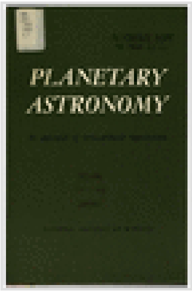

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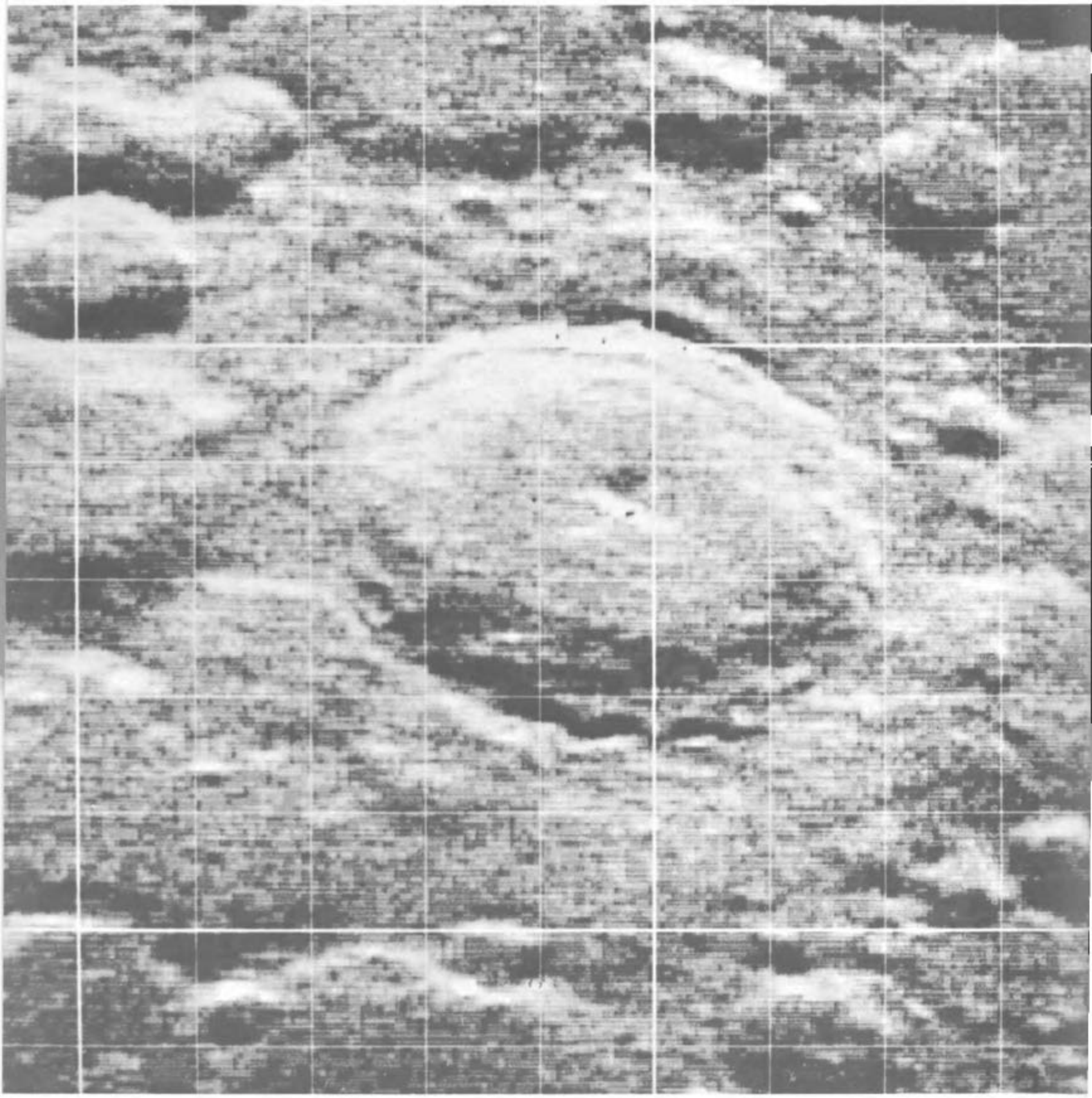

Map of the radar reflectivity at 3.8-cm wavelength for the region surrounding the lunar crater Tycho, made by the Haystack Microwave Facility. Surface resolution is approximately 1 km. (Courtesy MIT Lincoln Laboratory)

PLANETARY ASTRONOMY

An Appraisal of Ground-Based Opportunities

PANEL ON PLANETARY ASTRONOMY
SPACE SCIENCE BOARD
NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL

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Foreword

This volume presents the report of the Space Science Board's Panel on Planetary Astronomy convened to survey the present status and future needs of ground-based planetary astronomy.

Studies on space research conducted by the Board in 1962 and 1965 underlined the importance of ground-based planetary astronomy to complement and support planetary exploration with space vehicles and indicated the need for a thorough examination of the contributions that ground-based techniques can make to knowledge of our planetary system and the great questions of the origin and development of the solar system and life. In response to recommendations made at these studies, an *ad hoc* panel was formed in 1966 under the chairmanship of John S. Hall, Director of Lowell Observatory. Panel members were chosen to represent all pertinent scientific disciplines—astronomy, physical chemistry and biochemistry, geology, physics, geophysics, meteoritics, meteorology—and the observational, theoretical, and laboratory viewpoints.

The Panel was asked to evaluate the current state of knowledge in planetary astronomy; to indicate fields of ground-based astronomy likely to be particularly productive in the future; to assess and compare investigative techniques now in use or under development; and to make specific recommendations on present and projected requirements for personnel, personnel training, and new or improved facilities.

Individual panel members were assigned responsibility for preparing specific sections of the report; their papers were reviewed and incorporated at work sessions during the course of 1967. Consultants were called in to advise on some specialized topics; for example, a meeting of fifteen radio astronomers was held to advise on the potentialities of radio astronomy applied to study of the planets.

The Space Science Board is grateful to the panel members and specialists who contributed to this study. 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*
Space Science Board

Acknowledgments

A principal objective of the authors of this report has been to present their material briefly, in perspective, yet without oversimplification. The approach used here differs from that commonly employed in planetary surveys. To bring out more clearly the relationships within the system, the discussion, following a suggestion by Ann Wagoner of the Space Science Board staff, is organized according to the physical properties of interest to planetary astronomy rather than in an object-by-object sequence. This approach required far more effort and coordination than would otherwise have been the case.

The chairman wishes to thank each member of the panel and every contributor to this report. Each has exhibited a fine spirit of cooperation and a willingness to accept gracefully, and to carry out effectively, the tasks he was most competent to perform.

Several panel members contributed especially generously to the report. For example, Chapter 2 was written almost entirely by Elizabeth Roemer and Gordon H. Pettengill, and Chapter 4 is the work of Tobias C. Owen. The statistics in Chapter 7 were gathered by Bruce C. Murray. Cornell H. Mayer not only convened the conference of fifteen radio astronomers to discuss applications of the technique to planetary science but wrote nearly all the material pertinent to this field. Similarly, Pettengill contributed most of the material on radar, and Brian Mason is responsible for the sections on meteorites.

The advice and assistance given in the formative stage of this project by

Urner Liddel and William E. Brunk of the National Aeronautics and Space Administration were most helpful.

The chairman wishes to acknowledge gratefully the extensive assistance and advice rendered by Bruce N. Gregory of the Space Service Board staff in coordinating the project and in editing much of the report.

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1

Perspectives

INTRODUCTION

In classical times, men thought that Jupiter hurled thunderbolts at the unfortunates who displeased him. Recent detection of bursts of electrical energy from Jupiter appears to confirm one phase of this hypothesis; but it is obvious that during the intervening centuries the basis of proof required by mankind in its study of natural phenomena has undergone a radical change.

Planetary astronomy—the study of objects in the solar system—was for centuries the dominant field in astronomy. The advent of spacecraft and new instruments and techniques have given new impetus to the field.

There is reason to believe that despite their diversity the planets, satellites, asteroids, comets, and meteorites have a common origin: that they were created about five billion years ago at the same time the Sun condensed from the interstellar medium. Our present concern is to understand the planetary system—the details of its makeup and the relationships among its members. From studies now being carried out we hope to find records of our early history and clues to our future. Why does the planetary system look the way it does? Is it accidental, or is it in some sense typical of systems elsewhere in the galaxy? Is life unique to Earth, or does it exist elsewhere? The answers to these questions are some distance in the future, but the information we are gathering is part of the foundation for those answers.

CONTENTS OF REPORT

To establish an effective space program that is most likely to shed light on the origin of the solar system, a wealth of scientific background information is essential. In the case of the planets, we are still at the stage where more ground-based observations should and can make substantial contributions in the very near future. Requirements in both facilities and manpower must be defined in terms of the present status of the field and its future needs. That is the prime purpose of this report.

This report seeks to examine in perspective our present knowledge of the major scientific problems of planetary science and to discuss the specific objects in the solar system as they relate to these problems. Four chapters treat the dynamics of the planetary system, planetary surfaces, atmospheres, and interiors and magnetic fields. They are followed by chapters on new ground-based techniques and graduate training in planetary science. The report concludes with the Panel's prime recommendations concerning future developments in the field.

Some of the more important advances, described more fully in Chapters 2 through 5, which are likely to be made as a result of further ground-based observations are mentioned in the following paragraphs of this section.

The dynamics of the planetary system is a classical field of astronomy which has taxed the skills of mathematical pioneers since early in the seventeenth century. It is possible that Kepler discovered the reasons for "irregularities" in planetary motions in the same year in which Galileo first used a telescope for astronomical observations (1609). Two recent developments have given new impetus to ground-based activity in the field. One is the advent of the digital computer; the other is the tremendous increase in the range, accuracy, and resolution of radar, which adds the dimension of distance to measurements previously confined to angular position. The distance accuracy already achieved is so great that, when combined with traditional optical angular techniques, an improvement of several orders of magnitude can be achieved in the determination of some important orbital parameters.

As a result, the dynamical history of the planets and their satellites can be extended far into the past or projected into the future, and gravitational theories of fundamental importance can be subjected to extremely sensitive tests.

Ground-based radar and radio observations can now be used to study planetary surfaces. Radar can measure gradual slopes in planetary terrain as well as surface roughness. Radar measures of the Moon, when compared with high-resolution photographs, indicate that the accuracy of the method is very high.

Radio data can be interpreted to yield surface temperatures and, with very high resolution, the distribution of temperature with respect to place and time. Such measurements are of special interest for investigations by means of probes or landers into the existence of life on other bodies in the solar system.

The determination of relative abundances of various isotopes in planetary atmospheres as a function of distance from the Sun has a direct bearing on theories of the origin of the solar system. Such isotopic ratios can be compared with solar and cosmic abundances to give some idea of the fractionation processes that occurred during the formation and subsequent development of the planets.

The close association between the evolution of the terrestrial atmosphere and the development of life on Earth invites comparison with other planetary atmospheres to search for evidence relating to the possible development of extraterrestrial life. Applying this approach in reverse, a general understanding of the origin of atmospheres and the causes of the variety in their composition that we now observe can be expected to lead to new insights into the problems associated with the origin and evolution of life on Earth.

Finally, the opportunity to study the general and local circulations as well as condensation and deposition processes in atmospheres having radically different compositions, Coriolis forces, and heat budgets than our own will provide rigorous tests for meteorological theories that presently are limited to a single example.

A knowledge of the structure and composition of planetary interiors is important not only to a better understanding of the present state of the planetary system but also to understanding the manner in which the planetary system was formed and in which it evolved.

Observations of planetary magnetic fields cannot now be made from the surface of the Earth except by detecting radiation from charged particles trapped in the field; thus far only Jupiter has displayed such nonthermal emission. The study of this emission permits some understanding of the nature of the Jovian magnetosphere. This is of interest for comparison with the Earth's magnetosphere and may aid in understanding the processes underlying both. Changes in the Jovian magnetic field may well provide a clue to the processes taking place within the planet and on its visible surface.

RELATION BETWEEN GROUND-BASED AND SPACE OBSERVATIONS

There is little doubt that the most interesting discoveries in the planetary system will continue to result from space exploration in the form of probes, orbiters, or landers. However, the ground-based astronomer is in a position to assist his space colleagues materially. Since space measurements demand such long preparation, any new information their designers can get is of great importance. For example, improved ground-based measurements of the surface pressure of the Martian atmosphere supplementing data from the radio occultation experiment aboard Mariner IV have provided important data for the design of a Martian lander.

Ground-based observations are often more effective and are almost always considerably less expensive than measurements made in space. Ground-based instruments are capable of data rates several orders of magnitude greater than those of space instruments. They have a much longer useful lifetime than space equipment: lifetimes of several decades are not unusual for astronomical telescopes. Ground-based observations permit a degree of flexibility not approached by space techniques in that effective use can be made of recently acquired information and new technology. Spacecraft instrumentation, on the other hand, is designed several years before launch to make one type of observation. The data may thus be obtained by outmoded equipment or under conditions that had not been foreseen several years before. When the ground-based observer realizes that one technique is not obtaining the desired information, he is free to modify it or even abandon it in favor of another in a relatively short time.

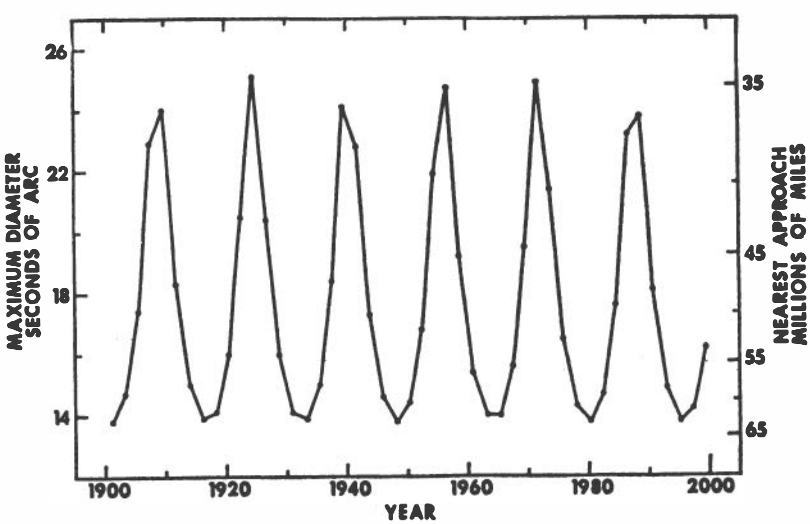

FIGURE 1 Oppositions of Mars during the twentieth century. The August 10, 1971, opposition is one of the most favorable.

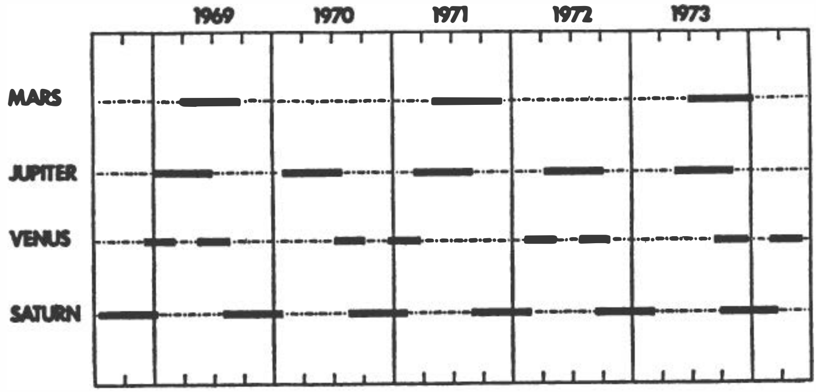

FIGURE 2 Favorable times for planetary observation, 1969–1973.

However, if ground-based astronomy is to make an effective contribution, the time element is an important factor: observations can be used best if the data are obtained and analyzed as far in advance of flights as possible. An additional time constraint is that the planets can be observed to advantage only at certain times: the most favorable times for observing Mars occur for only a few months every two years (Figure 1); there are similar but far less restricted opportunities for observing Jupiter, Venus, and Saturn (Figure 2).

Since a space measurement exchanges resolution for comprehensiveness (i.e., the higher the resolution, the more limited the area studied), it is extremely important to know how representative the spaceborne measurements are and to direct such devices as planetary landers to the most interesting locations. Such information can be provided by ground-based techniques.

Ground-based observations have limitations, however, which are largely caused by the Earth's atmosphere. One limitation is the result of the atmosphere's opacity to radiation of all but a few wavelength bands. Its opacity to gamma, x-ray, and ultraviolet radiation cannot be circumvented from the ground. Balloon techniques open up the ultraviolet to some extent, but observations outside the Earth's atmosphere are still necessary to obtain many important measurements in this region of the spectrum. The opacity in the infrared is somewhat more tractable; observatories at high altitudes in very dry climates open up several windows in the infrared, and airplanes flying above the tropopause permit further significant gains.

A second limitation on ground-based techniques is set by the turbulence of the terrestrial atmosphere. This turbulence places an effective limit on the resolution of which any Earth-based instrument is capable. For a number of years this factor restricted severely the information that could be obtained from several types of measurements. It is no longer clear, however, that we have reached the limits of resolution. Better observing sites have been found, and new techniques of image scanning and image reconstitution, discussed in Chapter 6, are now just beginning to be used in planetary astronomy. Considerable improvements in resolution have already been made, and the limits to which these techniques can be extended have not yet been evaluated.

New techniques in radio and radar planetary astronomy are just beginning to be exploited. Here limits are set not by the atmosphere but by instrumental characteristics; great increases in resolution are now technically possible.

We are fortunate that modern equipment and new observing techniques are becoming available at this time; the techniques of ground-based astronomy not only provide an opportunity to enrich our knowledge of the solar system but should also make it possible to ensure greater effectiveness in planning the space program.

2

Dynamics of the Planetary System

INTRODUCTION

Two recent developments have added new impetus to the study of the motions of the planets and their satellites. Planetary radar has added the dimension of distance to measurements previously confined to angular position, and the digital computer has permitted numerical solution of the exact equations of motion with far greater precision and speed than ever before possible. Because the computer has become an integral part of every scientific laboratory, it may not be necessary to stress its central importance to the solution of problems in celestial mechanics: classes of problems can now be undertaken which would otherwise remain inaccessible.

The significance of ground-based radar in the study of planetary motions rests on its ability to measure, with high resolution, the power-density distribution in time (delay) and frequency (Doppler) of the planetary echo. From these data the two-way light time to the surface of the planet can be inferred with an error which in some situations can be as small as a few microseconds. For the planet Venus, with which the most precise work has been done, the maximum echo delay is nearly 1,700 sec, yielding measurements that have a fractional precision of a few parts in 10^9. Using measurements of the Doppler-shifted frequency of the echo, the radial motion of the planet with respect to the radar can, under favorable conditions, be estimated to above 2 mm/sec, for a fractional precision approaching 10^{-7} near elongation. (For comparison it may be noted that a planetary angular determination can approach 0.″2 arc accuracy, which represents a fractional precision of about 4×10^{-7}.) A series of echo delay and Doppler measurements in combination with angular positions obtained by traditional optical techniques can be reduced to yield an improvement of several orders of magnitude in the accuracy of determination of some of the orbital parameters.

Granted that any improvement in the accuracy with which planetary parameters may be estimated will be eagerly awaited by students of orbital mechanics, what significance would it have to the larger scientific community? As planetary orbits, masses, and rotations become known more precisely, theories that purport to explain the dynamical history of the planets and their satellites will also require refinement. Certainly any tests that can verify or disprove the several theories of gravitation will have wide interest. The high accuracy of delay measurements obtainable with radar makes possible a number of such tests, as described below.

Improved orbital parameters are basic to the design of accurate space-probe trajectories to the planets and comets. The recent successes of the Mariner series of probes would have been compromised without access to the results of ground-based planetary radar, and the planning of missions to Jupiter and its satellites should similarly benefit from improved determinations of their orbits.

In the process of reducing radar measurements of a planet's motion, a number of other characteristics of the planet, such as its mass, radius, and shape, must also be taken into account. In some cases, these by-products may have interest equal with the improvement in the basic orbital parameters. Because the systematic errors associated with radar measurements affect the results in a manner qualitatively different from those accompanying optical observations, the presence of systematic errors in both types of data can be detected more accurately through cross-checking.

A few of the ramifications of the new techniques in celestial mechanics which appear to be of exceptional interest have been selected for more detailed discussion. These topics include the testing of gravitational theories and some studies involving the orbits of planets and comets.

TESTING OF GRAVITATIONAL THEORIES

Since the time of Newton, the solar system has served as a testbed for gravitational theory. Three of the classic tests of the general theory of relativity involve the solar system, namely, the gravitational deflection of starlight, the additional advance in the perihelion of Mercury, and the red shift of solar spectral lines. A way to more definitive testing of the general theory and its alternatives is now open with the precise measurement of propagation time by planetary radar.

In discussing the ways by which gravitational theory may be tested, it is useful to distinguish between (1) gravitational effects on the propagation of electromagnetic radiation and (2) perturbations (as compared with Newtonian theory) introduced into orbital motions in the solar system. The first category comprises not only the classical attempts to measure the apparent bending of starlight that passes near the solar limb but also the more recent proposal to measure the apparent retardation in propagation velocity along a similar path, made possible by the use of radar time-of-flight data. In the second category are included the additional secular advances of planetary perihelia and periodic orbital perturbations.

A number of attempts have been made during eclipses to observe the apparent displacement of a star when viewed near the solar limb. Because observing conditions for astrometry near the Sun are far from ideal even during an eclipse, and suitable target stars are often not favorably located, a positional accuracy of not much better than a few tenths of a second of arc can be obtained. Since the effect is typically of the order of about 1 sec of arc, the level of verification is very poor.

It has been suggested that interferometric observations at centimeter radio wavelengths of quasi-stellar sources (such as 3C279) might yield a positional accuracy near the Sun considerably better than that achieved optically. Because of the perturbing effects of the coronal plasma at radio frequencies, it will be necessary to obtain measurements at several wavelengths to separate dispersive plasma effects from nondispersive gravitational effects. Nevertheless, measurements can be made more regularly since eclipse conditions are not required and since optical limitations such as weather and seeing are not present to the same degree. The level of accuracy to which an angular displacement test based on radio observation could be pressed is not clear, but it very probably would surpass the present level of optical verification.

A second and potentially more precise verification of the predicted effects of gravity on the propagation of electromagnetic waves involves their measurable retardation near the Sun. A two-way radar ray path connecting Earth and Venus at superior conjunction and grazing the solar limb should show a retardation of about 200 μsec in addition to that calculated on the basis of uniform propagation at the speed of light. As the angular distance of the target from the Sun increases, the relativistic contribution to delay diminishes approximately as the logarithm of the inverse angle of elongation. At a distance of four solar radii (1°) the effect still amounts to about 150 μsec and represents a feasible measurement.

In the second category, involving dynamical effects on planetary motions, nearly two centuries of optical observation of Mercury has verified the additional secular advance of perihelion to an accuracy of about one percent of the effect (43 sec of arc per century) predicted by the general theory of relativity. Radar observations to an accuracy of 10 μsec, when continued over three years, should reduce the measurement error to less than 0".2 and should provide a useful determination of the magnitude of the effect in the orbits of Earth and Mars. In the general theory, the effect, expressed as perihelion advance per unit time, varies with the orbital semimajor axis, a, as $a^{-5/2}$. The advance resulting from a quadrupole moment in the solar gravitational field, on the other hand, varies as $a^{-7/2}$. Given sufficient accuracy and duration of measurement it should be possible to distinguish these two predicted contributions by comparing the values obtained for Mercury, Earth, and Mars and perhaps Venus as well.

Also in the second category of dynamical effects are included periodic perturbations of the orbits of the terrestrial planets, which if confirmed may establish the presence of a quadrupole term in the solar gravity. A precise calculation demonstrating a distinction between the effect of these perturbations and that of, say, general relativity has not been completed. Estimates, however, seem to place the periodic terms at a magnitude amenable to radar investigation.

Improved determinations of planetary orbits may also be applied to a closer examination of the possible time-dependence of the gravitational constant. It is known from observations that are presently available that the time-dependence cannot be greater than a part in 10^{-9} per year, whereas theory suggests a variation of as much as 10^{-10} per year. With the accuracy in delay measurement improved to the level of a microsecond, it should be possible after several years of radar observation to achieve a sensitivity of the order of 10^{-11} per year in this variation.

Many of the tests discussed in this section conceivably could be performed by an artificial solar satellite, suitably instrumented with radio and perhaps optical transponders. One advantage of the satellite would be our ability to determine its position at any moment with very high precision. Observations over a period of time are required, however, to establish with certainty many of the effects of interest here, and one must be concerned during this interval with vehicle accelerations arising from the unpredictable effects of solar radiation pressure, residual gas leakage, and the like. If the probe were in orbit around a planet, however, or better yet, landed on the surface, highly precise measurements of the planetary orbit would be facilitated.

OUTER PLANETS, ASTEROIDS, COMETS, AND SELECTED PLANETARY SATELLITES

At great distances and for the study of small objects, optical observations have major importance. More optical observations, extended to fainter magnitudes, are needed to determine, for example, the positions of the more remote major planets, of the smaller and fainter planetary satellites, and of asteroids and comets. Four satellites have been discovered within the last two decades, but fewer than a dozen positions of one of them, Jupiter XII, have been measured since the first determination of its orbit in 1952. All the comets and some of the asteroids discovered each year have orbits of sufficient interest to warrant more than superficial attention. Even so, not a single accurate position was reported for more than a month following the discovery of a recent naked-eye comet. Preliminary computation of its orbit was complicated by the need to adjust a collection of positional observations which by modern standards were of very low precision.

Positional observations of planetary satellites are important, first, to determine two-body orbital elements, then, as increased precision is gained through continued observations, to evaluate (1) secular effects arising from deviations from spherical symmetry in the internal density distribution in the planet and (2) gravitational interactions among satellites.

The asteroids, which are generally confined to the belt between the orbits of Mars and Jupiter, show striking avoidance, in the detailed distribution of their orbits, of certain simple fractional values of the period of Jupiter and a clustering around other values. The present distribution of asteroid orbits is believed to reflect conditions that prevailed during the formation of the solar system as modified by subsequent interactions of asteroids with each other and with other bodies in the solar system. Extension of precise observations of position to fainter magnitudes and to the longest possible orbital arcs is fundamental to a study of the dynamical evolution of asteroids and comets and to a determination of the place where comets originate. Interested astronomers are concerned over the paucity of current observations, which is sufficiently serious for some objects to risk losing track of them.

It seems well established that collisions resulting in progressive fragmentation occur between asteroids. Chemical and physical characteristics of most meteorites suggest that they have undergone processing within bodies of asteroidal size, and the few reliable atmospheric trajectories available are not inconsistent with asteroidal origin of meteorites.

The marked variation among meteorites raises questions of whether asteroids have comparable differences and variations in composition and whether their physical properties are related to orbital characteristics. The relative importance of collision processes can be evaluated from an analysis of the asteroidal size–frequency distribution. As a basis for such analysis, statistically interpretable physical and orbital data extending to fainter magnitude limits are needed.

In addition to the broader questions on physical and dynamical characteristics, certain asteroids are of special interest because of their unusually close approaches to the Sun, to the Earth, to Mars, or to another asteroid. Certain kinds of orbits are of special theoretical interest in celestial mechanics. Among them are those that exemplify the stable special solution of the restricted problem of three bodies and those whose perturbations reinforce through commensurabilities of the mean motion with Jupiter. It is useful to investigate the secular stability of some of these special classes of orbits, since the findings may be related to the capture or loss of planetary satellites. Relatively short-lived asteroid classes, such as those that cross the Earth's orbit, are of interest as the most immediate source of meteorites.

The presence of large amounts of volatiles in comets suggests that they are recent arrivals in the inner planetary system that have never spent an appreciable time in the vicinity of the Sun. Otherwise, most or all of the easily vaporized constituents would long since have been lost. The location of the reservoir from which they come, and such evolutionary effects on periodic comets as rates of mass loss, can be investigated by a careful study of comet motions. It must be noted, however, that the observed arc, even when observations are extended to the brightness limit of available telescopes, represents only a very small portion of the complete orbit of a nearly parabolic comet. Observations of even short-period comets have extended over as much as half of the orbit in only two cases.

The complex gravitational interactions of major planets with each other and with comets will require careful evaluation as improved determinations of distances, planetary masses, and orbital elements are obtained through refinement of classical techniques and from radar observations. To separate inadequacies in the application of gravitational theories from the effects associated with physical evolution of asteroids or comets is an important and challenging task. Execution of the complex calculations to the required order of precision has become practical only through use of modern high-speed digital computers.

Observational-selection effects strongly influence discovery of small asteroids and comets. Asteroid orbits, and orbits of short-period comets, are concentrated near the plane of the Earth's orbit, while orbits of nearly parabolic comets have, as far as is known, random orientations. The paucity of observatories in the Southern Hemisphere militates against discovery of comets having only a small part of their orbits north of the ecliptic plane and against detecting asteroids in orbital longitudes that correspond to opposition during the short nights of the northern summer season. A search program designed to sample volumes of space to a specific magnitude would add important weight to statistical data on sizes and orbit distributions of asteroids and comets. Special efforts would also be usefully directed toward the discovery and observation of asteroids crossing the Earth's orbit.

3

Planetary Surfaces

INTRODUCTION

Recently developed techniques promise to lead to a considerable increase in our knowledge of lunar and planetary surfaces. A much greater potential than had previously been realized has been demonstrated for investigating, with ground-based equipment, the surfaces of the planets in the visual, infrared, and radio regions of the spectrum. Techniques for investigation in other spectral regions may be expected to be developed as more extensive Earth-orbital facilities becomes available.

Our best information on the age and history of the Earth is derived from study of its surface structure. A detailed knowledge of the composition and structure of the surfaces of other objects in the solar system should provide us with similar information on those objects and lead to greatly improved knowledge of the origin and evolution of the solar system.

Comments on the information to be obtained from the study of planetary surfaces must be largely confined to the terrestrial planets—Mercury, Venus, and Mars—as well as Pluto and the satellites of the giant planets, whose solid surfaces are comparable with Earth's. The surfaces of the outer planets—if solid surfaces indeed exist—are blanketed by extremely deep and opaque atmospheres and are virtually inaccessible to study.

DIAMETERS AND ROTATION

Radar techniques have recently determined the diameters of Venus and Mercury to an accuracy of several kilometers, a precision far exceeding that achieved previously by telescopic observation. A very accurate upper limit to the diameter of Pluto was also determined recently by astrometric measurements made as the planet nearly occulted a star.

A planet's rotation can be used to infer some characteristics of its internal structure (Chapter 5) and the dynamics of its atmosphere (Chapter 4). It is, of course, relatively simple to measure the rotation of those planets that present easily identifiable surface markings by noting the times of meridian passage of these markings. Despite the recent important contributions of radar to the determination of the rotation of Mercury and Venus, telescopic inspection and photography remain the most accurate methods for studying the rotation of Mars and Saturn, while optical and radio measurements are essential for studying the rotational structure of Jupiter.

The markings observed on Jupiter are cloud features. These structures appear to move relative to each other at the same latitudes, as well as to display systematic differences in rotation for zones located at different latitudes. The rotation periods of these features around the Jovian axis can vary from the planetary average of just under 10 h by as much as ± 5 min; the rotational period is shortest near the equator. Radio measurements indicate rotation of the Jovian magnetic field which may be linked to the body of the planet; they are discussed in Chapter 5.

No distinct clouds are normally visible on Saturn, only belts parallel to the equator. These belts have differing tonal values but no discernible structure. Occasionally, prominent clouds do appear and last long enough (a month or more) to allow their rotational period to be determined with some precision. The results indicate that, as with Jupiter, the period is shortest near the equator and longest at high latitudes. This curious phenomenon has also been observed by careful analysis of the Doppler shifts in the solar spectrum reflected by the planet. The rotational period of Saturn's cloud features varies by as much as 11 percent, being roughly 10 h at the equator and 11 h at high latitudes. The very large shear motions between cloud zones at different latitudes are responsible for the comparatively short life of Saturn's spots, which are observed to be stretched out longitudinally in a matter of weeks and, eventually, to merge with the belts.

Telescopic determination of the rotation of Mercury and Venus has been difficult. Nearly a century ago markings were discovered on the surface of Mercury, but these did not move as rapidly as on Mars and became confused with the changing phase of illumination. It was assumed that Mercury had a long period of rotation, probably equal to its orbital period (as in the case of the Moon), and most optical observations were biased toward this value. Radar measurements have recently shown that the rotational period is actually about 59 days, or two thirds of the orbital period. A re-evaluation in the light of this discovery revealed that the visual observations are compatible with this unexpected result (in fact, more so than with the former assumption), and a new map of the surface markings has been constructed.

Venus shows telescopic markings in visual light only on rare occasions, when features with low contrast are observed. In the ultraviolet, a cloud pattern can sometimes be seen which appears to move in a retrograde direction across the planet at a speed corresponding to a rotation period of about 4.5 days. No data on the period of rotation of the solid planet were available, however, until radar measurements were first made in 1961. Since that time, precision has steadily increased, and the rotation period is now established as close to 243 days retrograde. This result is totally unexpected both for its retrograde direction and because the period appears to agree with a resonance in which Venus presents nearly the same face toward the Earth at each inferior conjunction. The connection between the Earth's orbital revolution and the rotation of Venus is not understood and will likely prove extremely important as a clue to the origin and early history of the solar system. The significance of the different period of the moving cloud pattern as seen in the ultraviolet also remains to be determined, but the differences are probably a manifestation of the complex planetary atmospheric circulation whose nature is entirely obscure.

The rotations of Uranus and Neptune have been determined spectroscopically in the same way as for Saturn, but the precision of current values is inadequate. Greater precision would be useful in improving the oblateness values derived from rotation for comparison with the oblateness as determined dynamically from observations of these planets' satellites. Such a comparison should yield further information on the distribution of mass between the surface and center of the planet.

THERMAL PROPERTIES

Temperature is a fundamental parameter of planetary surfaces that can be determined by ground-based observations. Mean temperature and temperature range are of great interest to biology because of their relevance to the existence of life. Temperature distribution and its variation with solar illumination provide information on thermal and electrical surface properties.

Temperature as measured by infrared or radio detectors properly applies only to the wavelength region measured; that is, the brightness temperature so obtained refers to the temperature of a blackbody that would emit the same intensity in the given spectral band. Since no surface is a perfect blackbody, measurements taken over a very wide range of wavelengths provide information about the actual radiating properties of the surface. In addition, measurements at the longer radio wavelengths yield data on subsurface emission, while measurements at shorter wavelengths can provide information on the degree and nature of atmospheric absorption.

Radio Measurements—Low Resolution

Planetary emission is most simply measured by including the entire disk of the planet; these measurements require less sensitivity and resolving power. Both the sunlit and unilluminated hemispheres of the inner planets can be measured; however, the geometry of the Earth's orbit limits observations of the outer planets largely to sunlit hemispheres.

Wavelengths longer than 3 cm are required to penetrate the atmosphere of Venus and to measure its surface temperature. From the outset, radiometric observations proved surprising. The first measurements of the unresolved disk of Venus in 1956 were made in the range of 3 to 10 cm and showed a radiation temperature of nearly 600°K. So high a temperature had not been anticipated, and for a number of years many scientists were reluctant to believe that it represented the true temperature of the surface. As a result, these measurements were important considerations in designing the experiment complement of Mariner II.

More recent measurements of the dark side made at a number of wavelengths indicated a nearly constant-temperature blackbody at about 600°K but with a sharp decrease in energy at wavelengths less than 3 cm. This energy distribution was interpreted as thermal radiation from the hot surface of the planet with absorption and emission at wavelengths shorter than 3 cm in the progressively higher and cooler atmospheric layers.

A gradual decrease in the disk brightness of Venus at wavelengths longer than about 20 cm has not yet been satisfactorily explained, and further work is needed.

The first radio measurements of Mercury also seemed anomalous. In 1962, the planet's emission at 3 cm was found to be much higher than that expected if one hemisphere were in perpetual darkness. These results were confirmed in 1965 when measurements made at 11 cm over a wide range of illumination showed the temperature of the disk to be nearly constant. Radar observations have subsequently shown that the sidereal period of rotation, rather than the expected 88-day sun-synchronous value, is 59 days; all parts of the planet are periodically heated by the Sun. More recent observations reveal phase effects at shorter centimeter and at millimeter wavelengths, as would be expected from radiation which originates just beneath the solid surface.

Observations of Mars over the wavelength range 3 mm to 20 cm show a disk brightness temperature near 200° with a slight dependence on solar distance. Attempts to detect radiation from Mars at wavelengths as long as 1.5 m have not been successful, giving no evidence for appreciable non-thermal radiation nor for ionospheric or atmospheric effects, consistent with the findings of Mariner IV.

Radio Measurements—High Resolution

Although present knowledge of planetary surface temperatures has, at radio wavelengths, been based primarily on the observed emission from the entire disk of each planet, it is important to consider what has been achieved, or might be in the future, with significant improvements in radio facilities. The emphasis should be laid on increasing angular resolution and sensitivity at wavelengths which have already been used extensively. High-resolution radio mapping of planetary surfaces can define the apparent temperature distribution over the disk, as well as its variation with the observed polarization, thus permitting more detailed and meaningful determinations of surface properties.

The first high-resolution radio observations of Venus used ground-based fan-beam scans at 3-cm wavelength with the narrow dimension comparable to the disk. Later, 1.9-cm scans from the space probe Mariner II were obtained with resolution of about one sixth the disk. Both indicated limb darkening consistent with the hot-surface interpretation. More recently, a significant series of observations using a high-resolution interferometer at 10 cm has measured the general features of the radio emission over the disk and revealed a brightness at the equatorial limb slightly higher than at the center of the illuminated side and about 25 percent higher than at the polar limb. As originally reduced, the observations were consistent with radiation from a smooth sphere with a dielectric constant of 2.2. Subsequently, a correction derived from the radar estimate of surface roughness has raised the dielectric constant to 2.5. Despite this correction, this value is still less than the dielectric constant of 3.7 derived from the 12.4-cm radar reflectivity, but a large part of this can likely be explained by the absorption of radio waves in the atmosphere of Venus. Discrepancy appears between values for the dielectric constant of the Moon derived from radio and radar observations and shows the incompleteness of our knowledge of the surfaces of these bodies.

High-resolution observations of Mars can provide a detailed picture of the dependence of the subsurface temperature on the phase of solar illumination and permit deductions on the thermal and electrical properties of subsurface layers. If the seasonal wave of darkening involves structural changes such as might accompany growth of vegetation, a simultaneous change in the polarization might be detected.

The small diameter of Mercury's disk requires an angular resolution of a few seconds of arc to achieve even crude resolution. High-resolution studies similar to those done on the Moon would require 300 times greater resolution than is presently available.

Considerable thermal mapping of the Moon at radio wavelengths has been carried out at a much higher relative resolution than can be achieved for the planets. Past observations have given some ideas of the gross thermal and electrical properties of the lunar surface. Although *in situ* measurements may soon replace remote observations, ground-based data should still be valuable as a source of information on large-scale inhomogeneities in subsurface properties. Also, the value of remote observations of all planetary bodies will be increased when direct calibration of Earth-based observations can be made using *in situ* lunar measurements.

Present low-resolution observations of lunar radio emission over a wide range of wavelengths suggest a small increase of temperature with depth beneath the surface. If confirmed, these findings would be important in determining the thermal budget and structure of the Moon. The observations, which require very accurate absolute calibration over a wide range of wavelengths, should be repeated.

Visual and Infrared Measurements

In recent years, there has been a great increase in the number of studies of the lunar surface by infrared techniques. These measurements show that the lunar surface has a very poor ability to conduct heat. Mild and broad variations of thermal conductivity have so far correlated with an age classification system recently developed by lunar geologists and based on the degree of rounding of originally sharp surface features. Thus, perhaps the same agent of cosmic erosion-deposition that increasingly subdues crater rims with time leads to the increasing accumulation of a highly insulating crust. Hot spots on the lunar surface have been found from observations of the night side of the Moon and, even more dramatically, the eclipsed lunar surface, in the 8–14- and 20-μ atmospheric windows. These spots are indicative of differences in surface structure or composition. The surface of Mars can be studied in detail in the visible and infrared using large ground-based telescopes equipped with new detectors. A considerable improvement in resolution can be obtained if such observations are combined with area scanning (see Chapter 6). Also, a direct improvement in resolution will result from the more favorable oppositions of 1969, 1971, and 1973, when the disk of the planet will have a maximum angular diameter of 19″.5, 24″.9, and 21″.4, respectively.

Detailed knowledge of Martian surface temperatures in critical regions such as at the edge of the waning polar caps, or in other areas when changes such as the wave of darkening occur, should add valuable clues to the nature of the surface.

When area scanning is combined with a photoelectric spectral scanner, many detailed surface and atmospheric features are revealed. In fact, it may be possible to separate the surface and atmospheric phenomena by means of polarization-phase observations obtained in different spectral regions.

A number of unsuccessful attempts have been made in the infrared to measure the temperature of the dark hemisphere of Mercury. The sunlit hemisphere has a temperature of about 620°K, while the upper limit for the dark-hemisphere temperature is 150°K.

SURFACE STRUCTURE

The detailed structure or geography of a planetary surface, in addition to its intrinsic interest, often provides insight into the nature of internal and external forces acting to modify that surface. High-resolution photographs from the surface of the Earth and from orbiting and landing space probes have provided a wealth of information about the lunar surface. With the exception of a very limited sequence on Mars from Mariner IV, however, we do not at present have a similarly detailed picture of the surface of any planet other than Earth.

The difficulty in acquiring optical information on the detailed structure of planetary surfaces is directly related to their distances. For example, even at its most favorable opposition, Mars is still about 150 times farther away from the Earth than is the Moon. A resolution of 0″.2 in telescopic photography under ideal conditions from the surface of the Earth, which corresponds to about 380 m on the surface of the Moon, thus is equivalent to about 50 km on the surface of Mars. It is clear, therefore, that telescopic study of planetary surfaces, while extremely useful in studying large-scale variations, does not provide the detail that we would like.

Earth-based radar can provide considerable data on the statistical properties and distribution over the planet of small-sized surface material. As compared with Earth-based telescopes, radar is capable of relatively high resolution and, in the case of Venus, has the advantage of penetrating the atmospheric cloud layers.

Two types of radar interaction with the surface of a planet can be distinguished. One is a quasi-specular reflection from relatively smooth but inclined surface undulations. In this case, the high degree of coherence of the incident wave is largely preserved on reflection, and backscattering is confined to angles near normal incidence. The other involves a scattering from small, wavelength-sized irregularities. Such irregularities cause considerable depolarization and scatter significantly over a wide range of angles of incidence. By observing the planetary radar scattering law in several polarizations and over a spectrum of operating wavelengths, it has been possible to gain information on both types of scattering for the Moon, Mercury, Venus, and Mars. The mean inclination of the relatively large-scale (as compared with a 70-cm radar wavelength) surface undulations varies from a typical value of 3° for Mars and 6° for Venus to approximately 10° for the Moon and Mercury. The average number of wavelength-sized surface irregularities per unit area is about the same for all the targets studied, although relatively less is known about this component for Mars and Mercury.

By taking advantage of the coherence of radio waves reflected from the lunar surface, it has recently become possible to draw radar maps of the distribution of reflected power on the Moon. The basis of the technique is a form of aperture synthesis and is related to the method currently used in airborne "side-looking" radar systems. A description is given in Chapter 6. Because of the large effective apertures that can be brought to bear, and because the atmosphere introduces far less distortion in the phase of radio waves than it does at optical wavelengths, the technique is particularly attractive as a means of mapping the planets. A result recently obtained for the Moon is shown in the Frontispiece, where a surface resolution of about 1 km has been achieved.

As larger radar systems become available, it should be possible using this technique to map the distribution of reflected power across Venus and Mercury, with a surface resolution far in excess of that presently obtainable with ground-based optical telescopes. Radar mapping of Venus has already been initiated. The fine delay resolution of radar also makes available a direct determination of the planetary topography along the track of the portion of the planet lying nearest the radar. Although limited to the tropical latitudes of a planet, this type of direct measurement is invaluable in studying equatorial shape.

PLANETARY COMPOSITION

Detailed analysis of planetary composition requires the soft landing of payloads on the planets. Surveyor V made the first such analysis of a very limited area of the lunar surface by measuring the backscatter of alpha particles. Oxygen, silicon, and aluminum were identified, and the general chemical composition of the maria sampled is similar to that of a basalt. This finding has been interpreted as favoring the hypothesis that differentiation has occurred in the Moon as the result of partial or fractional melting.

Our only other direct knowledge of the chemical composition of solid matter in outer space stems from meteorites. Although recovered meteorites are extremely small samples of the planetary system, their unique availability makes their study a matter of great importance, an importance which should grow as their origins are identified.

Meteorites differ in composition and structure from terrestrial rocks and contain minerals unknown in the crust of the Earth. In bulk composition they range from almost pure nickel–iron, through various mixtures of metal with meta- and orthosilicates of iron and magnesium, to almost pure magnesium metasilicate. Minor amounts of the other naturally occurring elements, hundreds of isotopes, and a wide variety of minerals have also been found. The isotopic composition of most of the elements is similar to that of terrestrial rocks; where it differs, the differences are usually in the light elements where terrestrial geological processes have resulted in isotopic fractionation of a different character.

Studies have revealed a complex history in meteorites of crystallization, accumulation, breakup, reaccumulation, and possibly long-term thermal metamorphism. Isotope studies have shown that meteoritic matter was formed 4.5 billion years ago, probably shortly (100 million years) after nucleosynthesis. The meteorites are thus the oldest, and some of them the least differentiated, rocks known. They contain information about the parent body breakup which exposed them as relatively small bodies to cosmic rays; one such major event appears to have occurred about 500 million years ago. It is not clear whether meteorities were formed from one or several parent bodies. If they originated on a planet, most, if not all, were formed on or near the surface.

The apparently short length of time between nucleosynthesis and meteorite formation, together with indications that all stony meteorites cooled sufficiently within about a million years to retain xenon, are of fundamental importance to an understanding of the origin of the solar system. Continued work on the xenon isotopes and other rare gases, coupled with careful petrological and geochemical studies of the meteorites, will give a more accurate time scale for the early stage of the formation of the solar system.

The Prairie Meteorite Network is currently being used to obtain orbits, masses, and densities for bright meteors. No meteorite observed with this network has yet been recovered, but there are indications that the observed fireballs are caused by large masses of low-density material, possibly related to carbonaceous constituents. If accurate orbits of recovered meteorites can be obtained, they may give additional information on the origin of meteors and their relation to comets and asteroids.

Information on the specific composition of planetary surfaces is extremely difficult to obtain from ground-based observations. Under ideal conditions, most natural rock-forming minerals either emit, absorb, or reflect radiation in a sufficiently individual pattern to permit identification by comparison with a reference standard. The potentially useful region of the electromagnetic spectrum extends from gamma rays to microwaves, but severe limitations are imposed by the opacity of the Earth's atmosphere to radiation in many of these spectral regions.

The Earth's atmosphere (as well as a number of planetary atmospheres) is opaque to gamma rays, x rays, and a major region of the ultraviolet. The near ultraviolet, however, is available and is usable in mineral identification. Laboratory studies show that many natural rocks luminesce in the ultraviolet when subjected to appropriate excitation. The resulting spectra, usually broad-band and extending into the visible, indicate that the intensity of the luminescence is higher for granitic than for basaltic rocks. It has not yet been demonstrated that useful mineralogy can be done by this technique, but the indications are that further laboratory work would be valuable.

Most of the visual work has been based on the assumption that albedo is indicative of gross composition. This assumption is, at best, dubious; several processes acting on planetary surfaces alter albedo in a manner that is to some extent independent of composition. Pulverizing tends to lighten material, sputtering may darken, and ultraviolet may bleach; the interactions and absolute effects are largely unknown.

Planetary surfaces exhibit a range of colors and polarizations, but, with the exception of the vaguest generalizations, it is almost impossible to associate these data with any particular mineral or rock.

Spectroscopic studies of the infrared radiation from planetary surfaces have had particular appeal, because silicate minerals exhibit several infrared absorption bands and are thought to be dominant on many planetary surfaces. Unfortunately, it has been demonstrated in the laboratory that as rock particles approach micron size, band structure is substantially modified and interpretation becomes difficult. The particle size of the lunar soil is sub-millimeter, possibly tens of microns in diameter, and there is reason to believe that the soil of other planets may be characterized by similar dimensions. Meaningful comparative and absolute studies are possible, however, and more measurements in the 8–14-μ window, together with further laboratory studies, should be pursued.

The use of radar or radiometric microwave measurements does not appear promising as a diagnostic tool for surface-material identification, except with regard to its mean density.

Although very little, if indeed any, positive identification of planetary surface composition can be made from Earth's surface, ground-based techniques can provide significant information in combination with spaceborne investigations.

The use of remote sensing as a differentiating tool does not depend on the ability to account for the detailed characteristics of the sensed spectrum, but only on sufficient spectral resolution and sensitivity to find differences among areas. Since relatively few locations on planetary surfaces will be sampled *in situ* by men or instruments, those that are sampled will be sites of particular interest to those engaged in remote sensing. It should then be possible to correlate spectra with composition and extrapolate to regions where remotely obtained spectra, but no direct information, are available.

SURFACE VARIATIONS

The sources of variation within the planetary system are diverse: the changing polar caps of Mars and the associated wave of darkening are surface effects; the changing patterns of Jupiter's belts are atmospheric effects; and the changing brightness of asteroids may be the effect of surface roughness, albedo, irregular shape, or all three.

Even the apparently dead surface of the Moon is not without change. Occasional emissions of light in the dark areas of the Moon have been reported by very competent observers for more than 200 years. With the possible exception of a single spectrogram, none has been photographed, and no satisfactory explanation has been advanced as to their origin or nature. Systematic searches for emissions in the visual region should be continued. If emissions occur, and especially if they can be observed spectroscopically, they would provide valuable information regarding the lunar subsurface.

In contrast with the Moon, almost continual change characterizes the Martian atmosphere and surface. The seasonal growth and disappearance of the polar caps, associated changes in surface coloring, and the wave of darkening, are of particular interest, in part because they suggest biological activity. Portions of the disk are sometimes obscured by vast dust storms, and clouds are observed to form over certain regions and move over the surface of the planet. The transparency of the entire atmosphere, especially in the near ultraviolet, can change dramatically in relatively short periods of time.

The surface of Venus is always hidden by clouds, but changes in the cloud structure, especially in the ultraviolet, have been reported. Further understanding of the meteorology of Venus must wait until a long-term photographic survey of the planet has given a more detailed picture of the motion of the clouds. The cloud belts of Jupiter have long been noted for their variability. A detailed study of the changing appearance of its apparent disk is of value, not only for meteorological information but also because of possible relations between the clouds, the interior of the planet, and its magnetic field (see Chapter 5).

Variability is also important to studies in celestial mechanics. Light variations of the satellites of the major planets and the asteroids can assist in determining the speed and sense of rotation and the direction of the rotation axis in space and in giving some indication of the shape of the object. Observations of this type have thus far been confined almost exclusively to some of the brighter minor planets and Pluto.

All the variations have in common the need for observations carried out on a regular basis. For some objects, one observation every night or so may be sufficient; for others, ten or more an hour may be desirable. Regular observations for a continuous period of time will require a worldwide network of telescopes, since one observatory can follow a given object only for a limited time, determined by the position of the object in the sky and by the longitude, latitude, and elevation of the observatory. These telescopes must be well distributed in longitude and devoted primarily to planetary work. Because of the scarcity of telescopes with apertures as large as 24 in., additional telescopes will have to be provided if the monitoring program is to give adequate coverage.

4

Atmospheres: Planets and Comets

INTRODUCTION

The most powerful method that has been employed in ground-based observations of planetary atmospheres is spectroscopy. Polarimetry, photometry of both reflected and emitted energy, and photography are also useful techniques, and both radiometric and radar observations can probe otherwise inaccessible regions in optically opaque atmospheres. With each of these techniques, the basic procedures are the same: to observe the given object, to interpret the observations with the help of laboratory calibrations and physical theory, and to develop comprehensive atmospheric models. Substantial progress in all three areas is required if a thorough understanding of planetary atmospheres is to be achieved.

Our own atmosphere constitutes one of the greatest obstacles to ground-based observations by restricting them to severely limited regions of the electromagnetic spectrum. Techniques for overcoming this obstacle without resorting to space probes are rapidly becoming available and have permitted significant new observations. Among these methods are ultraviolet spectroscopy from rockets, infrared spectroscopy from high-flying aircraft, and the new interferometric spectrometer technique developed by the Connes. Since the latter instrument is presently ground-based, observations are confined to atmospheric windows, but the gain in resolution over conventional methods has produced an amount of new data comparable with that expected from observations made above the atmosphere. Data of even higher quality may be obtained by using this instrument and its analogs at a drier site or on high-flying aircraft. Eventually it may be used in Earth orbit.

ORIGINS OF ATMOSPHERIC GASES

The commonly accepted division of the planets into two main groups is in accord with a difference in the composition of their atmospheres. The inner or terrestrial planets appear to have secondary atmospheres derived from outgassing. The outer or Jovian planets have reducing atmospheres containing large amounts of hydrogen, which strongly suggest an origin similar to that of the solar system itself. Comets probably represent a distinct third category, originating from evaporated icy conglomerate material. There are compositional differences within these broad categories, and detailed studies of these differences should throw light on the formation and evolution of the planetary system.

In the outer solar system, better values are needed for the relative abundances of both light and heavy elements and their isotopes. Present evidence suggests that relative abundances in the atmospheres of Jupiter and Saturn are similar to the solar values, but Uranus and Neptune have less light gases. These conclusions are consistent with observed planetary densities but cannot be accepted as definitive until more precise measurements are made. In particular, there is as yet no direct evidence for the presence of helium in the atmospheres of the outer planets, although it is generally assumed that this gas must be a major constituent. Knowledge of isotopic ratios would materially aid in determining the kind and extent of fractionation (and possible isotope formation) that occurred in the early history of the solar system. From such data, it may be possible to deduce the intensity of solar activity during the Sun's earliest evolutionary phases.

Among the inner planets, Earth appears to be the great anomaly. Assuming that our atmosphere is the result of crustal outgassing, its composition in the absence of chemical reactions with the crust and biosphere would be very similar to that presently observed on Venus and Mars, with the exception of the large amount of water found on Earth. It thus seems likely that the atmospheres of these other terrestrial planets are also secondary, but this assumption must be tested more rigorously. The reason for the abundance of water on Earth compared with Mars and Venus requires an explanation. Several possibilities have been suggested, but none is yet fully acceptable. The existence of life on our planet can explain the presence of methane and oxygen in the atmosphere, and life and water are both responsible for the relative lack of free CO_2. The relation between the atmosphere and life invites further study, particularly since it is generally assumed that the origin of life on Earth required a very different (reducing) atmospheric composition. The validity of this assumption can be tested in part by examining the atmospheres of the outer planets for signs of prebiological organic molecules, since these planets *presently* exhibit one type of atmosphere postulated for the primordial Earth. In this sense, the outer planets allow us to go back in time to examine conditions that may have existed in the early history of the solar system.

Comets also provide such an opportunity. This is true, in particular, of the "new," long-period comets that are entering the inner solar system perhaps for the first time. The relative abundances of the elements found in comets can be expected to reflect the composition of the region of the solar system in which they were formed. Using these data and those on the atmospheres of Jupiter and Saturn, it should be possible to determine original abundances in the icy and gaseous materials that formed the solar system, in somewhat the same way that meteorites and the Earth's crust provide clues to the less volatile materials. Such an analysis is handicapped by the fact that the molecules observed in cometary spectra are only daughter products, resulting from evaporation and dissociation of the parent material in the nucleus. In fact, identification of the parent material is perhaps the most significant problem in cometary physics at the present time. Progress toward this goal can be expected with observations in the ultraviolet and infrared, particularly using high spatial resolution that permits study of gases very close to the cometary nucleus.

ATMOSPHERIC COMPOSITION

The gases known to be present in the atmospheres of planets and their satellites are given in Table 1; in each case the most abundant identified gas is listed first. The large number of minor constituents that have been identified in the Earth's atmosphere give an indication of the incompleteness of present knowledge of other planetary atmospheres.

Supplementary Comments

MERCURY: Observations suggesting a CO_2 atmosphere now seem incorrect. The most recent studies indicate that the planet has no detectable atmosphere.
VENUS: $^{13}C^{16}O_2$, $^{12}C^{16}O^{18}O$, and $^{13}C^{16}O$ have been detected in addition to the abundant isotopic forms. $H^{35}Cl$ and $H^{37}Cl$ are both present. Isotopic ratios appear to be identical to telluric values. H_2O may be present in detectable

TABLE 1 Gases Identified in Planetary and Satellite Atmospheres

	Gas
Mercury	No definite identifications
Venus	CO_2, CO, HCl, HF, H_2O
Earth	N_2, O_2, H_2O, A, CO_2, Ne, He, CH_4, K, N_2O, H_2, O, O_3, Xe
Mars	CO_2, CO, H_2O
Jupiter	H_2, CH_4, NH_3
Saturn	H_2, CH_4; NH_3(?)
Uranus	H_2, CH_4
Neptune	H_2, CH_4
Pluto	No identifications
Jovian satellites	No definite identifications
Titan	CH_4
Triton	No identifications

amounts. MARS: ^{13}C and ^{18}O are found to be present in telluric relative amounts. JUPITER: Recent ultraviolet spectra from rockets revealed unidentified absorption at 2600 Å and below 2100 Å that may be caused by large organic molecules. A preliminary spectrum of the 8.5–13.5-μ region contains several puzzling features that require verification and explanation. SATURN: The question of varying amounts of ammonia in the planet's atmosphere has not been adequately tested. URANUS AND NEPTUNE: Previously unidentified absorptions near 7500 Å have been shown to be caused by methane. The possibility that this gas may be responsible for other, presently unidentified absorptions in the red region of the spectrum must be explored. PLUTO: Photometry of the planet gives no indication of the brightening toward the ultraviolet that would be suggestive of Rayleigh scattering. No atmospheric constituents have been identified. JOVIAN SATELLITES: Io shows an anomalous brightening after eclipse that could be attributed to surface deposition of an atmospheric constituent. Europa also exhibits this effect, but with a smaller amplitude. However, there is no definitive evidence for the presence of atmospheres on any of the Galilean satellites. Cooling during eclipses suggests lunar-type thermal properties.

Comets are not listed in Table 1, since cometary gases are excited differently—by resonance fluorescence—at much lower densities, and consequently different types of chemical species are found. In the coma, identified species include Na, O, Fe, CN, CH, OH, NH, C_2, C_3, and NH_2. Tail gases are predominantly ions, including such species as CO^+, N_2^+, and CO_2^+. A large number of observed lines are unidentified. The ratio of ^{12}C to ^{13}C in comets should receive additional study; the better of the two measurements made to date suggests it is equal to the terrestrial value.

The observed gases result either from photodissociation, or ionization of the stable parent molecules, or from chemical reactions occurring near the surface of the nucleus. These processes are poorly understood, in part because the nature of the parent material is unknown. Abundances have been determined only for those molecules whose resonance transitions happen to lie in the observable spectral region. It is highly likely that some of the most abundant species, which almost certainly include H, H_2, and He, are among those not directly observed. Observation of the intensity of OH and O I is important in establishing total gas relative to "visible" molecules. Both absolute and relative abundances of "visible" molecules are known to differ from comet to comet, but quantitative data are very weak and sketchy.

The potential of ground-based observations of comets is far from having been fully exploited. The first spectrographic observation of a comet at coudé dispersion and with fair spatial resolution was not obtained until 1957. Observations in the infrared and at radio wavelengths are in the pioneering stage. There are no spectra that include wavelength regions shorter than 3000 Å. Very few accurate photometric or polarization measurements, particularly at wavelengths corresponding to specific emission bands or to the continuum, have been made which concentrate on structures in the head and tail.

Acquisition of the needed observational data is hampered by the fact that only bright comets, which appear infrequently and with little warning, lend themselves well to detailed astrophysical study. Further, comets differ considerably in their physical characteristics. A comet comparable with the great Sungrazer of 1965, in which a number of chemical elements were observed for the first time, may be expected only at average intervals of several decades. Observational planning should include steps to recognize suitable opportunities as early as possible in order to exploit them fully.

The most pressing need for additional information on major constituents, next to accurate abundances of the gases listed in Table 1, concerns the abundances of N_2 and He. Since neither of these gases has ground-state absorption lines in the readily accessible spectral region, their presence and abundances must either be deduced indirectly or determined from Earth-orbital observations. With regard to minor constituents, isotopic forms of gases already identified, such as $^{13}CH_4$ and $^{1}H^{2}H$, should be sought and abundances estimated, and the possible presence of organic molecules and water vapor in the atmosphere of Jupiter further investigated.

The search for these gases requires high-resolution ultraviolet and infrared spectroscopy. The possibility of detecting some of them by means of their microwave resonance absorptions should not be overlooked. Finally, the interpretation of such observations requires a much better understanding than now exists of the formation of absorption lines in atmospheres containing absorbing and scattering particles.

ATMOSPHERIC STRUCTURE

The structure of a planetary atmosphere is determined in the most general case by the parameters of density, temperature, energy transport, velocity, and composition (both neutral and ionized species), as functions of height and time. In addition to their scientific importance, these quantities are of great interest to engineers designing spacecraft for atmospheric probing or landing on other planets. In principle, a temperature–density profile can be obtained from observations of absorption lines in planetary spectra. In practice, observational and interpretive difficulties have seriously hindered progress. Experience with satellite observations of the Earth can be expected to be very helpful for future planetary work.

One of the most dramatic of recent advances in this area has been the determination of the total pressure of the atmosphere of Mars with a far greater precision than was previously possible. The determination was made from observations of strong and weak bands of carbon dioxide in the planet's spectrum. Application of this spectroscopic method to other planets has been much more difficult, because the presence of suspended matter in their atmospheres introduces serious complexities in the analysis of the absorption lines. The theory of radiative transfer in such atmospheres is presently being developed and applied to the observations, with the result that a marked increase in knowledge of pressures and temperatures at different altitudes may be anticipated. Nevertheless, to provide rigorous tests of the theory, additional high-resolution studies of planetary spectra, for center-to-limb effects as a function of phase angle, are required.

Another approach to understanding atmospheric structure is the direct measurement of temperature at wavelengths ranging from the 8–14-μ window to the radio region of the spectrum. The resulting temperatures may correspond to different levels in a planetary atmosphere or may be indicative of surface or subsurface conditions, depending on the strength of the atmospheric opacity and its wavelength dependence. Radio observations allow investigation of the lower atmospheres of cloud-covered planets and should contribute to studies of the atmospheres of Venus and the major planets. Models for the structure of an atmosphere must be able to explain the temperatures observed at all wavelengths and the variation of temperatures with phase and position on the planet's disk (limb brightening or darkening).

In the case of Venus, a large amount of such temperature data is on hand but has not yet been successfully incorporated into a consistent model atmosphere. No model which does not take winds into consideration is likely to be adequate. Measurements in the 10–14-μ atmospheric window indicate a temperature of 210–235°K. Radio observations made between inferior conjunction and quadrature show a decrease of blackbody disk temperature from about 650°K at 6-cm wavelength to about 300–350°K at millimeter wavelengths. This variation is generally interpreted as absorption and re-emission by the atmosphere and clouds at higher, cooler levels of the radiation from hot, lower levels. The available data show a phase variation in the average disk brightness of about 10 percent at 0.8 and 3 cm, and of only a few percent at 10 cm, with minimum brightness after inferior conjunction, consistent with retrograde rotation. Limb darkening derived from Mariner II observations at 1.8 cm and from ground-based studies at 3 cm also indicates absorption in the atmosphere. Radar observations at 3.8 cm indicate at least 2.5 and possibly as much as 5-dB zenithal atmospheric absorption, which appears to vary slightly with time.

The problem is thus to assimilate these data into a consistent atmospheric model. Such models are generally tied to some form of greenhouse effect in which solar radiation penetrates to the surface of the planet at short wavelengths, while the thermal radiation re-emitted by the surface at longer wavelengths is trapped by the atmosphere. If the observed spectrum is produced by absorption in a CO_2–N_2 atmosphere, very high pressures must exist; if by absorption by water vapor, a great deal more water vapor must be present than seems consistent with observations; if by absorption by liquid water in the clouds, again too much water vapor is implied to be consistent; if by absorption by dust, large quantities of suspended material are required; and if by scattering, large particle sizes are needed.

In the case of Jupiter, thermal radiation dominates the radio spectrum for wavelengths shorter than about 3 cm. At longer wavelengths, the nonthermal synchrotron radiation of the magnetosphere increases in strength until, at 10 cm and beyond, the thermal component is very difficult to evaluate. The disk brightness temperature due to thermal radiation increases from 110–140°K in the millimeter wavelength range to at least 250°K at 10 cm. Measurements at 20 μ and from 8 to 14 μ indicate that the planet is radiating more energy than it receives, i.e., it is intrinsically warm, a result that is important for theories of the formation of the planets. The temperatures at these wavelengths are 150°K and 128°K, respectively. This spectrum suggests that the longer wavelength radiation is generated at lower levels in the atmosphere where the temperature is higher, a result that is consistent with present ideas on the planet's atmospheric opacity. Some observations of the intensity of the radiation at short centimeter and millimeter wavelengths differ significantly from the usually observed values and could indicate atmospheric activity. This also is indicated by the variable visual band structure and the hot shadows observed at 10 μ. It is important to observe Jupiter over long time periods to determine whether these variations accompany other evidences of atmospheric disturbance.

If construction of proposed new planetary radar facilities proceeds, it will soon be possible to obtain radar echoes from the Galilean satellites. The upper atmosphere of Jupiter can then be probed by studying the echoes received at the frequent times when one of the satellites is being occulted by the planet. Group velocity delay, extinction, and the Doppler phase shift of these echoes can all be used to gain information on the atmospheric scale height and dielectric properties.

The observed disk brightness temperature of Saturn increases from about 100°K at short millimeter wavelengths to about 300°K at 20-cm wavelengths, a spectrum very similar to that of Jupiter's thermal radiation. There is no evidence for a nonthermal component of radiation from Saturn. Unpublished high-resolution interferometer observations have been reported to show that the centimeter-range radiation is confined to the planetary disk, again suggesting atmospheric radiation. These studies require verification and extension.

The intensity of radiation from Uranus and Neptune is extremely weak, and observations of their radio emission have been accomplished only recently. Three measurements of the disk temperature of Uranus give 220 ± 35°K at 1.9 cm, 159 ± 16°K at 3.75 cm, and 130 ± 40°K at 11.3 cm. There is only one observation of Neptune, 180 ± 40°K at 1.9 cm. These fragmentary results are only a beginning in the study of the radio emission of these planets; the largest radio telescopes and most sensitive radiometers are required for additional research.

In the case of the comets, the structure of the coma, head, and tail is easily visible. However, the distribution of the atoms, molecules, and associated dust is very specific; the details vary from comet to comet and within the same comet as a function of time. The excitation mechanisms are still not completely understood, and the interaction of the released gases and dust in comet tails with the solar wind requires much additional study. Monochromatic photography at high spatial resolution is one important method to obtain this information; spectra of the coma and tail using objective prisms or fast slit spectrographs provide another. Temperatures of cometary nuclei can be inferred from brightness measurements with infrared detectors. This can be done only on relatively large comets when they are near the Earth and with the most modern detectors. Only one such measurement has been reported to date. Temperatures derived from analyses of molecular bands are difficult to interpret because of the nonequilibrium excitation mechanisms.

GAS DYNAMICS

Gas motions in comet tails are relatively easy to observe, but, as mentioned above, the relationship of these motions to the interplanetary medium through which the comets pass is not clear and constitutes an important area of research. One would like to understand the coupling mechanism between the ions in comet tails and the solar wind. It is not known, for example, whether comets have intrinsic magnetic fields, what is the origin of the system of tail rays, or what are the reasons for the sudden outbursts (observed as large increases in brightness) that are particularly puzzling in comets far from the Sun, even beyond Jupiter. Additional studies are required to define motions near the nucleus from which the gases are liberated. The characteristics of comet tails far from the Sun are also of interest.

Theories of general circulation in planetary atmospheres are still in their infancy. Motions of clouds in the atmosphere of Mars have been mapped in a preliminary way to try to define the general pattern of the planetary winds, but the observations have been too fragmentary to permit a definitive representation. Motions in the atmosphere of Venus are even more difficult to identify, since the cloud cover of the planet is virtually featureless. However, thermal energy maps at different phases imply large-scale wind systems and "storms" which are very important energy-transport mechanisms. Recent evidence for a four-day retrograde cycle in the ultraviolet cloud pattern (as opposed to the retrograde 243-day sidereal period for the planet itself) is extremely interesting and should be further verified. For both of these planets, theoretical studies of general circulation would appear to offer considerable hope for improved understanding as knowledge of the relevant parameters increases. Detailed knowledge of temperature, pressure, and composition, as well as of the nature of the particulate matter suspended in the atmospheres, is important for this work.

The theoretical study of angular momentum transfer on Jupiter, the nature of the pronounced equatorial currents on Jupiter and Saturn, and the nature and the motion of Jupiter's Great Red Spot have all received recent attention. Further work will require simultaneous determinations of the latitude, the longitude, and the shape of markings of all sizes. When such data are available, a test of the hypothesis that the extremely rapid rotation of the major planets may give rise to novel hydrodynamic effects will be possible.

Observations made some years ago indicated that gaseous ammonia and the clouds in Jupiter's atmosphere rotate at different speeds. The effect has been observed twice, independently and at widely different times but in the interval between the two positive observations; negative results were obtained by other observers. It seems likely that new observations and, in particular, a systematic search for a possible latitudinal dependence, would be worthwhile.

The determination of temperature variations, both spatial and temporal, in the atmospheres of these planets will be of great importance to theories of planetary interiors and atmospheric dynamics. That Jupiter's surface appearance varies has long been known. The variability manifests itself in the reflectivity of the planet; available measurements are inadequate to define a time scale for this variation, but the amplitude appears to be on the order of 0.5 magnitude. If a true period exists, which is doubtful, only a long series of new data will establish its duration. Variations in the magnetic field near the surface of Jupiter also bear on the dynamics of the atmosphere (see Chapter 5).

ATMOSPHERIC AEROSOLS

Every known atmosphere contains relatively large amounts of suspended matter, or aerosols. Aerosols are either condensates of a gaseous constituent of the atmosphere or particulate matter from meteorites or from the solid body with which the atmosphere is associated. Ignoring their presence can lead to serious misinterpretations of the observations. The opacity caused by such particles may contribute significantly to the planetary heat balance. Finally, planetary meteorology may be strongly affected by the presence of condensates able to absorb and liberate substantial amounts of latent heat during phase changes.

Despite their importance, relatively little is known about aerosols in the atmospheres of other planets. Recent, very low values for the abundance of water in Venus' atmosphere have virtually eliminated the possibility that the planet's cloud cover consists entirely of ice crystals or water droplets. Dust seems the most reasonable alternative, but its composition is not known. Polarization measurements are being made over the full 180° phase angle in several wavelengths from 3000 to 10 000 Å and should lead to new insights when interpreted with the help of computer programs capable of handling Mie scattering theory. However, the number of free parameters involved in making a fit to observations of this type is so great that unambiguous identification is unlikely. Additional data are needed and may be forthcoming from radar and radio observations at a number of wavelengths.

In the case of Mars, the presence of aerosols is manifested by several effects: white clouds, yellow clouds, and the blue haze. The white clouds appear to be condensation phenomena, probably ice crystals. The yellow clouds are airborne dust, often brought into the atmosphere in sufficient quantity to obscure a large fraction of the planet's visible hemisphere. The blue haze, whose nature is not well understood, causes the customary absence of surface detail in photographs of the planet made at wavelengths below 4500 Å. A baffling property of the blue haze is its variable transparency. It is commonly thought to be an atmospheric phenomenon, but suggestions ranging from ice-crystal clouds to a simple lack of contrast in surface features have been offered. High-resolution photography at selected intervals in the ultraviolet wavelengths is required to define the cutoff in surface detail and its temporal variation. Polarimetry at short wavelengths with high spatial resolution should also provide useful information.

Jupiter's atmosphere has a rich assortment of cloud phenomena which are generally thought to result from condensation of atmospheric ammonia. However, the colors in the clouds, as exemplified by the famous Great Red Spot, have not been satisfactorily explained. The most likely source of the colors would seem to be complex organic substances in the atmosphere. This hypothesis can best be tested by spectroscopic analysis of atmospheric gases, as suggested in the section on Atmospheric Composition (page 28). The deeper layers of the atmosphere should contain water clouds; direct investigation may be possible with radar at short wavelengths or by infrared measures from airplanes. Atmospheric models have been proposed that take into account the effect of condensation on the temperature gradient, but they require elaboration and observational verification.

On Saturn, the visible cloud surface may consist of ammonia crystals at very low temperatures; on the other hand, these clouds may be condensed methane or a mixture of the ammonia crystals and the methane. Clouds of condensed methane could exist in the low-temperature atmospheres of Uranus and Neptune; these clouds would be highest in the atmosphere. If the temperature rises with decreasing altitude, the lower layers may contain ammonia and ultimately water clouds. Again it appears that these hypotheses must be analyzed indirectly, although a few data may be provided by observations at radio frequencies (see the section on Atmospheric Structure, page 31).

The particulate matter associated with comets manifests itself most strikingly in their tails. The tails of most new comets contain a large amount of dust that produces a continuum of scattered sunlight in contrast with the discrete emission lines of the ions. Under certain circumstances, the gas and dust components may be separated by the action of radiation pressure and the solar wind, leading to the phenomenon of comets with multiple tails. Photometric and polarimetric observations suggest particle sizes on the order of

0.5 μ; such measures should be extended to include a greater range of wavelengths.

Like the gaseous components, the dust comes from the cometary nucleus, and spectral evidence of its composition is obtainable under proper conditions of excitation. Comets that approach the Sun rather closely exhibit the sodium *D* lines in spectra of the coma, while lines of iron, calcium, potassium, nickel, copper, chromium, and manganese were identified in the spectrum of the Sungrazing comet of 1965. The opportunity for such observations is exceedingly rare, so that the possibility of even more direct study is attractive.

This possibility stems from the well-established association between comets and meteor showers. Most of the cometary material entering the Earth's atmosphere when the planet passes through the comet's orbital plane disintegrates before it reaches the ground. However, a growing body of evidence suggests that some of the carbonaceous chondrites may come from comets (see Chapter 3). The relationship between comets, asteroids, and meteorites deserves much additional study, since meteorites are the only samples of extraterrestrial "dust" that can be analyzed in the laboratory.

INTERACTIONS WITH THE SURFACE

The effects on the surfaces of solar system bodies of evolved or captured gases can be examined only with respect to Mars and Venus. The other objects have either no detectable atmospheres (Mercury) or no detectable surfaces (Jupiter). Comets have both surfaces and gaseous envelopes, but whether the gases have any effect on the surface once they have been liberated is not clear. It has been suggested that the process of liberation of the gases from the icy conglomerate nucleus may gradually transform the nucleus into a rather porous and spongy semisolid mass. This low-density, low-strength mass may be the parent body of the bright, large meteors which do not result in recoverable meteorites, despite well-observed trajectories.

In the case of Mars, analysis of the Mariner IV pictures of the surface has shown significant deviations of the smallest craters from the frequency distribution curve that characterizes lunar craters. This disparity may be caused by erosion produced by wind-borne dust on Mars, a process that would obviously be lacking on the Moon. Such a mechanism is known to operate on Earth in arid regions, and it appears reasonable that winds capable of initiating the enormous Martian dust storms would have sufficient force to cause erosion. However, the details of the soil-moving process at very low pressures remain uncertain owing to the large extrapolation that is required to go from theories based on observations in terrestrial deserts at atmospheric pressure to expected

Martian conditions. Hence, experiments carried out at low pressure with a Martian mixture of gases are required to determine the wind speed and soil compaction at which dust begins to be picked up and, once airborne, the effect of this dust on solid surfaces of different strengths and compositions.

Study of the surface of Venus, made possible by radar, is just beginning. As noted in the preceding section, the clouds that obscure the surface may be largely composed of dust. There is no direct evidence on the wind forces that would be required to dislodge dust and carry it into the atmosphere nor on the effects of such dust on surface terrain under conditions assumed to exist in the lower atmosphere. Some insight into these questions can again be gained by laboratory experiments on dust-raising and -transport mechanisms, in this case for high pressures and temperatures.

5

Interiors and Magnetic Fields

INTRODUCTION

There are many areas of interest to planetary astronomers for which our knowledge is fragmentary, either because extensive studies have not yet been carried out, or because we are limited in our ability to investigate certain problems from the surface of the Earth. Two such areas are planetary interiors and planetary magnetic fields.

A knowledge of the structure and composition of planetary interiors is essential to a better understanding of the present state of the planetary system, how it was formed, and the manner in which it evolved.

The only method that has so far been applied to observe planetary magnetic fields from the Earth's surface is to detect radiation from charged particles trapped in the field. Thus far, only Jupiter has displayed such nonthermal emission. The study of this emission permits some understanding of the nature of the Jovian magnetosphere. This is of interest both for possible clues to the activities occurring within the planet and for comparison with the Earth's magnetosphere, which may aid in understanding the processes underlying both.

PLANETARY INTERIORS

The goal of the study of planetary interiors, ideally, would be to produce a table (or analytic expression) including such parameters as density, pressure, temperature, composition, and magnetic field at every point within each planet. Such a wealth of detail, however, is not possible nor even desirable on any reasonable scale of scientific priorities. Nonetheless, certain averages which could in principle be extracted from such ideal tables are of great interest, for from them could be obtained the answer to such questions as: Did a given planet originate by accretion of cold, solid objects or by contracting clouds of gas and dust? What are the gross mole fractions of the elements in extrasolar material in the present solar system? How will the radiative temperature of the planets vary with time? Would formation of a system of planets be a common or rare phenomenon in the Universe?

Since the data in such hypothetical tables cannot be obtained directly by measurements, they must be obtained from calculations using measurable parameters and theory. In principle, this is not a difficult process. A system of equations can be written, usually assuming hydrostatic equilibrium, that defines the equation of state, guarantees the conservation of mass and energy, and defines the mode of energy transport and the distribution of composition. Then, using the mass, radius, and measurable moments of inertia as boundary conditions, the set of differential equations can be integrated to produce a model of the planet. There are, however, a number of problems in formulating the detailed equations, problems that stem from our very incomplete understanding of the behavior of matter under high pressure.

One obstacle to model building is our limited knowledge of the equation of state. Experimental investigations using static compression and shock compression have, in recent years, yielded much information on the behavior of matter under high pressure. Experiments alone, however, cannot cover the range of situations that are of interest to planetary physicists, and advances in theory have not been nearly so impressive as experimental advances. Some theoretical studies of certain elements and compounds in cold, solid phases should now be made, despite their complexity. In addition, whereas it is possible to estimate for a given compound or mixture the variation of density with pressure and temperature, one cannot at the present time make any *a priori* prediction of phase boundaries. In the case of the Earth, some boundaries can be predicted when experimental data on chemically similar isomorphic structures are available, but, for other planetary interiors, the questions of phase boundaries are likely to remain enigmatic for a long period.

A second area of difficulty involves thermal transport. Energy in planetary interiors may be transported by ordinary thermal conduction, convection, or radiation. How much each of these transport mechanisms contributes to the energy budgets of planetary interiors is not precisely known. The thermal conductivity of planetary material is very difficult to estimate, if only because such conductivities are extremely sensitive to composition, lattice structure (or lack of it), temperature, density. Convection is well understood in gases and certain liquids when nonturbulent; but even here any slight complexity in geometry raises severe mathematical difficulties. Convection of very imperfect gases, or convection in condensed systems exhibiting phase changes coupled with the presence of gyroscopic forces (magnetic or Coriolis), presents formidable difficulties indeed. Finally, radiative transport is presumably of importance in planetary interiors. With planets, however, even if the hypothesis of local thermodynamic equilibrium suffices, one cannot use the simplified version of Kirchhoff's law or even its more general expression which includes the square of the refractive index.

This formula holds only for weakly absorbing media, because matter cannot have refractive indices which differ significantly from unity in some parts of the spectrum without having nontrivial absorption also present. Plasma physicists are faced with similar problems, and it seem likely that fundamental progress can be made in the next decade.

Because so little of the fundamental physics is well understood, and even when understood, is so sensitive to the value of the parameters involved, many workers have used the theory of the Earth as an aid in developing models of the terrestrial planets. The density of the Earth is fairly well determined as a function of depth, probably to within 5 percent over most of its volume. The distribution of its density, however, already includes assumptions about its composition. The general picture of a predominantly iron core and a silicate mantle seems established, but to attribute this composition to other planets is questionable. Some models of Venus have been based on the planet's similarity to the Earth; one should bear in mind, however, that although Venus has almost the same mass and radius as the Earth, its atmospheric composition, for example, is very different. Until the reasons for the major differences are clearer, it may be premature to assume that Venus and the Earth have similar interior compositions. A like attitude toward those inner planets which resemble the Earth even less, Mercury and Mars, is obviously prudent.

Objections are also raised against planetary models that assume abundances and structure based upon meteoritic samples, since evidence is rapidly accumulating that iron meteorites do not originate from the core of a sizable ($>$200 km) planet. For example, the irons were not surrounded by pallasites, since pallasite meteorites cooled ten times more slowly than most iron meteorites; and the assumption of chondritic composition of the Earth's mantle can be criticized. Even if meteorites originated on a parent planet, most of them (the chondrites and 80 percent of the observed falls) were formed near the surface.

Although available information is normally not sufficient to determine a planet's composition, Jupiter and Saturn are exceptions. In these cases, simple models based on the planetary radius, mass, moments of inertia, and the assumption of hydrostatic equilibrium yield such low densities that either the planets are composed largely of hydrogen or their internal temperatures are so high that thermal pressure is a substantial fraction of the total pressure. If such high thermal pressures were to exist, the planets would be extremely unstable to convection and would radiate tremendous quantities of heat. Such radiation is contrary to observation.

Since simple models indicate that 80 percent of the mass of Jupiter and 75 percent of the mass of Saturn are hydrogen, it follows that at least 70 percent of the extrasolar material in the solar system is hydrogen. These numbers are quite insensitive to anything but the assumed equation of state of hydrogen and the assumption that these planets cannot be stable against convection if the thermal pressure is high. Unfortunately, the remaining constituents of Jupiter and Saturn cannot be identified so simply. Here one is forced to resort to such arguments as: Any object containing so much hydrogen must have essentially cosmic abundances of the elements, and consequently most of the remaining matter is helium. Whereas that is a reasonable assumption, it must for the present remain merely an assumption.

The foregoing may perhaps best be summarized by stressing that the theory of planetary interiors is semiempirical. The models of planetary structure are far less convincing from the standpoint of physical theory than are the models of stellar structure. For the present we lack a detailed knowledge of the composition of any planet; and our theoretical understanding of such factors as the energy transport mechanisms and phase changes is extremely limited. Until fundamental theory is significantly advanced, there is no alternative to working under these unsatisfying conditions; and these conditions must be kept in mind before one places too much credence on planetary models.

PLANETARY MAGNETIC FIELDS AND MAGNETOSPHERES

Planetary magnetic fields are of interest because of the plasma phenomena produced by the interaction of the fields with the solar wind, and because, being produced by processes occurring deep within the planet, they provide a clue to the nature and extent of those processes. In principle there are four kinds of observational evidence from which the existence of a planetary magnetic field may be inferred: space-probe magnetometer measurements; nonthermal electromagnetic radiation from the planet of appropriate frequency, polarization, and intensity; evidence that in modulating the solar wind the effective planetary cross section greatly exceeds the cross section of the visible planet; and Faraday rotation of the plane of linear polarization either of visible light as it traverses the residual gas above the scattering atmosphere or of radar echoes from the surface of a planet or one of its satellites as the radio waves traverse the planet's magnetoionosphere.

Space-probe magnetometer measurements have so far been made for only two planets, Venus and Mars. Measurements made by Mariner V as it flew past Venus at a distance of 1.7 radii from the center of the planet gave no evidence of a planetary magnetic field; a bow-shock interaction between the solar wind and the Venus ionosphere was observed. These results place an upper limit on the intrinsic magnetic field of 10^{-3} that of Earth. There is no evidence of any electromagnetic radiation of nonthermal origin from observations of Venus made to wavelengths as long as 11 m.

Magnetometer data obtained as Mariner IV flew past Mars at a distance of about two planetary radii from its center gave no evidence at any point on the trajectory of a Martian magnetic field. If a fluctuation in field strength observed by Mariner IV was a shock front associated with the Martian magnetosphere, the ratio of the magnetic moment of Mars to that of the Earth is $\leq 2 \times 10^{-4}$. There is no evidence of nonthermal radiation from Mars to a wavelength of 17 m.

Nonthermal electromagnetic radiation from Jupiter at decimeter and decameter wavelengths is so strong that this planet is one of the brightest radio sources in the sky. At wavelengths of 10 cm to about 1 m the spectrum is nearly flat and is produced by synchrotron radiation from the magnetosphere. This radiation is 20 percent linearly polarized, and a small, circularly polarized component has recently been reported from equatorial regions at about ± 2.5 radii. From this, an order-of-magnitude estimate of 2 G for the strength of the magnetic field was obtained, consistent with the other characteristics of the synchrotron radiation and with the field estimated from measurements of the low-frequency decameter radiation.

The orientation of the electric vector of the linearly polarized radiation defines the magnetic axis of Jupiter as tilted by 10° from the rotation axis. The resultant rocking of the plane of polarization as Jupiter rotates defines a rotation period essentially the same as the System III period derived from the low-frequency observations at about 15-m wavelength. A small variation of intensity with rotation is observed, which is apparently due to beaming of the synchrotron radiation. Asymmetries in the rocking effects and analyses of the low-frequency radiation suggest asymmetry of the dipolar magnetic field.

High-resolution observations of the synchrotron radiation show the extent of the source to be about three times the disk diameter in the equatorial plane and roughly equal to the disk diameter in the polar direction, consistent with a radiation-belt structure generally similar to that of the Earth. High-resolution observations of the polarized brightness distribution are needed at other wavelengths to define the radiation-belt structure and to allow a separation of the thermal and nonthermal components of radiation so that the planetary properties relevant to the two components may be recognized and studied.

Apparent changes of the level of the synchrotron radiation over periods of days or longer have been reported; in some cases a connection with solar activity was indicated. It is important to observe Jupiter over long enough periods to confirm these results.

The low-frequency decameter radiation from Jupiter is intermittent, fluctuating, and of very high intensity. It comes in periods of short noise-like bursts, some of the pulse structure being due to propagation effects. The intensity of the radiation increases over a wavelength range from approximately 7 m to the ionospheric cutoff at about 100 m. The radiation is observed less frequently at the short wavelength end. The probability of occurrence of the radiation is greater (up to about 0.8) during three distinct portions of Jupiter's rotation period. This indicates beaming from one or more sources, and a new rotation period and longitude system for Jupiter System III have been defined on this basis. This period, $9^h55^m29.37^s$, based on observations made between 1950 and 1960, differs from both System I and System II but agrees well with the period found from the wobble of the magnetic axis shown by the synchrotron radiation. There is evidence from more recent observations of slightly different periodicities in the apparent source regions. A gradual change in the rotation period of the radio source was first suspected, but the observed apparent period may be influenced by changes with time in the source–observer geometry or in the radio-noise storm duration. The polarization of the radiation, except at the longer wavelengths, is measured as predominantly right-hand elliptical or partially right-hand circular, implying a magnetic field of at least several gauss. The angular extent of a low-frequency source on Jupiter has been determined by interferometer techniques as less than 3 sec of arc.

Recently, it has been recognized that the probability of occurrence of the low-frequency radiation depends not only on the System III longitude of Jupiter at the central meridian but also on the position of Io in its orbit. Io and the Jovian magnetosphere apparently interact in a way that is still unexplained, influencing the particle streams which may produce the low-frequency radiation.

Because of its sporadic nature and many interrelated variables, this radiation is very difficult to study, and it is important to continue and to improve the observations. It is also important to extend the ability to make observations at the low-frequency end of the spectrum by means of satellites in high Earth orbit or by space probes; to test coherence at very widely spaced stations to clarify the millisecond burst structure, which is apparently related to Jupiter; and to measure the absolute positions of the decameter sources.

If definite changes in Jupiter's magnetic field or changes in period are established, the reconciliation of these changes with the motion of other parts of the planet, as evidenced by the excursions in longitude of the Great Red Spot, will pose fascinating problems. The theoretical exploitation of these observations will bear both on the internal structure of the planet and on the origin of its magnetic field. The possibility that a dynamo mechanism is operating in the lower reaches of Jupiter's atmosphere is not inconsistent with the (admittedly limited) theoretical and observational evidence. If this is indeed the case, variations in the motions of the Red Spot and of the radio sources could be manifestations of hydromagnetic torsional oscillations of the planet. Moreover, the "topographical feature" with which the Red Spot may be associated might be magnetic in nature.

6

Observational Techniques and Facilities

INTRODUCTION

Many of the recent findings in planetary astronomy have been the result of applying new techniques to planetary problems. This chapter provides a brief description of the more important techniques, since they are likely to be unfamiliar to many. It also surveys the major optical, radio, and radar facilities with capabilities for planetary research.

RADIO AND RADAR TARGET MAPPING TECHNIQUES

The relatively long wavelength of radio and radar observing systems as compared with optical telescopes makes it difficult to obtain a high degree of angular resolution of the target by the straightforward use of large reflectors alone. For example, for the low-frequency radiation from Jupiter, resolution of 1 sec of arc requires an aperture of roughly 3000 km; and at the short wavelength end of the radio spectrum near 1 mm, an aperture of about 200 m is required for this resolution. To achieve angular resolutions comparable with those available optically, therefore, radio and radar astronomers have been forced to develop other methods that can synthesize the large effective apertures demanded.

A conventional "filled" receiving aperture, such as a parabolic reflector, contains highly redundant statistical information on most of the spatial Fourier components of the incoming signal, since a number of spacings of less than the full diameter can be found, all of which have the same separation and angular orientation. Thus, it is possible to devise an array of small antennas, each of manageable size, whose elements may be paired off with each other to produce substantially all the needed spatial Fourier components. In fact, the complete set of components need not be obtained simultaneously, provided the angular distribution of the received power in the sky varies only in a predictable way with time. Several installations based on these principles that should be able to yield angular resolutions of the order of 1 sec of arc at radio wavelengths have been proposed. The signal-to-noise ratio obtained from these "unfilled" apertures will be considerably lower than that produced by a filled aperture in the same observation time, but for many targets useful results can still be obtained.

For radar observations of a rigid body, there is even greater redundancy in the returning signal, since the echoes represent the scattering of a coherent transmission by a collection of scattering elements maintaining a fixed relationship to one another. Given *a priori* information concerning the motion of the target, the phase history of the echo from each element of the surface is completely predictable. It becomes possible, therefore, to analyze the returned echo power for its frequency Fourier components and to relate the components to the scattering from known locations on the target. The resolution thus obtained varies with the motion of the target, the radar carrier frequency, and the duration of the observation; but it frequently permits surface localization of the scattering that compares favorably with optical results.

Most of the celestial objects studied by radar have dimensions such that echoes from different regions on their surface will differ measurably from each other in time of flight. For nearly spherical targets like the Moon or planets, equidistant regions of the surface will lie on small circles concentric with the visible disk. Since the target is assumed to be a rigid body, all points at the same projected distance from the instantaneous apparent axis of rotation must have the same component of motion in the direction of the radar. Again, for a spherical target, these loci of constant Doppler shift become a set of small circles "edge-on" to the radar and, therefore, at right angles to the loci of constant delay. The geometry of this "delay-Doppler" coordinate system is shown in Figure 3. Since the returned echo power for many targets (including the Moon, Mercury, and Venus) may be analyzed simultaneously at high resolution in both coordinates, a basis exists for mapping the distribution of radar reflectivity.

The chief drawback in applying delay-Doppler mapping techniques lies in the need to resolve a basic ambiguity in the coordinate system as shown in

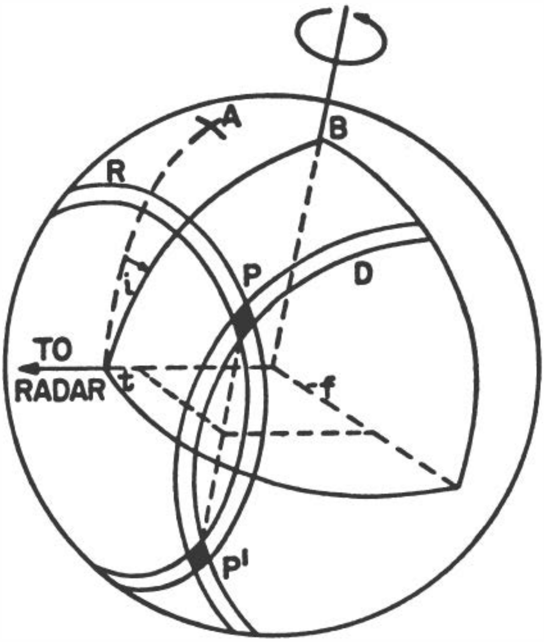

FIGURE 3 Geometry of the lunar surface with respect to the radar in the delay-Doppler mapping technique. The apparent lunar rotation differs from the intrinsic lunar rotation about its north pole because of the motion of the Moon in its orbit around the Earth and because of the motion of the radar with respect to the Moon due to the Earth's diurnal rotation. Note the two conjugate surface areas, *P* and *P′*, which have the same values of range (delay) and Doppler frequency. A, North lunar pole; B, pole of apparent rotation; D, Doppler contour for relative frequency, *f*; R, range contour for relative range, *t*.

Figure 3. This ambiguity arises because only two of the three surface Cartesian coordinates are measured, and, while the surface of a sphere is constrained by $x^2+y^2+z^2=r^2$, there are two roots to the solution for the third coordinate. It is interesting to note that an equivalent ambiguity would also exist for direct angular mapping if the target were transparent so that the back and front sides were equally visible. In the case of the Moon, where a disk of relatively substantial angular size is presented to the radar, the points of ambiguity can sometimes be isolated by using the angular resolution afforded by the antenna beamwidth. An example of the application to the Moon of this type of mapping is shown in the Frontispiece. The extension of this technique to the planets, where the target disk is very much smaller and where the antenna

beamwidth of any existing or proposed radar system is too large to resolve the ambiguity, will require interferometric measurements.

The interferometer is the basic tool of the high-resolution array. For baselines up to a few hundred kilometers, the individual elements of an interferometer or array can be connected by cables or radio links. The high-resolution arrays planned for the Owens Valley Radio Observatory and the National Radio Astronomy Observatory are designed to give resolution to a few seconds of arc at wavelengths over the 3- to 21-cm range using a number of moderate-sized reflectors interconnected by cables. These large facilities will satisfy many of the requirements for high-resolution planetary observations over this wavelength range. A similar array is needed to extend the wavelength coverage from 3 cm down to millimeter wavelengths.

For element separations greater than a few hundred kilometers, as in the case of high-resolution observations of Jupiter in the 15-m wavelength range, systems have been developed that record on magnetic tape the radio waves measured at each element location for subsequent correlation. In one system, the stored electrical signals from which the radio-wave phase information has been removed are combined in a video correlator. This system is relatively insensitive to scintillations. In the system, which retains the full phase information of the wavefront and thus has far greater sensitivity, atomic frequency standards are used at the separated locations to provide phase-stable local oscillators.

HIGH-RESOLUTION FOURIER SPECTROSCOPY

Fourier spectroscopy has recently been very successfully applied to the planets. The technique makes use of all the light reflected from a planet, collected by a large telescope, to derive high-resolution spectra. It is particularly effective for measurements in the 2-μ window in the infrared, where, because of practical considerations, the interferometer yields a very substantial gain in resolution over the spectrometer.

The recently developed Connes interferometer, responsible for the successful measurements, has a long-term mechanical stability that can be used in conjunction with a large telescope. The motion of the interferometric mirror can be measured to an accuracy of a fraction of a wavelength of visible light. Precise absolute wavelengths are obtained by this system, since the position of the moving mirror is monitored by observing the interference fringes produced by an accurately known visible wavelength. The spectrum of Venus was obtained to a precision of 0.002 to 0.003 cm^{-1} at 1.6 μ, closely approaching that of the best measurements available from laboratory sources. The resolution obtained is 0.08 cm^{-1}, which is approximately the theoretical resolution of a 4-in.-wide diffraction grating used at 60° angle of incidence. In a favorable case in the laboratory, a resolution equivalent to the theoretical resolution of a grating of 1-m width has been obtained. Several hours are required to scan the 1.6-μ atmospheric window; thus several runs can be made at a given atmospheric window in a single observation period.

The instrument has the same limitations as conventional spectrographs, for spectra can only be obtained in the atmospheric window regions. However, because of the great detail obtained and the high precision of wavelength measurement, the data provide a unique and nearly complete picture, both qualitatively and quantitatively, of the planetary atmospheric constituents outside of the telluric bands. It is true, of course, that only gases having infrared-active vibrations or a sufficiently large quadrupole moment can be observed. The spectra obtained by this interferometric method have been superior both in resolution and wavelength accuracy at least by an order of magnitude to those obtainable by conventional methods.

This instrument is best used in conjunction with the largest telescopes, since the spectral resolution attainable is directly proportional to the flux available. With such telescopes the interferometer seems to be able to achieve a spectral resolution limited only by the widths of the lines being observed and an accuracy of wavelength measurement that is a small fraction of the line-width. Results of this order have already been obtained on the spectra of Venus, Mars, and Jupiter. Since a smaller amount of flux is available for other planets, the resolution of their spectra will be somewhat less. Nevertheless, the interferometer could be used to search for an atmosphere of Mercury, and useful information could be obtained concerning any atmosphere associated with Jupiter's moons or Saturn's rings.

USE OF AIRPLANES, BALLOONS, ROCKETS, AND EARTH SATELLITES

Recent technical advances in the use of upper-air vehicles have opened up wider spectral regions for planetary investigations. Although this approach is much more expensive than ground-based observations, it is far cheaper than the use of Earth-orbiting satellites.

Observations in the near infrared, free from the heavy absorption of water vapor, are being made from airplanes just above the tropopause. A plot of the solar spectrum obtained at different latitudes in the spectral region 1–15 μ is shown in Figure 4.

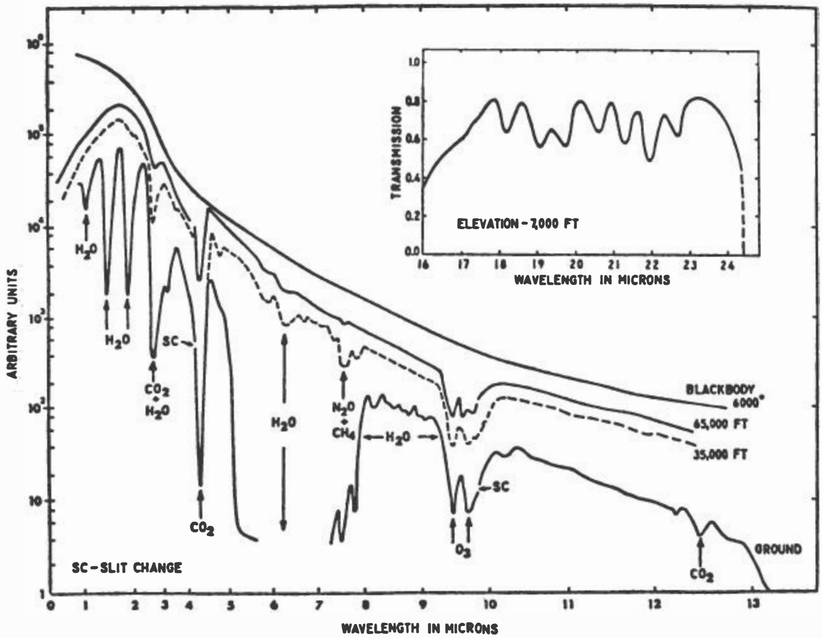

FIGURE 4 Solar spectra observed by Strong in the 1- to 13-μ region at different altitudes. Insert: atmospheric window from 16 to 24 μ observed by Adel at Flagstaff, Arizona. The total precipitable water was about 2 mm, and the cutoff of the KBr prism was near 24 μ. Because the atmospheric water vapor is somewhat colder than the Earth's surface, the transmission indicated may be somewhat high. More recent measurements from the surface under comparable water-vapor conditions by Farmer and Key have shown that this window (with lower transmission) extends to 38 μ. They also found a window with 5 percent transmission centered at 345 μ.

Atmospheric transmission at longer wavelengths has been observed at 7,000 ft when about 2 mm of precipitable water was present. Observations of the solar spectrum made under similar water-vapor conditions indicate a continuation of this window, but with significantly lower transmission, to 38 μ. Solar energy has also been detected in a region centered at 345 μ, where the maximum estimated transmission is 5 percent. The 20–38-μ window is particularly appropriate for work on Jupiter, Saturn, Uranus, and Neptune, because they radiate most of their energy in this spectral region.

Observations can be extended toward the ultraviolet through the use of unmanned balloons. Above 110,000 ft, measurements are possible from 1950 to 2350 Å and at wavelengths longer than 2750 Å. There are still ozone absorptions of the order of one magnitude, and since they vary with the float altitude, it appears that absolute photometry should not be attempted.

Some spectroscopy, photography, and polarimetry can be carried out from balloons. Direct photography is attractive, especially for Venus, where detail on the disk has been photographed at 3300 Å; the cloud features may be even more pronounced at shorter wavelengths. Determination of optical thickness of a molecular atmosphere, such as for Mars, also appears promising. Polarimetry may be the best technique, owing to the inherent precision of polarimetric differential measurements. The attraction of a balloon-borne telescope is that it can be flown during one night, and then, if desired, the experiment can be modified or changed and reflown.

Rocket flights offer considerable potential for exploratory observations of the ultraviolet spectra of the brighter planets. The region longward of about 1800 Å is likely to be observable, in the few minutes an Aerobee sounding rocket is above the atmosphere, with spectral resolutions of a few angstroms for Venus, Mars, Jupiter, and possibly Saturn. Not only absorption bands and continua may be expected, but fluorescent scattering of sunlight may be seen, depending on the atmospheric composition. Further, any resonance scattering of sunlight by atomic hydrogen or oxygen in the outermost atmospheres of these planets (analogous to the Earth's hydrogen "corona"), if detected in the 1200–1300 Å region, would be most informative and valuable. These emissions would not only indicate the presence of these constituents but would also give some indications of the temperature governing the rate of escape of the atmosphere. Raman scattering of the solar Lyman-alpha line of H (1215 Å) by H_2 and by He on Jupiter or Saturn, intense enough to be detected by a rocket, is also a distinct possibility.

IMAGING TECHNIQUES

Earth-based photography will continue to be a principal method of exploring planetary surfaces and atmospheres. It provides the greatest opportunity for the observation and recognition of totally unexpected features, conditions, and processes and the best method of monitoring changes of a planetary surface and atmosphere. Since photography gives a permanent record of constant, transient, and unexpected features, it constitutes a most important background for other investigation. Finally, comparison of close-up photography from spacecraft with Earth-based photographs made simultaneously should provide the basis for interpreting earlier photographs obtained with the same Earth-based telescopes.

Since photography is so important in planetary astronomy, any technique that increases the information obtainable from a planetary image is important. Improvements in planetary imagery can be made at three stages in the process: before the image is recorded, during the recording, and after the image is recorded.

The location of the telescope is a prime factor in determining the quality of the image that arrives at the detector, since resolution is usually limited by turbulence in the atmosphere rather than by the instrument. Recent studies have shown that sites exist, especially in northern Chile, where star images may average no more than half the size of images observed elsewhere. Telescopes at such sites would be capable of four times the areal resolution presently available and would constitute a significant advance in planetary image recording. For this purpose telescopes of aperture larger than 60 in. provide no additional advantages and may be inferior because of problems associated with mirror figure.

It has been shown that image quality may be improved by careful visual or photoelectric selection of the time at which a photograph is made. The typical exposure time of a planetary photograph is in the range from 1/100 sec to a few seconds; yet one image of exceptional quality per hour may be a satisfactory data rate. Many images have been recorded and sorted at a later time and the better quality ones superimposed to form composites. For several planets, exposures obtained several minutes apart cannot be used in this way because of the planets' rapid rates of rotation.

Image tubes can be used in such a way that high-speed corrections are electronically applied to the position of the centroid of a planetary image. The stabilized image on the output phosphor of the tube is then projected and photographed. This method is particularly effective when the planetary image is sharp but jumps about in the focal plane of the telescope.

Still more sophisticated image-correction methods might be further investigated. They would involve high-speed correction of irregularities in the wavefront arriving at the telescope.

It is possible that planetary images can be enhanced after they have been registered on photographic plates, perhaps after digitization or directly by an analogue technique. After-the-fact enhancement of detail in the Mariner IV television pictures of Mars and of the Surveyor pictures of lunar soil, and progress in restoring atmospherically degraded pictures of Earth satellites, indicate that postdetection processing may offer a promising means to improve ground-based photography in the next decade. Lunar and Martian image data in digital form have been treated by computer filtering; ground-based photographs of Earth satellites have been restored by direct digitization of film images; Ranger photographs have been treated by the optical analogue of computer filtering. The considerable experience with the filtering technique from radio-frequency applications can also be applied to ground-based planetary photography.

Further improvements in postdetection digital processing are also likely to result from making use of known characteristics of the images being reconstructed. For example, much *a priori* information about a planetary image already exists; it is circular, of finite size, has a known range of albedos, and so on. In principle, it should be possible to combine this information with knowledge of image degradation effects to produce a processed image of maximum resolution. An additional advantage of digital processing is that the integration of information from numerous individual images can be carried out in either intensity or frequency and with a variety of weighting factors.

Analogue filtering, which is accomplished by apodizing the aperture of a coherent optical system with a transparency of the image to be processed, and then filtering at the image plane of the special coherent system, appears to be particularly applicable to the great body of existing high-quality planetary photographs. Since digitization is avoided, the method is inexpensive and rapid.

SCANNING TECHNIQUES

Spectral or area scanning can be used advantageously in a number of ways to make quantitative measures of planetary features. These include spectrophotometry, polarimetry, and colorimetry.

A new method of scanning spectra has recently been used successfully: in a few seconds, the energy distribution over ranges of hundreds of angstroms is repeatedly measured and recorded by rocking the grating in such a way that its spectrum moves perpendicularly across the exit slit of the spectrograph. One of the advantages of the method is that it can be used when the atmospheric transparency is far less than what is generally regarded as "photometric." This is of particular importance in planetary observations involving transient phenomena and has the added advantage of effectively increasing telescope time for precise photometric photometry.

When an aperture is moved across the image in the focal plane of a telescope it is called area scanning. Area scanning has been demonstrated to improve substantially the effective photometric resolution obtainable in the polarimetry and colorimetry of planets. Quantitative measures of double stars have shown a four- or fivefold advantage over conventional photoelectric techniques used in work on visual binaries with separations of less than 5 sec of arc. Area scanning has also been used successfully by periodically moving a small focal-plane aperture along the entrance slit, while the exit slit of a spectrograph remains at a position corresponding to a preselected wavelength.

In the above applications, a quantitative and integrated picture of the physical conditions along the line of scan has recently become easily obtainable through the availability of multichannel analyzers which can add the pulse counts obtained during successive scans and accurately store them in a succession of channels.

For observations of the Moon and planets the apertures used in these scanning techniques can be substantially smaller than the seeing image of a point source at the focal plane of a telescope. Examples of Martian scans showing changes of intensity and polarization at different wavelengths are shown in Figure 5.

RADAR, RADIO, AND OPTICAL FACILITIES

Radar

Since the first radar contact with a planet in 1961, six working groups in three countries (the United States, the Soviet Union, and the United Kingdom) have reported research in planetary radar astronomy. For the present, the United States is pre-eminent in radar astronomy, with work proceeding at three major installations (see Table 2). The groups currently involved are centered at the Jet Propulsion Laboratory (using the Goldstone Deep Space Communication Complex), Cornell University (using the Arecibo Ionospheric Observatory), and the MIT Lincoln Laboratory (using primarily the Haystack Microwave Facility). The fourth U.S. working group, at the National Bureau of Standards, has been concerned almost exclusively with the ionosphere and is no longer active in planetary radar studies. Relative sensitivities at these, and several older, facilities are plotted in Figure 6. Observational opportunities are shown in Figure 7.

From the standpoint of personnel, the current U.S. effort in planetary radar astronomy is very small: a total of perhaps 12 professional scientists and six graduate students is actively involved. The total dollar investment in facilities is relatively larger; it must be remembered, however, that all the facilities were conceived and constructed primarily for other purposes, and the bulk of their activities relates to other fields. Prorating to the percentage of planetary radar usage is difficult and perhaps misleading; the average annual figure is probably between 5 and 30 percent of the total budgets of these installations.

As has been noted, the facilities listed in Table 2 were developed largely for purposes other than planetary radar astronomy, for example, ionospheric

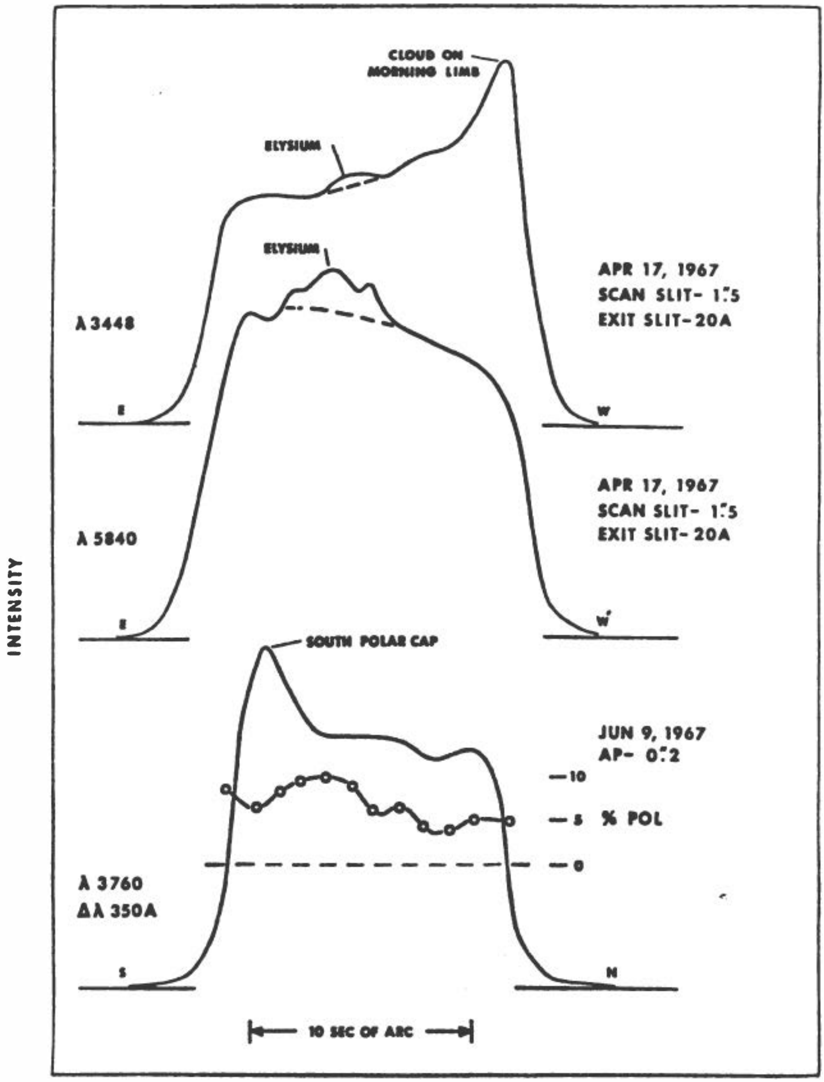

FIGURE 5 Scans of Mars near its 1967 opposition. The upper two curves are area scans made by Boyce in the E-W direction through Elysium. A spectral scanner was used to limit the wavelength band under observation. The solid curve at the bottom is one of eight intensity scans made by Hall in a N-S direction with a polarimeter. The resulting polarization is shown by the open circles.

TABLE 2 U.S. Facilities in Current Use in Planetary Radar Astronomy

Facility	Location	Operating Agency	Freq. (MHz)	Antenna Size	Average Transmitter Power (kW)	Typical Detection Sensitivity (Path Loss Threshold) (loss/m² in dB)
Arecibo Ionospheric Observatory (AIO)	Arecibo, Puerto Rico	Cornell University	430	1,000-ft diam, spherical	150	358
Deep Space Communication Complex (DSCC)	Goldstone Lake, Calif.	Jet Propulsion Laboratory	2,388	85-ft diam transmit, 210-ft diam receive, paraboloid	100	358
Haystack Microwave Facility (HMF)	Tyngsboro, Mass.	MIT Lincoln Laboratory	7,840	120-ft diam, paraboloid	400	365

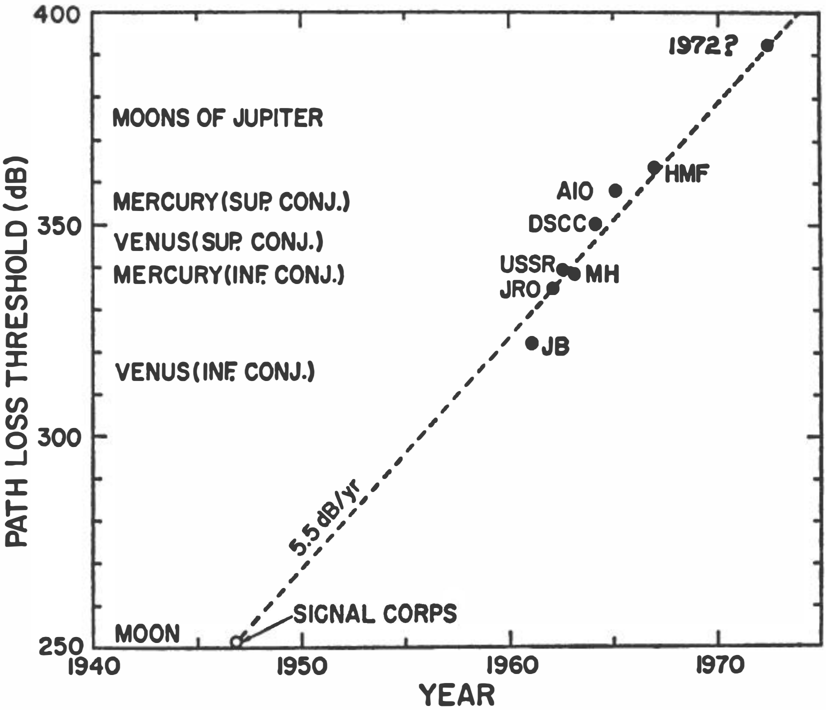

FIGURE 6 Growth in sensitivity of radar astronomy systems since the first detection of the Moon in 1946. The ordinate is a logarithmic scale and represents the path loss which the plotted facility is powerful enough to overcome. Several representative experimental landmarks are shown next to their associated path loss. JB, Jodrell Bank, University of Manchester, England; JRO, Jicamarca Radar Observatory, Environmental Science Services Administration and Instituto Geofisico del Peru, Jicamarca, Peru; MH, Millstone Hill, MIT Lincoln Laboratory, Westford, Mass.; USSR, Institute of Radio Engineering and Electronics, Crimea, USSR; DSCC, Deep Space Communication Complex, Jet Propulsion Laboratory, Goldstone Lake, Calif.; AIO, Arecibo Ionospheric Observatory, Cornell University, Arecibo, P.R.; HMF, Haystack Microwave Facility, MIT Lincoln Laboratory, Tyngsboro, Mass.

research, radio astronomy, and tracking and communicating with deep-space probes. Because of their high cost, future radar facilities will likely also be shared with other types of research that require large antenna systems. At the present time, no firm plans exist for the construction of facilities that would maintain the momentum of radar growth as shown in Figure 6. Table 3 lists several possibilities currently under consideration and the dates by which they might be realized if funding and authorization were provided in the near future.

The antenna is the element of a large radar system that normally costs the most and presses hardest at the frontiers of technology. Since it is involved twice in the radar process, first in transmission and later in reception, the sensitivity of the system is critically dependent on antenna size. In fact, at a given

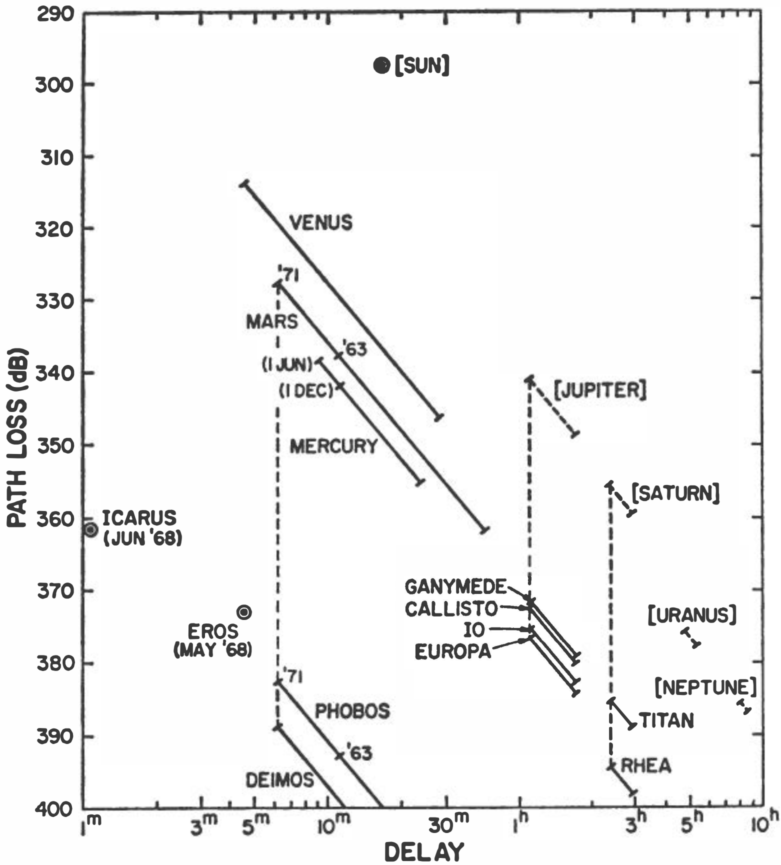

FIGURE 7 The estimated radar detectability of a number of possible targets in the solar system shown in terms of their logarithmic path loss and plotted against the round-trip radar echo delay. The variation in path loss and delay for a given target reflects its varying distance from Earth. Targets shown with dotted lines have deep atmospheres and consequently have radar scattering properties which are difficult to predict. They are shown for reference under the (unlikely) assumption that they have reflectivity as low as 0.1.

TABLE 3 Possible Future Configurations for U.S. Radar Astronomy Facilities

Facility	Location	Probable Operating Agency	Earliest Avail. Date	Freq. (MHz)	Antenna Size	Average Transmitter Power (kW)	Venus/Mercury Sensitivity (Path Loss Threshold) (loss/m² in dB)
Deep Space Communication Complex	Goldstone Lake, Calif.	Jet Propulsion Laboratory	1969	2,388	210-ft diam, paraboloid	500	372
Arecibo Ionospheric Observatory (Upgraded)	Arecibo, Puerto Rico	Cornell University	1970	2,400	1,000-ft diam, spherical	500	387
Northeast Radio Observatory Corporation	Not definite	Group of northeast regional universities	1973	4,500	440-ft diam, paraboloid	2,000	392

wavelength, sensitivity varies as the fourth power of the antenna diameter. Thus the antenna is identified as the key element in any radar configuration and should receive the major emphasis.

Since many years' lead time is involved in realizing the next generation of facilities, essential decisions on funding responsibility should be made promptly. Radar astronomy has come of age in the shadow of large installations built primarily for other purposes, and its source of support has tended to remain invisible. Both the value and the cost of radar research call for a more forthright recognition of its potential in planetary astronomy.

Radio

Radio observations have been used to study planetary surfaces either at low resolution, referring to the entire surface, or at high resolution to make more detailed studies. More than a dozen radio telescopes have been used to measure radiation from the entire disk of planets. Only two, however, at wavelengths greater than 3 cm, have sufficiently high resolution to study limited portions of planetary surfaces. They are described in Table 4. In addition, high angular resolution has been achieved with a very-long-baseline interferometer to locate the sources of decametric emission from Jupiter.

Using delay-Doppler techniques, the resolution currently attainable by radar for the Moon and Venus is about 2 sec of arc. The resolution of the existing connected radio interferometers having the highest resolution is about 10 sec of arc. A resolution of 1 sec of arc has been achieved with a very-long-baseline interferometer at 15-m wavelength.

There is now no plan or proposal to fill the need for greater collecting area or for higher resolution at wavelengths shorter than 3 cm. This spectral region is important in studies of planetary atmospheres and for surface studies of

TABLE 4 Major U.S. Facilities Used for High-Resolution Planetary Radio Astronomy

Institution	Location	Number and Size of Reflectors	Wavelength (cm)
California Institute of Technology	Big Pine, Calif.	(2) 90 ft	>3
National Radio Astronomy Observatory	Green Bank, W. Va.	(3) 85 ft	>3

TABLE 5 Possible Future Major Facilities That Could Be Used for Planetary Radio Astronomy

Institution	Location	λ (cm)	Facility
California Institute of Technology	Big Pine, Calif.	>3	High-resolution array of (8) 130-ft reflectors
Cornell University	Arecibo, Puerto Rico	>10	Upgrade surface of 1,000-ft reflector
National Radio Astronomy Observatory	Southwest U.S.A.	>3	High-resolution array of (36) 82-ft reflectors
Northeast Radio Observatory Corporation	Massachusetts	>5	Fully steerable 440-ft reflector

Mercury and Mars similar to those made of the Moon. Such radio telescopes would also contribute significantly to galactic and extragalactic research. Four possible future radio facilities which will make possible improved planetary studies are listed in Table 5.

Optical

The percentage of time currently allocated to the observation of the Moon and planets with large optical telescopes is shown in the final column of Table 6. Although these percentages seem very low, two points should be made with

TABLE 6 Recent Use of Optical Telescopes for Lunar and Planetary Research

Institution (Telescopes)	Aperture (in.)	Years Included	Use (Percent of Time)
Mt. Wilson and Palomar	200	1966–1967	3
	100	1966–1967	4
	60	1966–1967	10
Lick	120	1965–1967	5
Kitt Peak	84	1965–1967	5
	60	1965–1967	14
McDonald	82	1965–1967	23
Perkins[a]	72	1966–1967	13
University of Arizona			
Lunar & Planetary Laboratory	61	1966–1967	28
	60	1966–1967	28

[a]Perkins Telescope of Ohio Wesleyan and Ohio State Universities at the Lowell Observatory.

TABLE 7 Optical Telescopes under Construction for Lunar and Planetary Research

Institution (Telescope)	Aperture (in.)	Estimated Completion
University of Texas (McDonald)	105	1968
University of Hawaii (Mauna Kea)	84	1968

regard to their interpretation. Those responsible for the assignment of telescope time have made it clear that each request is judged solely on its merits and not on the branch of astronomy to which it pertains. Also, it is not possible to assign large blocks of time on a major instrument to any single project.

Except for the occasional need for large blocks of time (either for use of special instruments for very favorable planetary oppositions or for unusual events such as the appearance of a bright comet or unusually favorable weather conditions), ground-based observational requirements in the Northern Hemisphere appear to be met by existing telescopes. Additional needs in the near future could be filled at least in part by the two major instruments now under construction (Table 7) and by an inexpensive large telescope recommended in Chapter 8.

There is, however, only one moderately large (60-in.) American telescope in the Southern Hemisphere. Its use is shared by American and Chilean astronomers. Another instrument placed at a similar site of superb seeing is badly needed to permit observations of all planets where maximum resolution is of utmost importance and for observations of Mars at its most favorable oppositions which occur when the planet is at large southern declinations.

7

Graduate Training in the Planetary Sciences

INTRODUCTION

Until the last quarter of the nineteenth century, planetary research was in the mainstream of astronomy and in many respects dominated it. In Todd's *New Astronomy* (1897), only the final (and sixteenth) chapter is concerned with objects outside the solar system; three of 20 chapters in Young's *Manual of Astronomy* (1902) discuss the sidereal universe.

The effort expended in planetary, as opposed to sidereal, astronomy declined rapidly in the first 60 years of this century. This decline is related to the development of large telescopes with their ten- to twentyfold increase in light-gathering power and to the growth of astrophysics. There has been no corresponding increase in angular resolution, partly because of the severe limitations imposed by atmospheric turbulence. Such factors have turned the attention of astronomers to studies of the galaxy, interstellar matter, and the extragalactic universe. These studies have resulted in an evolutionary picture of the solar system prior to the formation of its solid components about 5 billion years ago.

Today, the opportunity to explore components of the solar system directly, with space probes or with improved indirect methods, has again opened the field to new interest, causing scientists trained in other disciplines to turn their talents to planetary research. The increased efforts promise to lead to a far better understanding of the more recent history of the solar system.

The question arises whether the total influx of new blood is adequate to support an imaginative space program. It is not possible at this time to provide an authoritative answer. It is, however, worthwhile to present as complete a picture as possible of the present educational trend, despite the difficulties involved in obtaining such information.

This educational trend has been studied. It has been done by examining the rate at which PhD's in planetary science are being produced in the United States and the growth of that rate. Further, it is of interest to learn something of the distribution by field of interest of the new PhD's and of the academic departments responsible for their education.

SURVEY OF DOCTORAL AWARDS IN THE PLANETARY SCIENCES

To carry out a meaningful survey it is first necessary to define a "planetary-science PhD." This was taken to be an individual whose PhD thesis clearly was concerned with the Moon, planets, comets, asteroids, or meteorites. Generally, mention of one of these objects was required in the title or abstract. Some leniency was exercised for theses on theoretical atmospheres and in a few other cases. On the other hand, a number of peripheral fields were excluded in order not to obscure the truly planetary-oriented works. Specifically excluded were: the low-density interplanetary medium, the field of "space physics," the Sun and its immediate environment, Earth-like models of planetary interiors, and dynamics of artificial Earth satellites.

Since no complete listing could be found of titles and abstracts of all U.S. PhD theses, an indirect approach was necessary. First, a survey was made of all planetary-science papers published from July 1960 to June 1967 in three leading journals: *The Astrophysical Journal*, *Journal of Geophysical Research*, and *Icarus* (initiated in 1962), and the authors having university affiliations were listed. A total of 243 such papers were identified, with 256 authors from 53 different departments or other organizational subdivisions within 32 universities.

A master list of departments and universities was thus obtained, and a search for specific PhD theses was begun. It was presumed that only under exceptional circumstances would a planetary-science thesis be prepared at a university at which there was no faculty publication in planetary science. Appropriate individuals at most of the institutions were interrogated and were asked to check with their own and other relevant departments and to send in the identified PhD theses' titles and abstracts for collation.

As a result of this survey and a few other independent checks, a total of 80 planetary-science PhD theses were identified for the July 1960–June 1967 period. The yearly rate is shown in Figure 8. Although the survey obviously was not complete—a few omissions are already known—it is considered un-

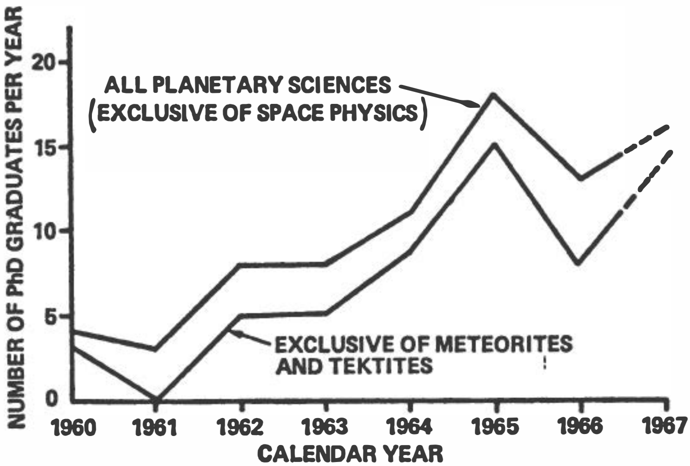

FIGURE 8 Number of PhD degrees granted in the United States in planetary science in recent years. The corresponding number of degrees in 1965 in physics, astronomy, and all earth sciences was about 1,000, 65, and 400, respectively.

likely that the correct number exceeds 100. The distribution by field, department, and university is shown in Figure 9.

ANALYSIS OF SURVEY FINDINGS

The survey shows that the current rate at which planetary-science PhD degrees are awarded is about 15 per year. It is clear that an insignificant fraction of NASA traineeships was used to support planetary-science training. It is difficult to understand why the annual rate is so low when the support available (until recently) for graduate study and research in planetary science has been both ample and diversified, and a national program of lunar and planetary probes was in operation. It is also curious that not a single thesis was identified that could be classified as in exobiology; not one was recognized as being truly "space-related."

Many factors undoubtedly are involved. However, a dominant reason for this may well be the fact that very few academic institutions have departments or other units committed to planetary science. Figure 9 shows that awards of PhD degrees in planetary science are not weighted heavily toward any single field, university, or department; and planetary science in three out of four cases is carried on as a sideline in departments primarily concerned with the Earth, the cosmos, or applied physics or engineering.

It is apparent that rapid development of new techniques has served to shift planetary research from the astronomy discipline to other departments. Radio and radar astronomy are often fostered in departments of electrical engineering, the interpretation of lunar photographs in departments of geology. While such shifts have served to increase greatly the number of workers in planetary astronomy and the number of PhD degrees awarded for theses in that field, one may raise the question whether they have always provided the best training for planetary astronomy.

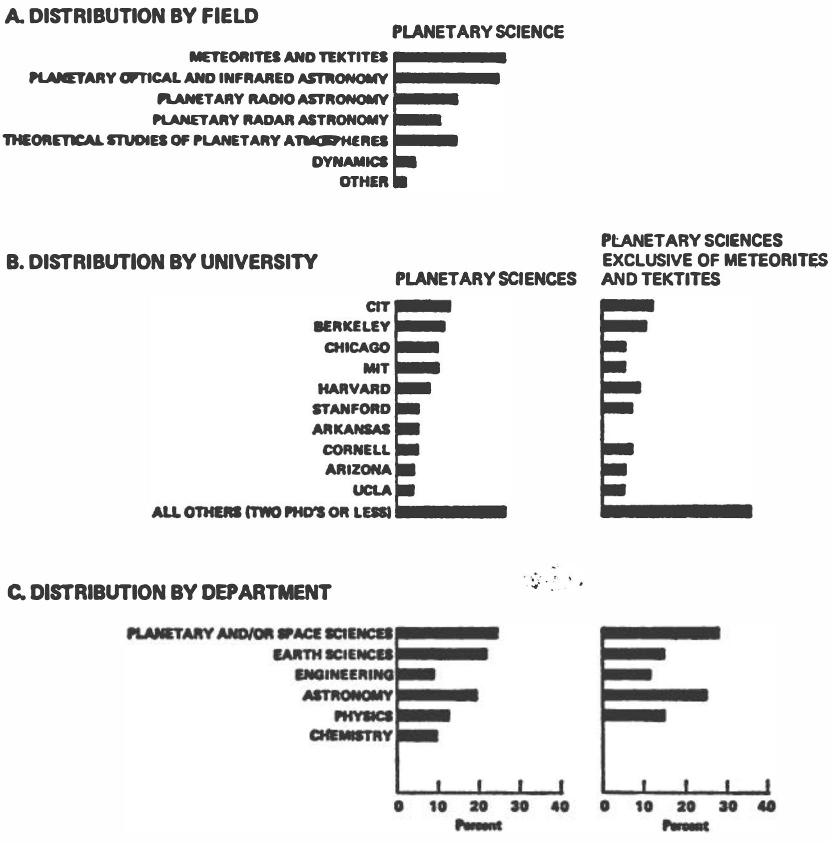

FIGURE 9 Distribution of planetary-science PhD's, 1960–1967. (Planetary science does not include space physics in this breakdown.)

A second reason for the small annual number of PhD's in planetary science may be that a planetary astronomer should have knowledge in a large number of fields: astronomy, physics, chemistry, mathematics, instrument design, geology, meteorology, and, in some cases, biology. This suggests interdisciplinary graduate programs in planetary astronomy. It is not of great concern which department is responsible for granting the degree, but it is important that work in several departments be not only permitted but actively encouraged.

This is borne out by the finding that six of the ten graduate schools most productive of planetary-science PhD awards have some form of interdisciplinary research, or an academic structure that has played a major role in providing a "home" for such students. The absence of a greater number of active, specialized planetary-science departments may reflect some skepticism about the permanence of the space effort, as well as the traditional conservatism of universities.

If the federal government, including the Congress, commits the nation to a long-term planetary-exploration program, the rate of PhD production in planetary science will probably increase as university confidence in the stability and continuity of the national program develops. Both an increase in national interest and interest at the university faculty level will probably have more impact on the number and quality of newly trained planetary scientists than will specific fellowship programs.

8

Recommendations

In this chapter, the Space Science Board's Panel on Planetary Astronomy makes eight prime recommendations involving new equipment and better use of existing facilities. In addition to the specific recommendations, the Panel indicates areas requiring greater attention if ground-based studies are to be conducted most effectively.

In making these recommendations the members of the Panel have endeavored to project the needs of planetary astronomy over a ten-year period.

Studies conducted by the Space Science Board * have indicated important gaps in our knowledge of the planets. Many of these can and should be partially filled by ground-based observations.

A large amount of time is needed by qualified observers on moderate-size telescopes for optical measurements on the planets, satellites, and comets. As already mentioned (see Radar, Radio, and Optical Facilities, page 55), this need becomes acute at times of special events or at the most favorable oppositions and for those projects that require either superb seeing or large blocks of time. Such blocks of time are rarely, if ever, available on existing telescopes.

For many planetary studies, a most important consideration is resolution.

* Space Science Board, *A Review of Space Research,* NAS-NRC Pub. 1079 (Natl. Acad. of Sciences–Natl. Res. Council, Washington, D.C., 1962); Space Science Board, *Space Research: Directions for the Future,* NAS-NRC Pub. 1403 (Natl. Acad. of Sciences–Natl. Res. Council, Washington, D.C., 1966).

This problem has been discussed with reference to planetary surfaces (Chapter 3), but it applies equally to features in atmospheres and comets. New techniques are becoming available which promise to improve photographic resolution after exposures are made (see Chapter 6). The most important requirement, however, is to locate instruments at sites where the seeing is optimal. Recently, a site has been developed in northern Chile (Chapter 6) that is capable of providing resolution far superior to that at other observatories. It would be difficult to overemphasize the importance of such improved seeing for planetary studies.

Special emphasis should also be laid on extensive and versatile spectroscopic facilities at a fixed (coudé) focus. Many recent advances in planetary spectroscopy have been based on spectral resolution of approximately 100,000. Such performance can be obtained only with large, delicate equipment.

Many of the requirements can be met by telescopes with apertures of approximately 60 in. With the limited size of available gratings, a telescope of larger aperture does not provide more useful light but allows a fixed amount of light to be taken from a smaller area of the planet. Also, with a 60-in. aperture, the occasional periods of very steady seeing can probably be fully exploited.

The study of highly variable phenomena in planetary atmospheres sometimes requires continuous observation over many hours. It is therefore important that the longitude chosen for a planetary telescope of this aperture be such that it complements the longitudes of other planetary instruments. The length of time any given instrument can be used to observe a planet depends upon the planet's position in the sky and the latitude and elevation of the observatory. Low southern latitudes are particularly favorable for observing Mars at its closest approaches. At a high elevation there is less atmospheric absorption. These requirements could be met by a site in northern Chile.

Because of its relationship to the space program, it is important that such a telescope be placed in operation as soon as possible, and certainly prior to the very close approach of Mars in August 1971.

1 *We recommend that a 60-inch telescope with mirrors of superior optical quality and designed specifically for spectroscopy, interferometry, photography, and photometry of the planets be erected as soon as possible at a dry site with exceptionally good seeing in the Southern Hemisphere.*

Chapters 2 and 3 have detailed the contributions that radar astronomy is making to planetary studies in testing gravitational theory and in determining orbital elements, planetary radii and rotations, and characteristics of planetary surfaces and atmospheres. Some of our most dramatic increases in knowledge in planetary astronomy have come from radar studies; and radar data have proved vital in the planning of space-probe missions. The further development of radar planetary astronomy will depend upon the development of new facilities with expanded capabilities.

2 *We recommend that maximum use be made of existing facilities capable of doing radar astronomical work. We also recommend the construction of a large filled-aperture radio-astronomical facility with maximum sky coverage and with capability for planetary radar astronomy.*

Although high-resolution work is becoming increasingly desirable, important infrared photometry and Fourier spectroscopy can be done at the coudé focus of an instrument of lower resolution than that required in the visible wavelengths. The recent development of inexpensive telescopes using all-metal mirrors has made significant contributions in the infrared region. A 120-in.-aperture telescope would collect larger amounts of radiation and would provide increased spectroscopic resolving power in the infrared windows and in the 1-mm regions of the spectrum. It would be essential, however, that image precision not be relaxed below 1 or 2 sec of arc in the visible because the signal-to-noise ratio of infrared detectors depends upon the detector size. The effectiveness of such a telescope will be highly dependent on the use of a site characterized by very low water-vapor content.

3 *We recommend that a 120-inch, relatively inexpensive light collector with a coudé focus for spectroscopic and photometric observations be constructed at a site having exceptionally low water-vapor content.*

Studies made in the infrared reveal the great potential of this region for studies of planetary atmospheres (Chapter 4). If the full benefits of such studies are to be realized, it is necessary to be able to make observations from above much of the water vapor in the Earth's atmosphere. NASA has considered the installation of a 36-in. infrared telescope on the Convair 990 jet airplane based at the Ames Research Center. Such an installation would provide planetary and stellar astronomers with a national facility capable of observations in the entire range from 1 to 1000 μ above 99 percent of the water vapor that obscures much of this region from the ground.

4 *We recommend that a 36-inch infrared telescope be installed in the Ames Convair 990 and that it be available to qualified users as a national facility.*

Radio astronomy has made important contributions to the study of planetary surfaces and atmospheres. Higher resolution must be achieved if we are to see marked improvement over observations already made, which tax existing capabilities. In addition to construction presently planned, a major facility is needed to provide resolution of a few seconds of arc in the region of the spectrum from 3-cm to millimeter wavelengths. Such a national facility would contribute significantly to galactic, extragalactic, and planetary research. Greater collecting area than is now available is also necessary to aid the search for spectral lines in planetary atmospheres in the millimeter region of the spectrum.

5 *We endorse the recommendation of the Whitford Committee* for construction of large radio-telescope arrays by the National Radio Astronomy Observatory and the California Institute of Technology. They will provide facilities for high-resolution planetary observations at centimeter and decimeter wavelengths. We also recommend that a high-resolution 3 cm-to-millimeter wavelength radio facility be constructed and made available for planetary studies; and that the feasibility of a radio facility able to provide large collecting area for low-resolution observations at millimeter wavelengths be studied.*

Recent work in the infrared spectroscopy of planetary atmospheres, discussed in Chapters 4 and 6, has emphasized the value of high-resolution Fourier spectroscopy. The technique makes possible new studies in planetary atmospheres: the determination of the rotational temperatures of the constituent gases and the detection of isotopes and trace elements. Fullest exploitation of this technique will be possible when observations can be made from airplanes above the tropopause.

6 *We recommend the development of Fourier interferometers with resolutions of at least 10,000 for ground-based observations. One such instrument should be sufficiently rugged for later adaptation to high-altitude aircraft.*

Chapter 6 was concerned with some of the newer techniques being applied to planetary observations. Such technological improvements and new developments often produce the most dramatic increases in our knowledge of the planetary system, yet it is virtually impossible to predict where such technological breakthroughs will occur.

7 *We recommend that the importance of technological development be recognized by ensuring that funds are available to support it. Advances in our knowledge are particularly dependent upon the development of radiation detectors in the ultraviolet, visual, infrared, and millimeter regions of the spectrum; further development of image tubes; and devices for improving the quality of astronomical images.*

* Panel on Astronomical Facilities of the National Academy of Sciences Committee on Science and Public Policy, *Ground-Based Astronomy: A Ten-Year Program,* NAS-NRC Pub. 1234 (Natl. Acad. of Sciences–Natl. Res. Council, Washington, D.C., 1964), pp. 50 and following.

Cooperative observational programs are important in planetary astronomy. The variability of many planetary features must be studied by extensive photographic patrol. Such a patrol can be expected to yield new understanding of the dynamics of the atmospheres of Jupiter, Mars, and Venus. It will also provide a necessary permanent and continuous record of planetary phenomena for timely comparison with more detailed or specialized technical studies.

8 *We recommend the establishment of a worldwide photographic planetary patrol, appropriately distributed in longitude to ensure adequate coverage, for the period from January 1, 1969, to January 1, 1974. One or two new reflectors in the 24- to 30-inch class may have to be erected at appropriate sites to complete this patrol.*

In addition to the above recommendations, other areas are important in the development of planetary studies.

Astrometric Observations of Comets and Asteroids

The present, almost total, lack of astrometric observations of comets and asteroids made in the Southern Hemisphere limits study of comets whose orbits are only fractionally north of the ecliptic and restricts observations of asteroids that come to opposition during the short nights of northern summer. An astrographic telescope of moderate size (capable of reaching a limiting magnitude of at least 17.0) located in the Southern Hemisphere, and available for astrometric observations of comets and asteroids, would do much to remedy the imbalance produced by such selection effects.

Observations of asteroids as faint as magnitude 17 are required on a regular basis to maintain the quality of orbits of known asteroids, to improve the orbits of recently discovered objects, and to extend orbital statistics to fainter asteroids.

A larger number of competent astronomers could well enter this field. Observations of asteroids and comets contribute fundamental data that may be very important to our understanding of the evolution of the solar system and in the past have laid the foundations on which exciting discoveries were made.

There is also a need for better measuring and data-handling equipment so that the more tedious aspects of reduction procedures can be automated as far as possible.

The Recovery of Extraterrestrial Matter

Meteorites are the only samples of extraterrestrial material that we can examine directly in the laboratory. This material comes to us without cost; it is necessary only to identify and collect it. While considerable effort is already being expended on this task, the great value and relative scarcity of the material calls for additional support and encouragement.

In particular, existing photographic networks could be supplemented with microbarographs and radar installations to extend to daylight hours observations of incoming objects. Existing radar facilities operated by the Air Force may be suitable for this work. A greater effort would be worthwhile for the recovery of truly unusual falls such as Revelstoke, where a powdery material was dispersed over a large area. This type of operation requires careful instruction of the searchers to prepare them to identify the material and, occasionally, the use of sizable teams to cover an area thoroughly. With respect to this problem of manpower, it may be useful to look into the possibility of mobilizing scouts, military personnel, or forest rangers to collect material from a special fall.

Ultraviolet Observations of Planets and Comets

The spectral region below 3000 Å has only recently become the object of systematic investigation. At the time of this writing, there have been only five observations of the planets, and none of comets. Yet in many respects this spectral region is fully as important as the infrared for the potential information it contains about atmospheric characteristics. (See also Use of Airplanes, Balloons, Rockets, and Earth Satellites, page 50.)

Resonance transitions of most atoms and molecules occur at these wavelengths, with the result that very small quantities of a given substance can be detected; for some species such as helium and argon, it is the only region of the spectrum where we can hope to obtain direct evidence of their presence. In addition, because of attenuation in planetary atmospheres, one is generally probing only the upper strata, regions that are generally very difficult to explore at other wavelengths.

Ultraviolet observations will also enable us to examine planetary coronas formed by escaping atomic constituents such as hydrogen and oxygen. Studies of these coronas with high spatial resolution will provide information on exospheric temperatures and thus the escape rate of atmospheric constituents.

In the case of comets, we can observe molecules and atoms such as H_2, N_2, O_2, N, O, and C with resonance transitions below 3000 Å. We may be able to observe more complex molecules—which are probably more closely related to the parent material of the nucleus—by means of their electronic transitions.

We recommend that additional rocket flights be supported for planetary spectral studies at relatively high dispersion (~1 Å) and that attention be given to the possibility of rocket firings at short notice to observe a bright comet. Furthermore, consideration should be given to the use of future

Orbiting Astronomical Observatories for ultraviolet observations of planets and comets.

Laboratory Measurements

There is need for laboratory intensity measurements of many of the gases thought to be constituents of planetary atmospheres. Equivalent widths or integrated intensities are needed, with much higher resolution than has been obtained, for band lines of CO_2, H_2O, CO, HD, CH_4, and NH_3 and for minor constituents that may be discovered in the future. Detailed analysis of the rotation-vibration spectrum of CH_4 and NH_3 is probably necessary because of complexities resulting from the dramatically different temperatures of outer planets and their satellites. An alternative to analyzing these spectra (at first in the atmospheric-window regions) is to measure the equivalent line-widths in the laboratory at the appropriate low temperatures. This is most desirable but very difficult because of the long path lengths required. For the outer planets, low-resolution spectra should probably be obtained in the laboratory with CH_4 paths up to 10-km atmospheres.

In many cases it would be desirable to simulate window-region spectra in the laboratory and measure them with a precision of from 0.001 to 0.002 cm^{-1}, since the Mars and Venus spectra can be obtained with this precision. This is particularly desirable for CO_2, for it is of interest to determine the $^{12}C/^{13}C$ isotopic ratio.

To obtain accurate abundances in the face of saturation produced by the strong absorptions, it will probably be necessary to determine curves of growth.

Facilities, both long-path absorption cells and suitable spectrographs, are available at several places in the country to accomplish the necessary laboratory calibrations. This work involves only conventional grating spectroscopy, and available facilities are adequate to the task. Calibrations can alternatively be made using Fourier interferometers with their distinct quantitative advantages.

A systematic, coordinated laboratory program should be supported to determine the effects on spectral signatures (ultraviolet to microwave) of varying the physical and chemical parameters of likely planetary surface materials. In conjunction with this, programs of lunar and planetary direct sampling should be planned in such a way as to permit the calibration of Earth-based observations.

Personnel Requirements

The following general recommendations arise from the statistical data and the discussion presented in Chapter 7. If the United States intends to carry on a substantial and effective planetary space program, and if the scientific community wishes to take full advantage of this unique opportunity to pursue studies in planetary science, then graduate schools where planetary studies are done, or those interested in developing programs in this field, should consider organizing interdisciplinary programs to provide broad training. Furthermore, emphasis and financial support should be given to postdoctoral training in the planetary sciences at centers at which planetary research is being actively pursued.

The establishment of a national society for planetary sciences or of an affiliate of an existing society would be highly desirable to serve as a forum for discussion and a cohesive force to facilitate recruitment of personnel, to assist in obtaining financial support or facilities for projects of unusual merit, and to encourage publication of results.

SUMMARY OF RECOMMENDATIONS

The Space Science Board Panel on Planetary Astronomy recommends ways in which ground-based planetary astronomy can advance our knowledge of the evolution of the solar system and contribute substantially to a significant planetary space program. These involve both instrumental advances and increases in personnel.

On the instrumental side, several telescopes are recommended. One is a precision optical instrument to be placed in the Southern Hemisphere, and two are reflectors suitable for use in the infrared. For longer wavelengths, the Panel urges that existing facilities for planetary radar observations be used more extensively and supports previous proposals for radio-telescope arrays. It recommends the construction of a new large filled-aperture facility suitable for planetary radar astronomy and a high-resolution 3-cm-to-millimeter facility for high-resolution radio investigation. It urges that continuing study be made to determine the type of radio facility most appropriate for low-resolution measurements at millimeter wavelengths.

The other recommendations include technological developments—particularly Fourier interferometers—and an effective worldwide photographic planetary patrol. The Panel recommends greater effort in astrometry, recovery of extraterrestrial matter, and laboratory spectroscopy. It emphasizes the importance of extraterrestrial observations.

In the light of findings of a survey, the Panel urges that curricula or organizational boundaries of graduate schools be revised if the planetary sciences are to attract more and better-trained students. Also, it suggests that further emphasis be placed on postdoctoral training and that a planetary society or subgroup of an existing society be established. These last two recommendations would be of particular importance to those trained in other disciplines who wish to apply their talents to problems in planetary astronomy.

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