atmospheres of the major planets. The University of Wisconsin OAO-A2 has already made a substantial number of planetary observations. The potential for doing planetary astronomy with OAO's and other earth-orbiting telescopes now being planned is large. We urge that the designs of these telescopes, which are primarily for stellar and galactic astronomy, be sufficiently flexible to facilitate planetary observations. Special care should be taken to ensure that imagery and spectroscopy experiments which can be done from earth orbit are not included in planetary probes. We therefore recommend that the capabilities for high-resolution imagery and ultraviolet spectroscopy of the planets from earth-orbiting telescopes be fully exploited, and we urge that these telescopes be designed to facilitate such observations.

Chapter 4

PARTICLES, FIELDS, AND RADIO PHYSICS

The study of fields and particles has provided direction and stimulus to a large fraction of the scientific effort in the U.S. space program since its inception. It has been demonstrated that interplanetary space involves phenomena that are of basic importance to our understanding of solar-planetary relations, of a wide variety of astrophysical problems, and of the sun itself. Missions to the outer planets will inevitably require that extensive observations be made of particles and fields within and in the vicinity of the magnetospheres of these planets. Furthermore, in any such missions, many years will be spent in interplanetary space en route to the planets; hence to guarantee some scientific results and to maintain a balanced program, observation of particles and fields in the outer solar system should be included in all such missions. For these reasons, and also because the flyby missions offer the possibility of out-of-ecliptic and interstellar trajectories, we must continue to pay a great deal of attention to the design of effective particles and fields experiments, with regard to both interplanetary and planetary observations.

SOLAR WIND

Near the earth's orbit, typical parameters of the solar wind are a radial velocity of 400 km/sec, a density of 5 protons per cm^3, an ion temperature of 100,000 K, an electron temperature several times as high, a flow direction (corrected for aberration) that is a couple of degrees east of the sun-earth line, and noticeable temperature anisotropies with the random ion velocity being greatest parallel to the magnetic field. All these quantities, plus the embedded magnetic field and chemical composition, vary substantially over intervals that range down to a few seconds and up to at least a week and perhaps a month.

The identification of velocity streams, sector structure, waves, and convected filaments or other structures has introduced some order into this chaos, but our understanding of the physical nature of some of these components, their origin, and their mode of evolution is incomplete in spite of much fruitful theoretical work. The ion temperature is higher and fluctuates more with time, and the anisotropies are less than is suggested by most theoretical models. The physical basis for the high ion temperature is presumably partially the thermal conductivity of the electrons and also a substantial conversion to thermal energy of the mechanical energy by wave-particle interactions. It seems likely that somewhere beyond 3 to 10 AU most of the velocity fluctuations would have been smoothed out and the waves damped out except as regenerated by plasma instabilities perhaps associated with the anisotropic expansion.

Observations over the space between the orbits of Venus and Mars are consistent with the basic theory. The average radial velocity should be essentially independent of radius. The average density should be inversely proportional to the square of the distance from the sun. The ion temperature should decrease as in adiabatic expansion, but over this range this effect cannot be disentangled from the fluctuations, effects of electron conductivity, and wave damping. The same theory should serve for these average properties out to the orbit of Jupiter and beyond to where the transition from solar system to interstellar regime becomes noticeable. But the theories governing the fluctuations, and our identification of the nature of the fluctuations are seriously deficient. Observations of as many as possible of plasma and magnetic properties as a function of distance from the sun out to 5 or 10 AU should form the basis for a vastly improved understanding of the rich diversity of plasma physics involved. On this basis, we should then be better able to extrapolate the fluctuations and structures in the solar wind upstream toward the sun to understand their origin and downstream to understand the interaction with the galactic magnetic field and interstellar plasma. The basic discipline involved is collisionless plasma theory. Many of the processes that can be understood by a comparison of theory and observation in the solar system should play important roles in the formation of stars, in phenomena produced by supernovas, in galactic and extragalactic radio sources, perhaps in quasars, and in all the other areas of astrophysics where plasmas are important.

The solar wind cannot continue to flow outward from the sun at hundreds of kilometers per second to indefinite distances. Somewhere at an estimated distance of 5 to 300 AU from the sun, it must begin to interact with the interstellar gas and the galactic magnetic field. The nature of this transition is of great interest. Quite probably it involves a shock across which the wind velocity drops substantially and outside which the flow is subsonic. Eventually there must be mixing with galactic plasma. The region within which the plasma is distinguishable as of solar origin is called the heliosphere. There is no reason to think in terms of a smooth, symmetrical model; there should be irregularities in plasma properties, magnetic fields, and fluxes of energetic particles over a vast range of scales. The region near the ecliptic, where the large-scale interplanetary field is mainly in the azimuthal direction and normal to the flow, may be very different from the sun's polar region, where even at very large distances the interplanetary field and the flow are expected to be nearly parallel except for the magnetic fluctuations generated by the probably inevitable instabilities.

The sun and solar system probably have a velocity of the order of 20 km sec^{-1} with respect to the surrounding galactic gas and magnetic field. In the direction of this relative velocity vector, the transition to the galactic region should be closest to the sun. The zero-order estimate of this direction is the direction of motion of the sun with respect to the fixed stars and 21-cm HI background, which is approximately at 270° ecliptic longitude, +30° ecliptic latitude (i.e., roughly the longitude of Neptune in 1980). This estimate is very tentative since the motion of the galactic gas and magnetic field may be anywhere from 0 to 20 km sec^{-1} in an unknown direction. Any mission to or beyond 5 AU should include both the capability of detecting the shock if it should unexpectedly be so close that it is traversed and of searching for any clues available on the transition region. Cosmic-ray observations might provide such a clue, as might a slight decrease in solar wind velocity with radius that could be ascribed to momentum lost by charge exchange between solar wind protons and incoming neutral atoms from the interstellar gas. Direct detection of the neutral particles would also be significant. An indication in an early flight of the best direction in which to go would be invaluable in planning later flights to explore the transition. It should be

emphasized that our knowledge of plasma physics is so limited and our history of predicting such effects is so spotty that we must be prepared for a wide range of possibilities, and almost any observations at large distances from the sun will be valuable in restricting the number of possible models and in stimulating plasma theory.

Although the missions considered here are to the outer planets, radio propagation observations can be made that provide information on the solar corona and interplanetary plasma. The coronal information is important in itself and also for its bearing on the origin of the solar wind. Radio links between the earth and the spacecraft can be used during the cruise phases of the flights to study certain properties of the solar corona and the interplanetary plasma. These could be the same links that are used for communications and tracking, but they should have the capability of measuring range rate, range, dispersion, absorption, scattering, and polarization rotation.

On the long flights to Jupiter and beyond, the spacecraft will repeatedly go through superior conjunction, so that the radio paths will pass near, and perhaps be occulted by, the sun. Dispersion and polarization measurements conducted simultaneously will make it possible to separate effects of the plasma density of the solar corona from magnetic field effects, so that one may study space and time variations of the coronal plasma density and of longitudinal components of the coronal magnetic field. Range measurements, corrected by the results on dispersions, would provide accurate determinations of the 30-km apparent change in range due to the general relativistic effect of the solar gravity field, perhaps making it possible to test alternative theories. Amplitude and spectral measurements would provide information on irregularities and mass motions in the solar corona.

The average plasma density between the earth and the spacecraft could be measured to very high precision. Radio propagation experiments on Pioneer A through Pioneer D show the expected values of the interplanetary electron density, with marked changes due to pulses of plasma from the sun, for regions near the orbit of the earth. These investigations could be extended to great heliocentric distances using outer-planet spacecraft. Differential measurements to several such spacecraft would be particularly sensitive to the very low densities expected at great distances from the sun and should be able to detect a possible increase in density and subsequent drop-off at the limits of the solar-wind region. Observation of the galactic radio emission at frequencies down to 1-10 kHz may provide independent evidence for the large-scale structure of solar-wind plasma at the boundary of the heliosphere. Galactic radio emission in this frequency range will not be accessible to any other kind of observation than from outer-planet spacecraft. Its measurement will yield two results: clarifying both an important galactic phenomenon related to particles and fields in interstellar space and also the structure of the solar wind.

INTERPLANETARY MAGNETIC FIELD

The solar wind convectively transports the solar magnetic field into interplanetary space. Here its presence controls the motion of more energetic charged particles originating from transient events on the sun, such as solar flares, as well as the continual flux of extrasolar origin. The solar cycle modulation of galactic cosmic rays is due to the existence of the interplanetary magnetic field permeating the outward flowing solar plasma.

Assuming a spherically symmetrical expansion of the solar corona into interplanetary space permits the theoretical prediction of the variation with distance (r) of the magnitude and direction of the "frozen-in" magnetic field. Near the solar equator, the radial component is given by $B_r = B_o(a/r)^2$ and the azimuthal component is given by $B_\phi = B_o(a^2\Omega/rV)$, where B_o is the radial solar magnetic field close to the sun (on a surface of radius a), Ω is the equatorial angular velocity of the sun, and V is the velocity of the solar wind. In this simplified model, it is also assumed that the solar wind velocity is constant beyond $r = a$.

These two formulas represent geometrically an Archimedean spiral centered at the sun. Thus with typical solar-wind velocities of 300-500 km $\sec^{-1}$, the angle between a field line and a radius vector from the sun will be $\sim 45°$ at 1 AU. However, the "spiral" becomes much more tightly wound beyond this distance until at 5 AU, the orbit of Jupiter, this angle is $\sim 80°$. Hence the field direction in the context of the outer planets is expected to be principally transverse to the local solar-wind velocity.

Direct measurements of the interplanetary magnetic field have been made, mainly by the IMP series of satellites at 1 AU and the Pioneer and Mariner series of space probes between 0.7 and 1.5 AU. From statistical analyses of these data it has been shown that at 1 AU the average magnitude is 60 μG with short excursions to values as large as 400-500 μG, while the average direction is close to the expected spiral angle of 45°. The sense of the field along the spiral direction, either outward or inward, is referred to as positive or negative polarity, a terminology consistent with that used in the study of the solar magnetic field.

The radial variation of the magnitude of the field has been found to be consistent with the simple formulas given above. The variation in direction around the spiral angle is sufficiently large that it obscures the detection of the anticipated small variation in angle between 0.7 AU and 1.5 AU (from 35° to 56°). At the orbit of Jupiter, the field magnitude is expected to be ~ 8 μG and to decrease as $1/r$ beyond the orbit. However, nothing is known directly about either the geometry or magnitude of the magnetic field beyond 1.5 AU and a major objective of the exploration of the outer planets should include a definitive study of the interplanetary medium and its imbedded magnetic field.

The observed magnetic field of the sun shows a complex variety of patterns and characteristic behavior. The most significant feature relative to the large-scale structure of the interplanetary magnetic field is the existence of large unipolar regions which persist for several to many solar rotations, although changing their size and location continuously. These unipolar regions appear to be directly reflected in the "sector" structure of the interplanetary magnetic field in which the "sense" of the field is observed to be constantly outward or inward for several days when observed between 0.7 and 1.5 AU.

Evidence for the existence of a sectored structure of the interplanetary magnetic field should be detected at distances > 1.5 AU, although the terminology of outward- and inward-directed fields obviously is no longer appropriate. Instead, the positive polarity will refer to fields directed in a sense opposite to the solar rotation and negative to that parallel. The time delay between the passage of successive sector boundaries should not vary with radial distance, but the lag between central meridian passage and the space probe should increase linearly with distance. The correlations of these measurements with those conducted by earth-orbiting satellites will be an important method of studying the large-scale structure and dynamics of the interplanetary medium.

As the sector and filamentary magnetic structures in the solar wind are swept far out from the sun, the spiral direction becomes nearly the azimuthal direction at low solar latitudes and there must be many interfaces between tubes in which the field runs in opposite directions. To some extent there should be reconnection of field lines across these interfaces to form loops. These are pulled by magnetic forces in the azimuthal direction. Thus plasma experiments should search for localized regions of denser than normal gas that is moving azimuthally as well as radially. Magnetometer data would be relevant. Low-energy cosmic rays should be accelerated in these structures, and the flow of low-energy galactic and solar cosmic rays into and out of the solar system may be substantially modified.

The small-scale fluctuations of the interplanetary field have been studied and reveal that transverse perturbations are the most prevalent. In addition, a unique feature of the interplanetary medium is the presence of a copious number of discontinuities, surfaces across which the properties of the plasma-magnetic field change suddenly, on a time scale < 30 sec. These surfaces, when observed simultaneously by satellites between 0.7 and 1.5 AU, appear to separate regions of magnetized plasma which are being convectively transported outward from the sun. However, the origin of these discontinuities is not known, either the sun or the interaction of fast and slow plasma streams being the principal contending sources. Characteristically, the field magnitude does not change across these surfaces, although the direction does change significantly.

The measurement of the spectrum of the interplanetary magnetic field fluctuations is made difficult due to the supersonic solar-wind flow. This transports the interplanetary field past the satellite at velocities many times larger than wave-propagation velocities. Thus, explicit time variations of the field, as observed by satellites and space probes, in fact represent principally spatial variations of the field. Due to the large numbers of discontinuities present, the spectrum shows the expected characteristic dependence $f^{-\alpha}(1 \leq \alpha \leq 2)$ for frequencies (f) less than 1 Hz. This is well above the Doppler-shifted ion-gyro frequency. Variations in the coefficient and the amplitude of the spectrum are dominated by the size and distribution of the discontinuities. Thus any attempt to study these spectra must properly assess the relative contribution of discontinuity surfaces.

The distance to which discontinuity surfaces and small amplitude fluctuations extend is not known, and no theory yet treats this problem. Thus a fundamental experiment in the study of the interplanetary field is to determine the variation of its microstructure with distance from the sun.

The discontinuity surfaces and the small fluctuations may eventually decay beyond 1.5 AU, but exactly how and why is not known. Depending on how the solar-wind anisotropies and inhomogeneities vary with distance from the sun, the medium may become more or less intrinsically unstable to certain disturbances. The eventual merging of the solar with the galactic plasma may not occur at a sharply defined surface, and the identification of the extent of the heliosphere may depend on the gradient of the microstructure of the interplanetary medium. Accurate vector measurements of the interplanetary magnetic field and its variations for frequencies less than 1 Hz are of fundamental significance in a study of the interplanetary medium and the dynamics of the solar-system plasma.

GALACTIC AND SOLAR COSMIC RAYS

Knowledge of the composition and energy spectrum of galactic cosmic rays is of considerable astrophysical importance. Such knowledge is crucial in understanding the origin of cosmic rays and the major nonthermal process of astrophysics including x- and gamma-ray astronomy, processes occurring in supernovae envelopes and, perhaps, radio sources and pulsars. It is also essential in understanding the propagation of cosmic rays through the galaxy with their important influences on the galactic magnetic field and gas structures. Until we have a sure knowledge of the flux of low-energy cosmic rays (below 1 GeV per nucleon), their influence in a variety of astronomical problems, including the heating in the interior of dense clouds, their effect on dust grains, and the production of rare isotopes, will remain uncertain. Measurements near the earth do not provide the necessary information, since low-energy cosmic rays are partially screened out of our part of the solar system by the irregular magnetic fields convected outward by the solar wind. This effect is called modulation, because the magnitude of the effect is a function of solar activity.

Careful measurements of the mean intensity and anisotropy of different cosmic-ray nuclei (e.g., e^-, e^+, ^1H, ^2D, ^3He, ^4He, Li, Be, B, C, N, and O) as a function of distance from the sun out to 5 or 10 AU should allow the modulation process to be understood and the essential characteristics of the unmodulated cosmic rays in our part of the galaxy to be observed directly or at least deduced with considerable confidence. It is plausible that the outer boundary of the region of modulation may be somewhat closer to the sun at high solar latitudes and hence that cosmic-ray observations in this region may be the best way to get this essential data.

Existing theories of galactic cosmic-ray modulation are quite rudimentary, although the general features of the phenomenon at the orbit of the earth are reasonably well established. At the higher energies (greater than 10^2 GeV), modulation is essentially absent, and the anisotropy appears to result mainly from the proper motion of the solar system and possibly from some net streaming of cosmic rays within the galaxy. At intermediate energies (greater than about 200 MeV for protons), the degree of modulation does not amount to more than a factor of ~ 2 in the intensity, and the intensity appears to behave as if the particles were being influenced by a heliocentric force field. In this energy range, the anisotropy has a small radial component associated with the modulation and a much larger ($\sim 0.4\%$) azimuthal anisotropy resulting from the tendency for the particles to corotate with the interplanetary magnetic field structure. At low energies (1 to 10^2 MeV per nucleon) the anisotropy is essentially radial but, depending on the form of the energy spectrum, may be outwards or inwards. The degree of modulation in this low-energy range is quite large, but since we do not yet understand the modulation process properly, it is not possible to do better than make an informed guess at the unmodulated intensity (a factor of 10 or more might easily be involved).

Since solar modulation occurs at all energies up to at least 10 GeV, there must be a radial gradient of the cosmic-ray intensity somewhere beyond the orbit of earth, and the full intensity is presumed to be reached beyond ~ 10 AU. However, measurements of the gradient in the region between Venus and Mars (0.7 to 1.5 AU) have given quite contradictory results. It is possible that most of the modulation of the lower-energy particles involved in these measurements takes place in a thick shell of turbulent plasma at 3 to 5 AU, and that the interplanetary medium near 1 AU is relatively smooth so that the radial gradients are small. The determination of the radial gradient is of fundamental importance to our understanding of the modulation problem, and, accordingly, the experiment must be carried out with due care. In order to establish a base level, identical detectors should be placed on spacecraft near the earth. Furthermore, since the radial gradient is intimately related to the radial anisotropy, the shape of the particle energy spectrum, and the spectrum of interplanetary magnetic field fluctuations, some provision should be made for measuring each of these quantities concurrently. Experiments designed to measure the interplanetary magnetic field should be such that they provide an adequate power spectrum of fluctuations up to frequencies of the order of 10^{-1} Hz.

It is a great advantage to be able to observe the behavior of different components of the galactic cosmic rays concurrently, since the modulation (and hence the radial gradient and anisotropy of the particles) is expected to depend on the particle charge-to-mass ratio. Furthermore, in the case of cosmic rays of secondary origin (notably positrons, but also ^3He, Li, Be, and B), the unmodulated spectrum can be estimated directly from the spectra of the primary particles, and hence observations of the behavior of these particles at various heliocentric distances should provide a very good direct test of modulation theories.

There have been as yet no in situ measurements of the interplanetary magnetic field or plasma at high heliographic latitudes. Comet tail observations suggest that the characteristics of the solar wind in the high-latitude region are essentially similar to those found in the ecliptic. Observations of the scintillation of small-diameter radio sources are consistent with the comet tail results, although some preliminary analyses indicate that the solar-wind speed might be higher at higher heliographic latitudes. It is expected that the interplanetary magnetic field is more radial at high latitudes than in the ecliptic since the geometrical factors that produce the spiraling are different. Thus there are reasons for believing that degree of modulation of galactic cosmic rays at a given distance from the sun varies with heliographic latitude, and indeed there is some indirect evidence that this is the case. Clearly a mission to high heliographic latitude could provide a great deal of new information on these effects.

Energetic particles (solar cosmic rays) are released from active regions on the sun, especially following solar flares. These events provide a useful means of probing the interplanetary medium along the path followed by the particles as they move from the sun to the point of observation. It should be noted that in order to interpret the observations properly, it is necessary to measure both the intensity and anisotropy of the particle distribution. A solar cosmic-ray event observed in the vicinity of Jupiter, for example, should have quite different characteristics from the same event observed in the vicinity of the earth. The time delay must, of course, be very much greater, because the particles have to travel 10 to 20 AU (depending on solar-wind velocity) along the spiraled interplanetary magnetic field lines, the anisotropies are likely to be correspondingly less pronounced, the direction of arrival must be typically from 80° west of the sun, and the relationship of the event to observed solar flares might not be clear. Furthermore, since the distribution of magnetic field fluctuations along the field line connecting the sun to the space probe (and beyond) might be quite complicated, the temporal behavior of the intensity and anisotropy could be noticeably different from that seen at the earth.

It would be interesting to be able to observe events occurring when the earth and the space probe are magnetically linked. This will occur at various radial distances, depending on the relative solar longitudes of the two bodies. Observations of solar electron events would be especially interesting in this regard. In the case of particles which are being emitted almost continuously by an active region on the sun (and therefore produce recurrent events), correlated observations of this nature should yield useful information on the diffusion coefficient perpendicular to the mean direction of the magnetic field. Furthermore, since the particles move essentially parallel to the interplanetary magnetic field lines, it might be possible to make use of observations of their direction of arrival as a means of correcting the magnetometer measurements if the spacecraft fields become noticeable.

PLANETARY STUDIES

Plasma Flow Past Planets and Their Satellites

Three modes of flow of the magnetized solar plasma past a dense body in the solar system have been identified.

In the case of the earth, which has a large intrinsic magnetic field, the entire interaction is dominated by this field, which supports the magnetopause (the boundary separating the geomagnetic field and plasma from the solar-wind plasma) at about 10 earth radii above the subsolar point. Outside of this, at about 14 earth radii on the sunlit side, is the bow shock, inside of which heated solar plasma flows around the magnetopause. Behind is a tail produced by the part of the geomagnetic field that is swept back to very large distances, greater than $100R_E$.

In the case of the moon, which has essentially no intrinsic field, no ionosphere, and a very low conductivity, the solar wind flows unimpeded into the surface, leaving a nearly empty cavity behind. The interplanetary magnetic field passes through the moon and through the cavity with small and sometimes undetectable perturbations.

In the case of Venus, which has little, if any, intrinsic field but does have a highly conducting ionosphere, the magnetic field of the solar wind cannot quickly penetrate the ionosphere and the solar wind cannot flow unimpeded into the atmosphere. There is a bow shock at about 1.3 Venusian radii above the subsolar point; the shocked solar wind flows around Venus between this shock and a bounding surface (called the anemopause or wind shield) just above and supported by the ionosphere. On the dark side there is some indication of the presence of a wake filled with relatively stagnant plasma whose density is hundreds of ions per cubic centimeter and extending to at least 2 Venusian radii. It may be speculated that the wake is bounded by interplanetary field lines that are entangled in the Venusian atmosphere or ionosphere in the front and swept back by the wind at the sides.

It seems of great interest to learn whether the solar-wind flow past other planets and their satellites (when the latter are exposed to the wind) can be classified as one of these three types or whether there are new and surprising further modes of interaction. Also, the interaction of the Jovian magnetosphere and Io (as well as other satellites) needs clarification. According to most estimates it is unlike any of the three types discussed above. Studies of these phenomena will substantially further our understanding of the behavior of collisionless plasmas, a subject that lies at the heart of many problems in astrophysics.

Magnetospheres

Of all the outer planets, only Jupiter has thus far been identified as possessing a magnetic field and a significant radiation belt. This conclusion is based on the discovery, study, and analysis of radio emission in various frequency ranges. This permits estimates to be made of the topology and magnitude of the planetary magnetic field. Present estimates of relevant parameters suggest a model in which the dipole and quadrupole moments, magnetic centroid, axes, rotation rate, and field direction have fairly specific values. Observational verification or modification of this model would put the explanation of the wealth of radio astronomical data that can be obtained from Jupiter on a much firmer basis.

The interaction of the solar wind and the Jovian magnetic field most probably leads to the formation of a magnetosphere, magnetosheath, and bow shock similar to the earth's. The above-mentioned estimates of the Jovian magnetic field and extrapolated measurements of the solar-wind flux at 5 AU lead to a magnetopause subsolar distance of $50R_J$ and a bow-shock distance of $70R_J$ from the center of the planet.

The flow in the magnetosheath of thermalized (or shocked) magnetized solar plasma should be similar to that for the earth. Finally, there may exist a huge tail to the Jovian magnetosphere if the wind extends the polar field lines in the antisolar direction. It is possible that, due to the large angular velocity and large magnetic moment of Jupiter and the distribution of plasma within the magnetosphere, the entire magnetosphere corotates with the planet, drastically modifying the tail and the rest of the magnetosphere. Only by direct measurements of the distant Jovian magnetic field will it be possible to determine the correct configuration of the tail -- if it exists.

There is almost no knowledge of or reliable estimate for planetary magnetic fields and magnetospheres of the other planets. There is some inconclusive evidence (only one tentative observation) for perhaps intermittent radio emission from Saturn, but it is clear that it is not nearly so spectacular a radio source as Jupiter and hence that its radiation belts must be far less significant even though, of all the planets, it most resembles Jupiter in size, rotation rate, and composition. However, if the rings of Saturn are an effective absorber of charged particles, it could still possess a significant magnetic field. Thus only by direct, in situ measurements can the existence, geometry, and magnitude of a possible field be determined.

There are essentially no clues in the case of Uranus and Neptune; we should approach their magnetic exploration with no preconceived ideas.

Planetary Radiation Belts

Only two planets are known to have radiation belts, composed of electrically charged particles moving in temporarily trapped orbits in the external magnetic field of the planet. The radiation belts of earth were discovered by in situ observations with a Geiger-Müller tube flown on the first American satellite, Explorer I. Those of Jupiter were suggested shortly after as an explanation of the nonthermal decimetric radio noise of that planet. The absence of radiation belts at Venus and at Mars has been established by direct observation on close flyby missions by the United States and the Soviet Union. Also, the moon has been found to have no radiation belt.

There is no comprehensive quantitative theory of the origin of planetary radiation belts. Only those of earth have been studied in detail. The following appear to be the rudimentary conditions for the existence of planetary (or satellite) radiation belts:

(a) The dominant physical mechanism for the creation of a radiation belt is the electrodynamic interaction of the solar wind with the intrinsic magnetic field of the planet.

(b) The magnetic field of the planet must have approximate rotational symmetry about some axis and the strength of the external field B must be such that the hydromagnetic stagnation condition

$$nmv^2 = B^2/8\pi = M^2/8\pi r^6 \qquad (1)$$

(n is the number density of charged particles in the solar wind of mass m and velocity v, and M is the equivalent dipole moment) must be satisfied at a distance r from the center of the planet that is greater than the radius of the effective "top" of its appreciable atmosphere. The foregoing condition is met at $r = 10R_E$ for the earth and probably at $r = 50R_J$ for Jupiter. The absence of radiation belts at Mars, Venus, and the moon is presumably due to the failure to satisfy condition (b) for r exceeding R_M, R_V, and R_{moon}, respectively. Tentatively, it is thought that the existence and intensity of Jovian radiation belts certify that the directed flow of solar plasma (the solar wind) persists to at least 5 AU and that Jupiter has a magnetic moment in the range 10^{30} to 10^{31} cgsu.

The theory of planetary magnetism, incomplete as it is, requires two basic properties: a fluid electrically conducting core and a rotating body, though definitive quantitative criteria are not known. Jupiter and earth are very likely to possess both properties. Both Mercury and the moon rotate slowly and also, probably, are solid throughout. Mars has a rotational period similar to that of the earth, but it probably has a solid interior. Venus may well have a fluid core but rotates very slowly (245-day rotational period). Hence, the body of present evidence is internally compatible with the two sets of rudimentary conditions given above. However, nonthermal radio noise has not been detected from Saturn, Uranus, Neptune, or Pluto despite systematic searches. Saturn may well be regarded as a special case on the grounds that directly trapped energetic particles cannot exist in the region of its rings of particulate matter. Hence, the absence of nonthermal radio noise cannot be adopted as definitive evidence against the intrinsic magnetization of Saturn. Because of the large sizes and high rotational rates of Saturn, Uranus, and Neptune, it would be a matter of astonishment and fundamental significance if each of these planets does not have a magnetic moment comparable with that of Jupiter. The absence of detectable nonthermal radio noise from Uranus and from Neptune may be simply due to their great distances from the earth or perhaps to some change in the character of the solar wind at heliocentric distances greater than, say, 15 AU.

It is clear from the foregoing discussion that the following investigations are of significance in illuminating the detailed physical character of the earth's radiation belts and, more broadly, in clarifying the basic physical conditions for planetary magnetism and planetary radiation belts:

(a) Detailed study of the external magnetic field of Jupiter

(b) Detailed study of the charged-particle populations in Jupiter's magnetosphere

(c) Search for magnetic fields and radiation belts of Saturn, Uranus, Neptune, and Pluto and detailed investigation if positive findings occur in exploratory studies

(d) Study of solar-wind flow characteristics to large heliocentric radial distances (out to or beyond 40 AU)

Exploratory missions to the outer planets will require particle detectors having a wide dynamic range, simply because we have no knowledge of the nature of their radiation belts. It is clear from the observation of Jupiter's nonthermal radio emission that large fluxes of relativistic electrons exist in its magnetosphere. Some information could also be obtained from observations at the earth of x rays from Jupiter; at present, no positive measurements of x rays have been made, but the sensitivity of the detectors used to date could be substantially improved.

RADIOPHYSICS IN THE EXPLORATION OF THE OUTER PLANETS

Radio astronomy works in a spectral region where surprises are the rule rather than the exception. At low frequencies, electromagnetic emissions from astronomical objects represent plasma physical effects that are novel in today's physics. To support this point of view, we can cite the dynamical radio phenomena of the solar corona and atmosphere, the existence of cosmical masers in the interstellar hydroxyl radical and in the water vapor molecule, the pulsars, and, finally, the extraordinarily intense decametric emissions from Jupiter. (Recent source size measurements set an upper limit of $\leq 0''.1$ to the source size and correspond to an equivalent temperature brightness of 10^{19} K.)

Only the last of these phenomena is accessible to in situ observations from spacecraft. Its relation to other planetary parameters, such as the magnetic field, the thermal and nonthermal particle populations, and the different forms of wave motion in Jupiter's magnetosphere and ionosphere will surely clarify the at present still schematic suggestions about its physical origin.

That novel plasma physical effects are involved appears to be an implication of the strong modulation of decametric emission by the first Galilean satellite Io (similar effects have not been detected for Europa, Ganymede, or Callisto). (For many reasons it seems unlikely that the actual emission occurs at the satellite; confirmation of this conclusion by observation of signals leaving Jupiter not in the plane of the ecliptic is highly desired and exceedingly difficult if not impossible from the ground.) Io acts at a distance. It is probably unreasonable to suppose that magnetospheric parameters vary so rapidly with distance that, say, Europa, the next Galilean satellite, fails to create a disturbance comparable with Io's. Therefore, we should conclude that not only Io's disturbance, but those of the three other Galilean satellites, plus Amalthea's and the other smaller satellites, are present and sloshing about in a complicated pattern within Jupiter's magnetosphere.

In situ measurements of particles and fields may in this case represent an extremely complex superposition of phenomena originating at different source points distributed over Jupiter's magnetosphere. The observational problem is to identify and connect these waves and particles to decametric emissions in a meaningful way.

The needs for radio physical studies of Jupiter seem clear in this context. First, measurements of the highly intense, highly directive, and variable decametric emissions should be made directly in Jupiter's vicinity where direction of arrival effects are easier to observe on account of the large angle subtended by Jupiter and the absence of interplanetary or terrestrial phase shifts. Furthermore, we note that, at Jupiter, decametric emissions can be directly related to wave phenomena. The alternative of ground-based or near-earth observation of the emission simultaneously as a particle-and-fields (without radio) vehicle flies through the magnetosphere suffers the difficulty that the richness of the wave phenomena will not be easy to sort out.

Finally, the radiation beams into solid angles, either cones of 3° or 4° half-angle or sheets of less than 1° thickness, which do not intersect the position of the spacecraft and the direction of the earth in any clear way. As a consequence, we may expect, for example, that the Europa decametric emissions lie in some other direction than the extremely limited range of angles about the ecliptic to which our earth-based data correspond.

To discover the decametric emissions connected to the other Galilean satellites, especially Europa, requires, we infer, a vehicle orbiting Jupiter at high inclination. Simultaneously, we might hope to disentangle the complex of wave phenomena observed at the vehicle by their relation to the (then) observable radio emissions associated with the other satellites.

The result of these radio astronomical studies, carried out synoptically over a range of orbiter positions with respect to the major satellites and to the rotational aspect of Jupiter, should be an adequate physical explanation of one of the most intense emissions known to astronomy.

Galactic Low-Frequency Radio Noise

The local plasma density of the solar wind near the earth limits observations of galactic radio waves to frequencies above ~30 kHz. In interstellar space, the plasma cutoff may be as low as 1 to 10 kHz. The spectrum of galactic emission turns over somewhere near 2 MHz but is still observed from space outside the plasmasphere down to frequencies of a few hundred kHz. On vehicles passing out through the solar system, the local plasma density should decrease monotonically; observations of the low-frequency cutoff in galactic radio emission could in principle identify the plasma frequency as well as provide new information on galactic vlf emissions. The data could be simple total flux measurements on several radio frequencies observed with antennas with hemispheric directivity.

Very-Low-Frequency Emissions from Jupiter

Jupiter's magnetosphere very likely also contains another radiophysical phenomenon even more closely related to the plasma than the decametric radio emission. Below 100 kHz, waves in the earth's magnetosphere stand in an intimate connection with basic properties of the trapped-particle radiation, such as its energy density, loss mechanism, and radial and pitch angle distributions. The origin and loss of electrons and protons in the belts depend on these electromagnetic phenomena. Clearly, a rational study of Jupiter's magnetosphere also requires instrumentation *in situ* to detect and establish the properties of vlf emissions. Since the propagation properties of these waves require close interrelations between plasmas and fields, they are unlikely to escape from the magnetosphere. It is therefore important that they be studied from orbiters as well as flybys.

Planetary

The same radio links between the spacecraft and earth discussed earlier in this chapter as a means of determining some of the plasma parameters of the corona and solar wind can also be used to provide accurate plasma measurements near the planets, for study of their magnetospheres and ionospheres and their interactions with the solar wind. Occultation would be desirable, although the upper reaches of magnetospheres might be studied even without occultation. Measurement accuracies are such that electron number densities of a few ten's per cubic centimeter, or possibly a few per cubic centimeter, could be detected. Polarization measurements would add magnetic field information over regions not measured by on-board magnetometers. Spacecraft radio receivers could make useful measurements of noise from trapped particles in the magnetospheres over regions not covered by direct sampling of particles with on-board instruments. The receivers could detect weaker radiation, to higher spatial resolution, than can be obtained by use of radio astronomy facilities on the earth.

Ground-Based Radar

The sensitivities of ground-based radars proposed for the future are sufficient to obtain echoes from the Galilean satellites of Jupiter and from Titan, the large satellite of Saturn. Interplanetary measurements to Jupiter and Saturn, and occultation measurements at Jupiter, could thus provide data of the types described above. These would not have the sensitivity and range of the measurements based on links to the spacecraft but could be done without the use of a spacecraft.

RECOMMENDATIONS

We *recommend* the following as the major scientific objectives in the study of particles and fields and radio physics of the outer solar system:

Interplanetary

1. Unmodulated (interstellar) values of the cosmic-ray flux and distribution as a function of rest mass for $1 \leq Z \leq 30$ energy in the range $1\text{-}10^3$ MeV should be obtained. This requires observations over a solar cycle. (This objective is of considerable importance in high-energy astrophysics as well as in the study of cosmic rays observed near the earth.)
2. The properties of the solar wind and interplanetary magnetic field at great heliocentric distances should be investigated, both at low and high ($>80°$) heliographic latitudes, and an attempt should be made to study the termination of the solar wind.

Planetary

1. A detailed study of the external magnetic field and of the charged particle population in the magnetosphere of Jupiter should be undertaken. In particular, the nature of Jupiter's nonthermal radio emissions should be studied both from spacecraft and from the earth.

2. A determination should be made of the mode of solar-wind interaction with the major outer planets and the interactions of Jupiter's satellites with its magnetosphere. A search should be made for magnetic fields and radiation belts associated with Saturn, Uranus, Neptune, and Pluto, and if the findings are positive, detailed investigations should follow.

We recommend that full use be made of the cruise mode of planetary missions to carry out interplanetary research.

We recommend that first priority be given to a balanced program that combines planetary and interplanetary objectives and that smaller purely interplanetary missions to the outer solar system be used only if their scientific objectives cannot otherwise be met.

To give a reasonable balance between the first exploration of new regions and extensive investigation of the most significant problems, we recommend the following order of importance of the missions (which is not the recommended chronological order):

1. The 1974 Jupiter flyby test mission with an orbit that brings it back over the sun at high heliographic latitude, with the inclusion of a deep atmospheric probe if at all possible
2. The 1976 earth-Jupiter-Saturn-Pluto grand-tour mission, with the hope that at least one of the two vehicles could drop a beacon that would be occulted by Saturn
3. The 1979 earth-Jupiter-Uranus-Neptune grand tour
4. The 1978 Jupiter orbiter with a periapsis of about 1.2R and an apoapsis of from 75 to 100 R_J
5. A Uranus atmospheric probe
6. Saturn and Neptune orbiters and probes
7. A mission to Halley's Comet

Further Recommendation

We recommend that careful attention be given to the calibration of cosmic-ray experiments in order that results obtained at different places and times may be compared with confidence.

Chapter 5

PLANETARY INTERIORS

The fundamental importance of studying planetary interiors derives from the need to understand the total physics of each planet and the origin of the entire solar system. There is considerable interest in the outer planets (i.e., Jupiter, Saturn, Uranus, and Neptune) because of their size, low mean density, internal sources of heat (in Jupiter and Saturn), and because 99 percent of the mass of the entire planetary system resides in these four bodies. In particular Jupiter, the largest planet, accounts for most of the mass and angular momentum of the solar system and may be the most accessible sample of material whose chemical composition is similar to that out of which the system was formed. The study of planetary interiors is a particularly difficult task because of the need for relying on indirect observational evidence and often inadequate theories. It should be stressed also that our views on planetary interiors affect rival interpretations of what is observable on planetary surfaces and in atmospheres.

Various observational and theoretical aspects of investigations of the interiors of the outer planets are outlined below.

THEORETICAL QUESTIONS

Equations of State

A basic problem which limits our understanding of the planetary interiors is the lack of knowledge of the pertinent equations of state of matter and of the various transport coefficients. As far as the interiors of Jupiter and Saturn are concerned, there is a need for a better understanding of the behavior of hydrogen, especially in its molecular form at high pressures and in particular in that range where the predicted phase change between the molecular and metallic forms occurs. Present values of the transition pressure are uncertain by perhaps 50 percent, which implies a comparable uncertainty of the depth of the phase boundary between the two layers. Furthermore, no detailed study has been made of the effect of helium either on the metallic or molecular form of hydrogen at high pressures and temperatures. The problem of solubility of these two elements in each other and the question whether there is a miscibility gap has not yet been answered. This knowledge is essential for estimating the depth and composition of various layers in the interiors of Jupiter and Saturn and for drawing conclusions about their state of aggregation. It also may play an important role in evaluating one of the "floating raft" models of the Red Spot of Jupiter. Very little is known about the chemical composition of Uranus and Neptune, but there too the equation of state of hydrogen as well as of denser terrestrial type materials is likely to be of importance.

Experimental Studies

Parallel with theoretical studies of the hydrogen-helium system should be experiments leading to verification of some of the predictions. Present-day technology of high pressures has progressed sufficiently to promise important results even though the phase transition pressure in solid hydrogen may not yet be attainable in laboratories.

Transport Coefficients

The problem of transport coefficients such as viscosity, diffusion, and thermal conductivity, including a radiative component, in planetary interiors is an extremely difficult one. Even an approximate evaluation of these quantities for at least the hydrogen-helium system would be of great value. The recent progress in the theory of dense fluids may be of help here. There should also be some consideration of the role of impurities. Such information is essential for bracketing the probable values of the heat transport and for evaluating the efficiency and kinetics of convective phenomena. The latter play a paramount role in determining the magnetic fields of the planets, their heat budgets, and in many instances even the motion and configuration of visible surface structures.

Internal Energy Source

Both Jupiter and Saturn are believed to emit more energy than they receive from the sun. Presumably this can be accounted for by the gravitational self-energy and a progressive shrinkage of these planets. A detailed theoretical investigation of this process in terms of the best available equations of state is badly needed.

HEAT FLUX AND BALANCES

The heat "budgets" of Jupiter and Saturn are of great importance. These planets receive heat from the sun, the precise amount being the solar constant appropriately diminished by the inverse square law and by "pure" reflection. The amount of pure reflection would be obtainable if one could measure, in spectral detail, the radiation coming from Jupiter for the entire 4π sr, and, of course, if one had some knowledge of how much of the radiation was reflected sunlight and how much was planetary radiation. In this context, it is usually assumed that radiation coming from Jupiter or Saturn, whose wavelength is less than 2.5 μmP, is reflected light; 4π detection has to date not been possible for any planet. However, if a planet's surface is spherical and homogeneous (statistically), 4π detection could in principle be accomplished by varying the angle α subtended by the earth and sun at the planet by 180°. For the moon, α ranges over almost the required range; and for the inner planets, respectable ranges of α are achieved. For Jupiter, α cannot exceed 12°; and, for Saturn, α cannot exceed 6°. Moreover, for Saturn the reflection of the rings further complicates matters. Then too, both these planets, particularly Jupiter, have zonal structure parallel to their equators, and the reflection of sunlight perpendicular to their equators is possibly quite different from reflection in their equatorial planes. The total elastic cross section of a planet is $\pi R^2 A_B$, where A_B is Bond or bolometric albedo. The best that can be done is little more than an evaluation of the back elastic scattering differential cross section of Jupiter$(d\sigma/d\Omega)=R^2 P_B$ (which defines the geometric bolometric albedo P_B). A recent careful study (D. Taylor) of Jupiter gives $P_B=0.28$ with an error of 10 percent. Comparison with earlier data seems to indicate that P_B varies by perhaps 0.5 magnitude or by a factor of 1.6 between its maximum and minimum values. Also, it has been noted recently that Jupiter's infrared emission is variable. Consequently, the possibility that Jupiter is functioning as a gigantic heat engine with intake and exhaust "strokes" is not out of the question. Clearly such an eventuality would need to be reckoned with in virtually all Jovian investigations.

Measurements of albedos and of phase functions of Jupiter and of other planets made over a suitable period of time thus have a basic importance from the point of view of the physics of the planetary interiors. These measurements would be done best from orbiters, although rough values could be obtained also from flybys. Data obtained on the dark hemispheres of the planets as well as across their terminators would be of particular interest for calculating their rates of cooling and heating. Measurements from earth or from an Orbiting Astronomical Observatory would also be of value in spite of the inherent limitations of the phase angles.

PLANETARY MAGNETISM

The discovery, just over a decade ago, and subsequent investigations of radio emissions from Jupiter at decimeter and decameter wavelengths have led to the inference that Jupiter produces a poloidal magnetic field whose strength at the visible surface is tens of gauss. The configuration of the magnetic field inferred from the radio-astronomical data is more complicated than that of a centered axial dipole. The direct measurement of this configuration by means of an orbiter will settle certain points that are controversial at the present time and greatly extend the usefulness of the radio-astronomical data.

The sources of decametric and decimetric radiation currently rotate about the axis of the planet with a period of $9^h\ 55^m\ 29.7^s$ that is 5 min less than the period of rotation of visible markings near the equator, but only 10 sec less than that of the Great Red Spot. The continued monitoring of these motions and the interpretation of the observations in terms of the dynamics and magnetohydrodynamics of Jupiter's interior (at present a matter of controversy) will lead in due course to information about the internal constitution of the planet that may be obtainable in no other way.

If Jupiter's poloidal magnetic field is not primordial in origin, then a mechanism for maintaining the field against dissipative agencies has to be found. The atmosphere of Jupiter may be sufficiently deep (greater than 10^4 km) and electrically conducting (conductivity greater than about $10^3\ \Omega\,\mathrm{m}$ in its lower reaches for fluid motions (not less than about 10^{-2} m sec^{-1}) there to be capable of producing, or at least modifying, the poloidal field. A concomitant of such a dynamo process might be toroidal fields of 10^3 or 10^4 G confined to the interior of the planet.

Owing, among other things, to the rapid rotation of Jupiter, planetary-scale motions in the lower reaches of the atmosphere should be correlated with motions at higher levels, including the visible surface. It follows, therefore, that if the magnetic field is produced in the lower atmosphere then features of the visible surface (e.g., the Great Red Spot) might be expected to show significant correlation with the magnetic-field pattern in the vicinity of that surface. As a corollary, no correlation is expected if the magnetic field is produced in a (hypothetical) fluid region well below the atmosphere.

The other major planets -- Saturn, Uranus, and Neptune -- should contain extensive fluid layers that are sufficiently well stirred to produce magnetic fields by the aforementioned "dynamo mechanism," the process thought to be responsible for the magnetism of the two planets known for certain to produce magnetic fields of their own (earth and Jupiter). If Saturn, Uranus, and Neptune are indeed magnetic and possess radiation belts, then improvements in radio-astronomical techniques might ultimately lead to the detection of these magnetic fields. Until and if such investigations prove feasible, however, serious consideration should be given to the design of appropriate orbiter and probe experiments.

The best way to obtain significant data necessary to answer the questions concerning the interior of Jupiter is with an orbiter. A flyby could give some rough information, especially about the planets beyond Jupiter.

GRAVITATIONAL POTENTIALS

Gravitational potentials of planets can be expanded in a series of spherical harmonics which indicate the distribution of density in the planet and the degree of deviation from sphericity. For a planet without a north-south asymmetry one obtains

$$V(r) = - \frac{GM}{r} [1 - \frac{2}{3} J (\frac{R}{r})^2 P_2(\cos \theta + \frac{4}{15} K (\frac{R}{r})^4 P_4(\cos \theta) \ldots],$$

where R is the radius of the planet. Knowledge of coefficients J and K is essential for obtaining proper distribution of density in the planet. The coefficients themselves are usually deduced from a study of orbits of satellites. The J values for Jupiter, Saturn and Neptune are known with precision decreasing in that order. The K value for Jupiter quoted in the literature, $0.00111 < K < 0.00395$, (standard error) is actually within the limits $0.00174 \leq K \leq 0.00369$ of any hydrostatic model of Jupiter with the correct J value and thus is of little significance. Higher precision in determining Jupiter's K and any additional information about gravitational potentials of other planets would be of great value.

Furthermore, important information about the shape and stiffness of a planet as a whole can be obtained if odd harmonics in the series expansion of the gravitational potential do not vanish. Such is the case for earth as deduced from orbits of artificial satellites, and similar information could be obtained from Jupiter's orbiters provided their orbits were sufficiently inclined. Actually, a precise knowledge of the orbit of Amalthea, Jupiter's fifth moon, could perhaps give that information also, although its inclination is small. This is discussed more fully in Chapter 6.

It thus appears that all efforts should be directed at obtaining as precise data as possible about the paths of flybys and about the orbits of orbiters. Furthermore, ground-based systematic observations of Amalthea's orbit should be made and corroborated by detailed study of the paths of Jupiter's orbiters as well as by imaging techniques.

PLANETARY DENSITIES

The family of outer planets has long been held to comprise two physically distinct genera, containing Jupiter/Saturn and Uranus/Neptune, respectively. The case for this dichotomy, reflecting an alleged substantial difference in mean density between the two genera, has now been somewhat weakened. While the masses of the four planets are known to a sufficient precision, the mean densities of Uranus and Neptune (which are of basic importance in determining their composition) quoted in the current literature depend crucially on the adopted radius and oblateness of figure. A new radius for Neptune derived from the occultation of a star in 1968 reduces the mean density to 1.65 g/cc, i.e., almost to that of Jupiter. Very likely the radius of Uranus too has been underestimated. Nevertheless, the disparity between the two genera has not been obliterated. The relatively small masses of Uranus and Neptune, even if the mean densities are reduced, still imply the presence in the interior of a fair amount of elements heavier than hydrogen.

Ground-based observations of the diameters of Uranus, Neptune, and Pluto are unsatisfactory, as they require corrections for diffraction and physiological effects (contrast theory) compounded with limb darkening. Improved diameters of these bodies, which might be obtained during flyby, are a prerequisite for refined planetary models. The terrestrial observations of occultations of these bodies are so valuable and so rare that a determined long-range effort to predict occultation of fainter stars ought to be made so that astronomers will be better prepared for future opportunities.

Nothing meaningful can yet be stated about the interior of Pluto. Almost any observation of Pluto's diameter at closer range would be a marked advance.

In summary, the radii and oblateness of trans-Saturnian planets are of such fundamental importance that effort should be made to measure them with all available means: imaging from flybys, imaging from orbiters, and observation of occultations -- either visual occultation of stars, radar occultation of satellites, or radio occultation of probes.

GROUND-BASED RADAR OBSERVATIONS

It is expected that important ground-based radar observations of the outer planets and their satellites will become possible with present radar systems or systems now being planned.

From the point of view of the interiors of planets and the nature of their satellites the following data would be particularly valuable: (a) Radar reflectivity of the satellites of Jupiter and Saturn would indicate an approximate value of the dielectric constant of the surface material and thus place some restrictions on the nature of that material. (b) Occultation of satellites by parent planets would lead to better values of planetary radii, which are of fundamental importance for estimating planetary densities. (c) Measurement of secular terms in motions of satellites would throw light on the tidal interaction with the parent planet. This information would be of particular significance for Jupiter. These same measurements can be conducted with higher sensitivity in the bistatic radar mode, for example, by using the same ground-based transmitter and a receiver in a spacecraft near the object of study.

Chapter 6

GRAVITATIONAL AND CELESTIAL DYNAMICS

This chapter includes both a discussion of earth-based observations that do not require the presence of a spacecraft and consideration of experiments in which a spacecraft is an essential component of the system.

EARTH-BASED OBSERVATIONS

Radar systems now in existence and expected to undergo improvement within the next five years, and proposed new radar systems, will be able to range on the principal satellites of Jupiter and Saturn. The high accuracy of such measurements will add to the precision of the ephemerides of at least the four large Galilean satellites of Jupiter and the two largest satellites of Saturn.

Interesting questions related to the apparent existence of secular terms in the mean motions of the satellites have arisen, and there is also great interest in the commensurability relationships that exist between the mean motions of pairs and triples of satellites. An improvement in the ephemerides may allow new deductions to be made concerning the mechanisms responsible for these effects. One of the forces suspected to be of importance in this respect is the tidal interaction with the planet. The time scale for the evolution of satellite orbits may have been dominated by tidal friction, and new information is thus of considerable value in cosmogonical discussions.

Radar reflectivity can provide useful information on the dielectric constants of the surfaces of the satellites, especially if measured at two or more wavelengths. The scattering law for different angles of incidence indicates the surface roughness. Satellite rotation rates can be observed through Doppler broadening of the returned signal or through periodic variations in reflected power. Any departure from synchronism between spin rate and orbital motion about the planet would be of great interest, especially in view of the recent knowledge, also obtained by radar, of the resonant but nonsynchronous rotation rates of Venus and Mercury.

Occultations of the Gallilean satellites by Jupiter occur frequently, and in each case the detailed manner of decay or rise of the reflected radar signal can be detected. From measurements of changes in amplitude and phase, information can be obtained concerning the density and structure of the ionosphere of Jupiter, the existence of an ionosphere on Saturn, and the scale heights of the upper neutral atmospheres of the two planets. This radar information becomes clearer and less ambiguous when results at more than one frequency are available, owing to the different frequency dependence of the refraction produced by the ionosphere and the neutral atmosphere.

A parallel effect is the retardation of the radar signal as it passes out and back through the strong gravitational field of a planet. This effect of general relativity is independent of frequency and is largest when the signal grazes the planet; it then causes an apparent increase in round-trip path length of the signal of ~60 m for Jupiter and ~18 m for Saturn. This retardation is of interest both as a further test of general relativity theory and as a correction that must be taken into account in determining ionospheric and atmospheric refraction.

SPACECRAFT EXPERIMENTS

Many of the observations described above can be performed more precisely from a spacecraft, either flyby or orbiter, than from the earth. The principal advantages of the spacecraft from this point of view are shorter range and variable line of sight with respect to the sun-target line. It is, however, apparent that the spacecraft must be tracked very accurately from the earth, in order that spacecraft-based observations may be properly interpreted. Further, the bistatic mode (reception of both direct and scattered earth radar signals by the spacecraft) should provide useful information.

In addition to improved radar observations of the principal satellites of Jupiter and Saturn, there is the possibility of direct measurement of the motion of the innermost satellite of Jupiter from a nearby spacecraft. Jupiter V, or Amalthea, would make a particularly interesting radar target. It is only 1.6 Jovian radii above the surface of the planet, so that its orbit will be especially sensitive both to departures of Jupiter's gravitational field from spherical symmetry and to tidal interaction. Since the orbit of Amalthea is slightly inclined to the equatorial plane of Jupiter, it may be possible to detect a lack of symmetry between the northern and southern hemispheres of Jupiter. Such a "pear shape" of the earth has been discovered from observations of artificial satellites in inclined orbits. Secular changes in the orbit of Amalthea would give valuable information concerning tidal elasticity and friction of Jupiter.

It is even possible that extremely precise Doppler radar observations of Amalthea could detect a gravitational anomaly arising from the Great Red Spot of Jupiter. For example, if we assume that the Red Spot is an island of density 0.01 g cm^{-3} floating on a substrate of zero shear strength and twice this density, it is equivalent to a somewhat localized dipole source of gravitational field, with positive mass on top and negative underneath. With an assumed thickness of 20,000 km, it would then give Amalthea a downward velocity component of roughly 4 cm sec^{-1} each time it crosses the longitude of the Red Spot.

This assumed gravitational anomaly of the Red Spot would also affect the spacecraft trajectory. Since the spacecraft speed is comparable with that of Amalthea, its travel time near the Red Spot will also be comparable and the change in vertical velocity component will be roughly the same as that of Amalthea for the same altitude. For other altitudes, the effect is approximately inversely proportional to the cube of the altitude.

If the spacecraft trajectory is chosen so that it is occulted by the planet, all the effects mentioned earlier -- of refraction by the ionosphere and the neutral atmosphere and of general relativistic retardation -- can be measured. There is also a very much smaller general relativistic effect which arises from the rotation of the planet. This is a "dragging" of the inertial frame by the rotating massive planet, in the neighborhood of the planet. It is proportional to the planet's angular momentum and, hence, could, in principle, provide a measure of the moment of inertia if rigid-body rotation is assumed. The effect consists of a slight speeding up of the radar signal that passes on one side of the planet in the equatorial plane and an equal retardation on the other side. Unfortunately, the pathlength change is extremely small, only 10^{-3} cm for Jupiter and less for Saturn -- far too small to be of observational interest.

Because of the duration of a spacecraft mission to the outer planets and the motion of the earth, the spacecraft will be on the opposite side of the sun from the earth several times while en route. These opportunities can be used to measure the solar corona plasma and the general relativistic effects of the sun's gravitational field, in much the same way as just described for occultation of the spacecraft by Jupiter or Saturn. All these effects are much larger in the case of the sun; the apparent round-trip pathlength is increased approximately 60 km because of the gravitational field, the inertial frame dragging effect caused by solar rotation amounts to a change in pathlength on the order of 1 cm.

Finally, it is worth mentioning a new kind of test of the equivalence principle that may be possible from a precise measurement of the orbital parameters of Jupiter. The Eötvös - Dicke experiments show that the ratio of gravitational to inertial mass is the same for a wide variety of materials, with a precision of one part in 10^{11}. Since these materials differ in chemical composition, their important difference is in nuclear binding energy. Thus, existing experiments show that the decrease in mass of atomic nuclei in comparison with their component protons and neutrons -- the mass defect -- affects equally the inertial mass of the material and the gravitational force exerted on it by the earth and the sun.

The question remains whether the mass defect of a massive object caused by the gravitational attraction of its parts will affect the object's inertial and gravitational masses differently. Such a departure from the equivalence principle is best looked for in an object of large gravitational self-energy, and Jupiter is the most likely candidate. A lower limit for the ratio of the mass defect to the total mass is obtained if Jupiter is assumed to be a homogeneous sphere, in which case this ratio is 1.2×10^{-8}. If the entire mass defect were effective in contributing to Jupiter's inertia and none to the force of gravity exerted on it by the sun, or vice versa, the relation between orbital radius and period would be slightly different from that predicted by Kepler's third law in conjunction with the orbital parameters of the other planets. For example, for given known period, the fractional change in mean distance from the sun would be one third the above ratio, or 0.4×10^{-8}. This would result in a discrepancy in the radius of Jupiter's orbit of 3.1 km, if the lower limit for the mass defect obtained above is entirely effective as a contributor to either the gravitational or inertial mass of Jupiter but not to both. Such an effect might be detected in detailed studies of the scale of the solar system based on radio tracking of spacecraft and radar and optical observations of the planets.

RECOMMENDATIONS

1. Existing earth-based radars should be improved so that precise observations of the principal satellites of Jupiter and Saturn can be carried out with the objectives of improving their ephemerides, determining their radar reflectivities, and observing their occultations.

2. Spacecraft to Jupiter and the outer planets should be tracked with the greatest possible precision, in order to improve the ephemerides of the satellites of Jupiter and Saturn and also of Jupiter itself.

3. Spacecraft should be used to study the motion of Amalthea, the innermost satellite of Jupiter.

4. At least one spacecraft trajectory should be planned to be occulted by Jupiter.

5. Advantage should be taken of the occultations of the spacecraft by the sun during the mission.

examining chemical species as they evolve with distance and time into the solar-wind environment. Measuring the absorption spectrum of transmitted sunlight is of benefit.

Pluto

Atmospheric considerations relating to Pluto are very important. For the last 200 years, Pluto has been moving closer to the sun and is now nearly as close as is Neptune. Pluto's spectral energy distribution shows no ultraviolet brightening characteristic of a Rayleigh scattering atmosphere; however, its rotational light curve suggests brightening at the morning terminator as though an atmospheric component had formed frost during the night. The possibility of observing He, A, and Ne cannot now be ruled out on theoretical grounds. In addition, the very basic result of obtaining the diameter from radio occultation or flyby imagery and the mass from spacecraft tracking during encounter gives the only clue presently possible for its mean density -- with its attendant cosmogonical significance.

If Pluto were to appear rock-like, the nature of experiments one would consider would be that of those previously recommended for Martian exploration, exclusive of exobiology.

A most interesting result would follow directly from the determination of the mass. Presently, a free parameter determined in the mutual perturbation equations of Uranus, Neptune, and Pluto -- which results in a very inaccurate mass determination (± 200 percent) and is, as a process, an imperfect theory unless the eighteenth-century observations are ignored -- is that the specification of the mass might result in the prediction of the existence of a trans-Plutonian planet on the basis of present observations.

Even at the distance of Pluto, bistatic radar could provide information on reflectivity, roughness, and topography, as well as measuring the atmosphere by occultation.

RECOMMENDATIONS

We recommend, on the basis of the scientific importance of small bodies in the region of the outer planets:

1. Flyby missions should be undertaken to all the outer planets as a balanced beginning -- none should be ignored at the expense of optimizing the missions to others. Opportunities to view satellites at great increases in resolution should not be sacrificed on the grounds that more images of the primary are of greater value.

2. The flyby missions should carry high-resolution imaging systems of high photometric and photogrammetric integrity.

3. A Jupiter/comet mission should be undertaken in which the experiment design priorities are weighted in favor of the comet, and an imaging system should be involved together with a spectroscopic experiment. In addition, the feasibility of a sufficiently precise rendezvous maneuver that the spacecraft would slowly fall into the comet nucleus after burn-out should be considered, in which case more sophisticated probe-type instruments for chemical analysis and isotopic ratio determination would be strongly urged.

4. We strongly recommend the encouragement of the radar developments now envisioned which will extend to Jupiter, the Galilean satellites, and Saturn and perhaps its rings the capabilities now being exercised on Mars and Venus.

5. We recommend the development of bistatic radar techniques for study of the small solid bodies in the outer reaches of the solar system and the improvement of radio tracking accuracy for determining their masses and orbits.