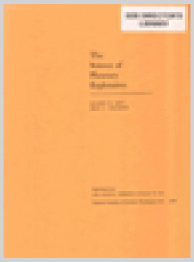

The Science of Planetary Exploration

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The Science of Planetary Exploration

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Scientific interest in solar-system bodies and the motivation to explore and study them are driven by a number of expectations. We expect that, by determining the composition, structure, and distribution of planets and of smaller objects orbiting the Sun, we will take major steps toward understanding conditions in the early solar nebula and the processes that controlled formation of the planets. We expect to discover important clues about the evolution of the planets to their present states and about the chemical and physical conditions that led to the appearance of life. We believe that intensive study of other planets will strengthen our grasp of the general rules by which planets behave and ultimately will enable us to decipher the Earth's history and to understand the nature and stability of planetary environments. This last goal may take on increasing significance as perturbations of

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the Earth's atmosphere and ocean resulting from human activities grow in magnitude.

Scientific exploration of the solar system and its bodies is one of the ways that we extend our direct experience of the laws of nature and their manifestations. Many natural phenomena are governed by processes only discernible in objects of extremely large physical scale and over times of long duration. These processes are not readily amenable to controlled laboratory investigation and often are not even potentially susceptible to that approach. We expect that, by extending our direct experience to the diverse but accessible bodies in which these processes may occur naturally, we will improve our understanding of the behavior of the world in which we live. These exotic phenomena range over broad areas of science; they include, for example, the tectonic processes that shape the surfaces of terrestrial planets, the escape and evolution of planetary atmospheres, and the energetic plasma processes that seem to accelerate particles in objects as diverse as planetary magnetospheres, the solar corona, and astrophysical radio sources.

GOALS AND CONSTRAINTS IN PLANETARY EXPLORATION

Direct exploration and study of the solar system demand a dedication of effort and resources only possible through a significant national commitment. The return, however, is comparably significant. The level of intellectual and scientific inquiry is not only an important measure of a people's vigor, but also a stimulus to progress in modern societies.

Nevertheless, realistic constraints limit the level at which such activities can or should be conducted. These constraints are especially apparent in the exploration of planets and other, similar deep-space adventures. By their very nature, these activities involve many people, large amounts of time, and large expenditures. Spacecraft missions are limited in number and frequency, so that the empirical basis of solar-system science depends, to a large extent, on the technical and intellectual success of a relatively small number of measurement opportunities. It is important, therefore, to make optimum use of these limited opportunities, to ensure that exploration programs elucidate significant questions and that the quality of returned data makes a substantial contribution to our knowledge and understanding.

In practice, the planning and execution of a planetary exploration mission takes five to ten years. This inhibits the normal conduct of scientific investigation, which relies on the ability to interact with experiments and to devise new measurements in response to the results. Planetary exploration inevitably reveals unanticipated and surprising facts that cause us to rethink our assumptions and that promote enthusiasm for a new generation of studies. It is important that exploration strategies chart a balanced course between responsiveness to new discoveries, continuous attention to major scientific questions, and coherence in planning on the roughly ten-year time scale necessary for designing and carrying out many of the exploratory missions. Generally, the ability to strike a balance in this kind of scientific exploration is enhanced by setting long-term goals for study. Substantial progress toward realization of these goals requires specific strategies of investigation that should rest securely on our current knowledge of solar-system bodies and should aim at testing our ideas about their behavior, origin, and evolution.

PRESENT KNOWLEDGE OF THE SOLAR SYSTEM

The planets divide naturally into two classes on the basis of size, density, and position in the solar system. The major planets—Jupiter, Saturn, Uranus, and Neptune—contain most of the mass and angular momentum of the solar system, are of low mean density (1–2 $g cm^3$), and range from 5 to 30 AU (Astronomical Units) in distance from the Sun. (An Astronomical Unit is the mean distance from the Earth to the Sun, approximately 93 million miles.) These large outer planets are rich in volatiles, especially hydrogen and helium, have low surface temperatures, and have well-developed satellite systems that mirror, in a fashion, the solar system itself. The inner planets—Mercury, Venus, Earth, and Mars—are by contrast smaller in diameter, higher in density (4–5 $g cm^3$), and range from 0.4 to 1.5 AU in distance from the Sun. The inner planets are composed chiefly of rock and metal, are comparatively poor in volatiles, and have few satellites. The ninth planet, Pluto, which is 40 AU from the Sun, is clearly different from the other outer planets with its small mass and radius and the unusually large satellite-to-planet mass ratio of its single known moon.

In addition to the planets and their satellites, the solar system contains numerous small bodies with a wide range of sizes and characteristics. The asteroids are dominantly rocky and metallic objects up to 1,000 kilometers in diameter and are chiefly confined between the orbits of Jupiter and Mars. Comets are volatile-rich bodies; many have highly eccentric orbits and pass close enough to the Sun to give rise to spectacular comas (nebulous mass surrounding the nucleus of the comet) and tails.

Comets are thought to have spent most of their lifetimes in cold storage in a large cloud surrounding the solar system and extending to about 50,000 AU. Occasionally, a comet is deflected by gravitational disturbances produced by nearby stars and is sent into the inner solar system where it can be observed. Meteorites were probably originally derived from either asteroids or comets.

Origin of the Solar System

All these solar-system bodies—planets, satellites, asteroids, and comets, as well as the Sun—are believed to have originated in the expanse of gas and dust that constituted the proto-solar nebula. The mechanism of collapse of this nebular cloud into the proto-Sun and proto-planets is not known. One theory, stimulated by the recent discovery of distinctive isotopic anomalies in certain primitive inclusions in carbonaceous chondrite meteorites, suggests that star formation in the proto-solar nebula was triggered by a supernova shock wave. Matter injected into the nebula from the supernova, according to this view, would be rich in such nuclides as ^{16}O and ^{26}Al and would not likely be homogeneously mixed throughout the nebula. Isotopic anomalies dating from this event might be expected to be preserved in portions of those primitive objects distant from the Sun and never subjected to substantial heating and isotopic reequilibration.

The chemistry and mineralogy of chondritic meteorites and the bulk composition of the inner planets and the planetary satellites are crudely consistent with the idea that these characteristics were shaped by chemical equilibrium in a medium of roughly solar composition. According to this theory, pressure and temperature decreased with distance from the center of the early solar nebula, and equilibrium thermodynamics dictated which materials condensed as solids and which remained gaseous at varying distances from the Sun. At some point, much of the uncondensed material must have been dissipated, perhaps by an unusually strong solar wind. Whether proto-planets with massive atmospheres formed prior to the dissipation of nebular gases is not certain. In any case, this sweeping out of gas is called upon to leave the inner solar system volatile-poor while preserving the gaseous material now in the atmospheres of the outer planets.

This chemical equilibrium model for the formation of planetary material leads to the prediction that the planets should range in composition from Mercury as the most refractory to the volatile-rich objects in the outer solar system. Equilibrium at 600°K can account for the characteristic assemblage of metallic iron, ferromagnesian silicates, and ferrous sulfide in the ordinary chondrites. Equilibrium at still lower temperatures, below 150°K, yields the ices of H_2O, NH_3, and CH_4 as major components of the condensed phase, which are characteristic of planets far from the Sun.

The Inner Planets

Among the objects in the solar system, the inner planets and their satellites are the best known. Though broadly similar in composition, the inner planets vary in mean density from 5.5 $g cm^3$ for Mercury to 3.9 $g cm^3$ for Mars. The variation in planetary mean density with solar distance can generally be explained by the equilibrium condensation model for proto-planetary material. The moons of Earth and Mars, substantially lower in uncompressed density than the planets they orbit, are less easily explained by the simple nebular condensation model.

All the inner planets, including the Earth's Moon, have undergone significant internal heating and differentiation. The oldest preserved rocks on the Earth are about 3.7 billion years old, and most of the Earth's surface—the ocean floor—is less than 0.1 billion years in age. In contrast, the Moon has preserved some rocks dating back to its early episode of melting and crust formation 4.5 billion years ago and contains no rocks younger than the period of volcanic flooding of the lunar maria from 3.9 to about 3.0 billion years ago. The Moon has also recorded a period of intense meteor bombardment that ended about 3.9 billion years ago, a bombardment that produced many of the large impact basins on the Moon and presumably also occurred on all the inner planets at about the same time. This assumed heavy bombardment of the inner solar system has provided a chronological reference marker that has been the basis for constructing the geologic history of Mars and Mercury and may serve a similar purpose for Venus.

The inner planets differ substantially in the characters of their atmospheres. Both Mercury and the Moon are devoid of any stable atmosphere. The dominantly CO_2-rich atmosphere of Venus is nearly one hundred times more massive than the Earth's, while the CO_2-rich atmosphere of Mars is one hundred times less dense than that of the Earth. The noble-gas abundances in these three respective atmospheres roughly correlate with their atmospheric density. Venus and Earth have similar abundances of nitrogen with respect to planetary mass, while Mars is relatively depleted. Venus is covered by a dense global blanket of clouds composed in part of sulfuric acid droplets. Cloud motions indicate a global wind pattern with a substantial height-dependence to mean wind speed. Mars is known to have episodes of high-velocity winds that give rise to global dust storms. Mars also has climatological seasons, with cycling of CO_2 between the polar caps providing a major component of atmospheric circulation.

The Earth

The Earth is unique among the planets in the large quantities of free water on its surface and in its atmosphere. Water is present in the atmospheres of Mars and Venus, but is substantially less abundant. Water ice is also the chief component of the small residual polar caps on Mars. Mars shows evidence on its surface, however, of ancient large-scale flooding and fluvial erosion, suggesting both a denser atmosphere and abundant liquid water at some time in the Martian past. The present fate of that water is a major mystery; that substantial quantities of volatiles are held in a "permafrost" layer at some depth beneath the Martian surface is currently the most favored hypothesis. The Earth also stands alone among the planets, so far as is known, in that its surface, atmosphere, and hydrosphere have provided an environment conducive to the development of life and the evolution of complex living organisms. Because the surface of Venus is so hot (750°K), Mars has long been thought to be the planet next to Earth most likely to harbor life. The absence of detectable organic molecules on the Martian surface and the apparently hostile surface chemical and physical environment suggest that living organisms are not present on Mars. Whether Mars was less hostile to the development of life during earlier times, when it may have had a denser atmosphere and flowing surface water, is an important but open question.

The Earth's surface is now known to be in a state of continuing dynamic evolution. Crustal material is continually created at mid-ocean ridges and destroyed beneath the deep-sea trenches, as the plates that make up the Earth's surface move in more or less steady relative motion. The creation of huge mountain belts, the development of chains of volcanoes, and the driving force behind many large earthquakes are all linked to these plate motions. Neither the Moon, nor Mercury, nor Mars show evidence for global tectonics of such vigor or for the wholesale recycling of the surface into the interior. The surfaces of the Moon and Mercury preserve a clear record of early heavy meteor bombardment and of limited ancient volcanism and tectonic features associated with that volcanism or with tidal spindown and global cooling. The surface of Mars also shows a record of heavy meteor bombardment, slightly softened by subsequent wind erosion, but demonstrates a more extended and extensive history of volcanism and tectonics, though still less than on the Earth. The Venusian surface, hidden by permanent clouds, is largely an enigma. Limited low-resolution Earth-based radar images suggest a surface with both craters and large volcanoes, as on Mars, together with mountain belts as on Earth. Many of these are currently being mapped at low resolution by the Pioneer–Venus radar altimeter and imager.

The Earth's interior is known to be layered, a product of global differentiation. At the Earth's center is a metallic core, largely fluid and in convective motion, but with a small solid inner core. The core is surrounded by a mantle of ferromagnesian silicates, mostly solid and in very slow convective motion. The mantle is capped by a thin crust of igneous and metamorphic silicate rocks, generally overlain by a veneer of sedimentary material. Each of the other inner planets is thought to be similarly layered, but the evidence for this varies. The Moon is known to have distinct crust and mantle layers, and is covered by a regolith layer that is continually "gardened" by repeated meteor impacts. Mars is thought to have a core because of its low moment of inertia factor and a crust because of the isostatic compensation of its surface topography. Mercury has a lunarlike regolith, but global-scale structural information is lacking. That Venus likely has a crust is revealed by long-wavelength topographic and gravity information and by the density and radioactivity measurements by Venera landers.

The Earth has a substantial magnetic field of internal origin, evidently produced by the action of a hydromagnetic dynamo sustained by the interaction of convective motions in the fluid core with the Earth's rotation. The field is dominantly dipolar, with a polarity that reverses at apparently random times, and has nondipole terms that tend to show a systematic westward drift. The Earth's field extends through a volume of space many times larger than the planetary volume, forming an umbrella that shields the Earth from the flowing interplanetary plasma. Of the other inner planets, only Mercury has a magnetosphere comparable in character, though much reduced in size. The Moon shows evidence for a past magnetic field of substantial magnitude, now recorded in the remnant magnetism of lunar rocks and of large segments of the lunar crust. The origin of the ancient magnetic field of the Moon is not known. Venus apparently has no internal magnetic field. The existence of a magnetic field in Mars is currently a matter of debate; if any field exists, it is small.

The Outer Planets

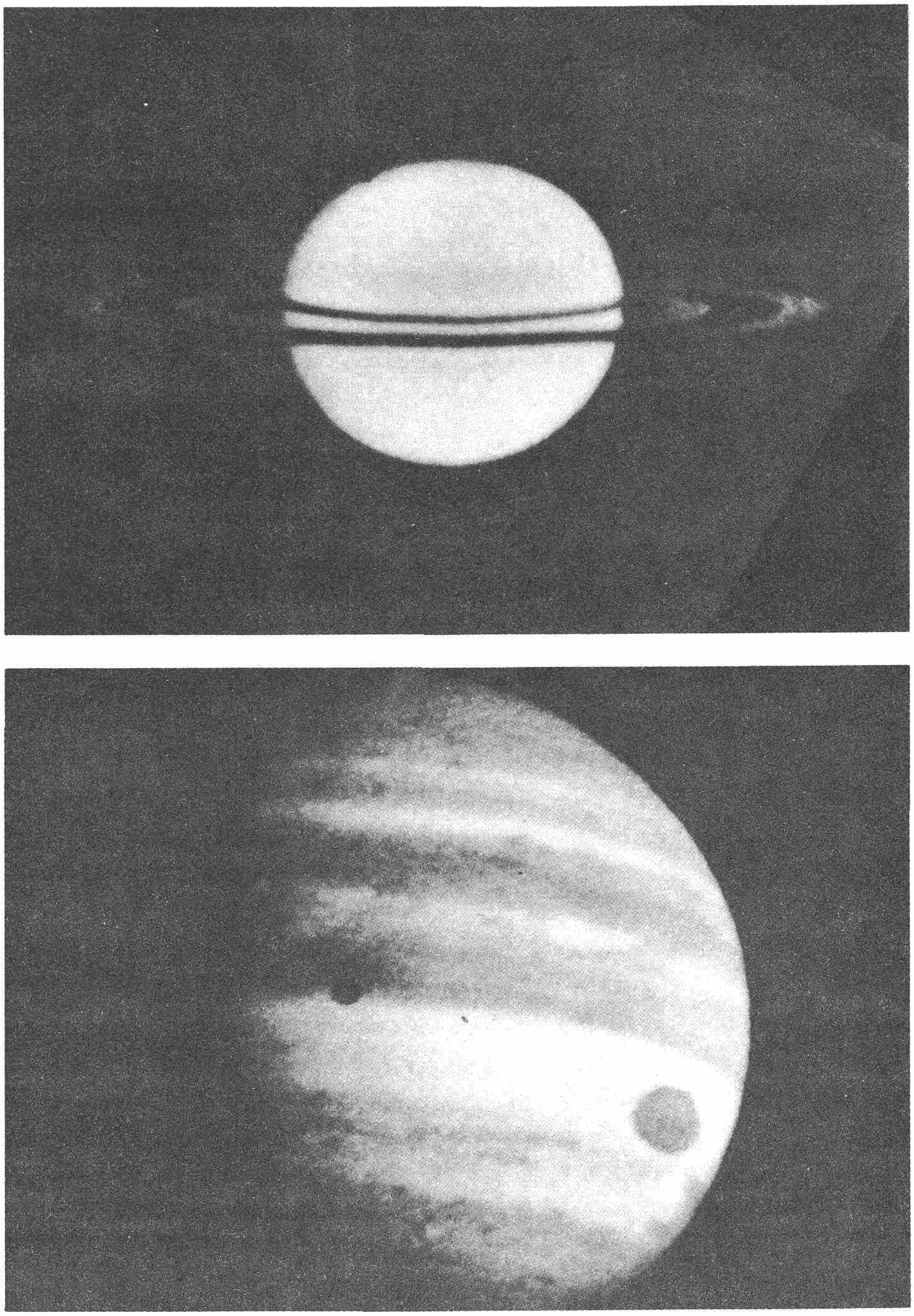
Information on the outer planets is much sketchier; so far, only Jupiter has been visited by spacecraft. On the basis of mean density, the major planets fall into two gross compositional groups. Jupiter and Saturn, the two largest bodies and the two with the lowest mean density, appear to have roughly the same composition as the Sun. Uranus and Neptune, in contrast, contain proportionately larger fractions of ice and rock. For Pluto, our present understanding is so meager that not even the mean density is well known. Even for Jupiter, about which the most is known among the outer planets, compositional information is very sketchy. The abundance of helium, the second most abundant species, has been inferred only indirectly and, though other molecular species have been identified, their precise abundances are not established. The compositions of the several cloud layers on Jupiter are not definitely known. Even less chemical information is available on the other outer planets.

The net energy balance and large-scale atmospheric dynamics of the major planets are of interest, both for their own sake and for the information they carry on the state and dynamics of the interior. Jupiter, Saturn, and Neptune each appear to radiate substantially more energy than they receive from the Sun, indicating an internal energy source, perhaps gravitational in origin. Much is known about the atmospheric circulation on Jupiter from cloud observations and radiation measurements, but the vertical atmospheric structure is not well established. Even less information is available about Saturn's atmospheric dynamics, and almost nothing is known of atmospheric dynamics for more distant bodies.

Jupiter has an internal magnetic field and a large magnetosphere that accelerates energetic particles. The origin of the field—as for the Earth—is ascribed to dynamo action in an electrically conducting fluid interior, but the conductor is thought to be metallic hydrogen in Jupiter, rather than iron–nickel as in the terrestrial planets. The magnetospheres, if any, of the other outer planets are uncharted. On the basis of observed nonthermal radio-frequency emissions, presumably produced by energetic charged particles trapped in a magnetosphere, Saturn is thought to have an internal magnetic field.

The satellite systems of the outer planets might be regarded as miniature solar systems. The larger satellites are presumed to have formed at large distances from the Sun. At least three planets, Saturn, Uranus, and Jupiter, also have rings of small particles orbiting at distances within the range at which large satellites would be disrupted by tidal stresses. The rings of Saturn may be largely water ice.

The larger satellites of the outer planets are of planetary size, and include objects with their own atmospheres and ionospheres. Compo-



Pioneer pictures of Saturn and Jupiter

sitional and structural information on these bodies is very scanty. The four largest satellites of Jupiter decrease in mean density with distance from the planet, from 3.6 to 1.8 $g cm^3$. These densities suggest compositions ranging from rock to roughly equal mixtures of rock and ice. The variation in density with distance from Jupiter has been ascribed to a decreasing temperature with distance from the protoplanet during its formation and evolution, much as the variation in density of the planets has been ascribed to heliocentric temperature and pressure gradients.

The recent Voyager mission revealed that some of Jupiter's moons are active planetary bodies. For example, Io may be one of the most volcanically active bodies in the solar system. Moreover, Io is unusual in that the energy source for its volcanism may be its tidal interaction with bodies in the Jovian system. Europa shows evidence for global tectonic processes, perhaps in an outer shell consisting of water and ice.

Comets and Asteroids

Comets and asteroids are objects that may have escaped most of the internal heating and differentiation to which the planets have been subjected. Although these objects have been studied only remotely from Earth to date, they may have sent samples to us in the form of meteorites. Though much intensive work has been performed in laboratories on the chemistry, mineralogy, and detailed chronology of meteorites, a definite link between any meteorite and any individual or class of asteroid or comet has not been established.

Asteroids and comets differ in their sources of origin in the solar system, in their abundances of volatiles, and in their orbits and interaction with the Sun. Asteroids are largely rocky or metallic and most likely were formed approximately at their present solar distances. There is a similarity—on the basis of spectral-photometric comparisons—between asteroid surfaces and those of a variety of meteorite classes. The significance of this similarity is not now understood. There is evidence that some asteroids, and the parent bodies of some meteorites, have undergone some heating, metamorphism, and, in some cases, differentiation since their formation. Other asteroids are thought to be composed of material that has undergone no significant change since accretion. The asteroids are extremely heterogeneous in size and surface composition. There is some indication that the average composition of asteroidal material varies significantly with solar distances.

Comets are thought to be mixtures of ice, dust, and rock that remain from solar nebula condensation in the outermost regions of the solar system. Stored for most of their lifetimes in orbits at great distances from the Sun, the comets with which we are familiar were perturbed into eccentric and often highly inclined orbits around the Sun and with perihelion distances within several Astronomical Units. The interaction of a comet with the solar heat and wind near perihelion (the point of its closest orbital approach to the Sun), through a process not well understood in detail, gives rise to the cometary coma, or atmosphere, and to the often spectacular cometary tail. The nucleus of a comet is thought to be a solid mixture of ice and less-volatile silicates. However, no nucleus has ever been seen as other than an unresolved point of light. Like asteroids, the population of comets is extremely diverse in orbits and in remaining volatile content. Many of our ideas about comets are untested. Both the testing of these ideas and the establishment of a link between comets and the basic building blocks of the outer solar system require *in situ* study.

TECHNOLOGY FOR SOLAR-SYSTEM EXPLORATION

Strategies for exploring the solar system require not only a strong scientific foundation, but also an awareness of technical capabilities and restrictions. These restrictions take many forms but are, of course, clearly related to the level of available financial support. Strategies must also incorporate new developments and constantly changing technical capabilities.

So far, all solar-system exploration has relied on spacecraft that travel along nearly ballistic trajectories. Spacecraft journeys are spent mostly in free, unpowered flight after a relatively short interval of thrust following launch and are possibly terminated by another short thrust to produce orbital capture about the target planet. This mode of operation leaves many bodies relatively inaccessible. Trips to the outer solar system require long flight times and large expenditures of fuel even for the delivery of modest scientific payloads. Not only are the requirements for doing scientific research taxed, but so also is the long-term reliability of spacecraft components during extended travel times. An unfamiliar dynamics governs the motion of objects that move in orbits rather than in straight lines. In terms of the propulsion needed to reach and achieve orbit, even some objects that seem to be nearby are relatively inaccessible. For example, Mercury's orbit, at four-tenths of an Astronomical Unit from the Sun, is only six-tenths of an Astronomical Unit removed from the orbit of the Earth. Getting to Mercury and orbiting it is comparable in difficulty, however, to getting to and orbiting planets of the outer solar system, which are ten times, or more, farther from Earth. Other objects are similarly inaccessible to traditional ballistic launch capabilities. For example, most young and middle-aged comets travel on highly inclined orbits and at high velocities when in the inner solar system, making it difficult to achieve the low-velocity, sustained encounters needed to address many of the fundamental scientific questions we wish to ask of these interesting objects. The ability of spacecraft to reach difficult targets with significant payloads can, in some cases, be augmented by maneuvering past planets and taking advantage of deflection in their gravitational fields. This depends on fortuitous planetary alignments and, even when possible, often exacts a penalty by extending travel times. An exploration strategy and its pace must take into account what is possible and practical in terms of spacecraft propulsion. At present, this is a real limitation.

Freedom from this limitation requires new approaches to propulsion. There is now under development a continuously thrusting propulsion system—the so-called ion drive—that operates on electricity and produces a high specific impulse thrust. This should provide us with a new measure of capability, beyond that currently available, in addressing significant scientific questions of difficult-to-reach objects such as Mercury, Saturn, and comets. The continuously thrusting propulsion system should relieve our dependence on relatively rare launch windows, allow the delivery of greater scientific payloads, and, in some cases, shorten trip times.

Aside from the problems of accessibility, other technological limitations also hamper our ability to carry out scientific measurements. An important example occurs in the case of Venus, where extremely high surface temperatures curtail the useful life of scientific instruments. The longest operational interval—two hours—was accomplished by a recent Soviet vehicle. Using present technology, measurements taken on Venus are restricted to those that can be made quickly; long-term monitoring of the planet's seismicity, for example, is not technologically feasible. Much of the surface of Mercury presents similar barriers. Development of a capability to operate scientific instruments for extended times in such hostile surroundings will enable us to address important questions that are now beyond our reach.

So far as we know, the technological difficulties inherent in planetary exploration are not insurmountable; adequate planning and research should overcome them. In some cases, there are advantages to carrying out measurements in laboratories, rather than with instruments aboard spacecraft. For the detailed chemical and isotopic analyses needed to read the ages and histories of solar-system materials, for instance, there are great advantages to analyses by the full panoply of laboratory techniques. Return of extraterrestrial samples for analysis, therefore, is an important component in the study of many solar-system objects, and sample-return techniques should be planned as an integral part of an overall exploration strategy that should also include *in situ* measurements. The two kinds of investigations should be structured so as to take advantage of their mutually supportive aspects in a continuing program of solar-system studies.

ADVISING ON SCIENTIFIC GOALS

The Space Science Board Committee on Planetary and Lunar Exploration has developed a new approach to advising on solar-system exploration. Traditionally, a set of specific missions was recommended, which implied that exploration of the solar system was defined by a sequence of missions, rather than by a set of scientific goals. A strategy identified in terms of missions rather than expected accomplishments is extremely vulnerable to the vagaries of fiscal and programmatic decisions. But a strategy based upon expected accomplishments remains valid and useful independently of the missions that may be chosen to carry it out.

When formulating a strong, coherent science strategy, a line must be drawn between those areas of the scientific endeavor that should be very strongly influenced by a concerted advisory process and those areas that are not well served by such a process. Much of the empirical basis of solar-system science depends on the intellectual success of a very few deep-space ventures. A strong advisory component is important, therefore, to ensure taking maximum scientific advantage of exploration opportunities. However, most of the scientific endeavor depends on the efforts of individuals in laboratories and offices—areas that do not lend themselves to a strong advisory process. In these cases, centrally controlled planning and allocation of resources is likely to result in stifling the creativity of the investigators to the detriment of the scientific enterprise.

EXPLORATION STRATEGIES

Planetary exploration can proceed on many levels. To organize and keep track, at least in a crude way, of the progress of our investigations, it is useful to define several levels of study. This provides a convenient framework within which to construct our plans for exploration of any object. Such an organizational framework is particularly useful to the effort to understand basic aspects of the origin and evolution of solar-system bodies. This scientific thrust requires emphasis on comparative studies and enhances the value of a broad-based exploration program with a balance of attention to relevant and accessible objects. Cataloging the progress of our investigations of various bodies according to a carefully thought out set of levels helps to maintain a reasonable balance. There are important reasons for achieving balance in the exploration of solar-system bodies. Science is characterized by the application of a small set of ideas to the elucidation of a large set of phenomena. Unless we have comparable information about a class of objects, we have no way to judge the generality and correctness of our ideas, and it is then easy to be seduced by *ad hoc* explanations that appear successful when applied to only one or two bodies, but that collapse when examined in a broader context. However, the definition of levels of investigation should not be allowed to dominate and restrict our thinking. The desire for a balanced approach to planetary exploration should not be allowed to destroy the flexibility of our programs and our responsiveness to new information. For many reasons it is natural to expect that planetary studies, especially at the more intensive levels, will concentrate on some bodies more than on others. This will come about for reasons of easier accessibility as well as the relationship of questions that may be asked to the concerns of Earth-bound man.

Levels of Investigation

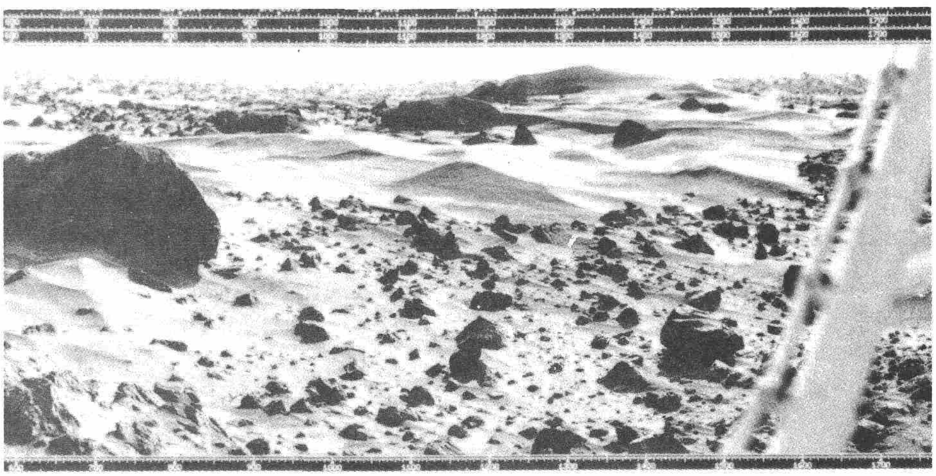
The Committee on Planetary and Lunar Exploration (COMPLEX) has defined three levels of investigation applied to planets: reconnaissance, exploration, and intensive study. These levels are arranged hierarchically, proceeding at one end from measurements aimed at grossly characterizing a body's properties and environment to performing experiments designed to answer specific and well-defined questions. This hierarchical sequence of investigation levels corresponds closely to the sequence in which planetary exploration will normally be carried out, experiments designed for the later phases coming in response to questions posed by earlier, less-intensive investigations. Generally speaking, as defined by COMPLEX, the objectives of planetary reconnaissance are met in the first brief encounters by spacecraft, usually as they fly by the planet. The next level of study—exploration—which begins to aim at understanding important aspects of a planet's present state as well as the processes involved—requires more intimate association and generally involves orbiting spacecraft and probes that enter the atmosphere and land on the surface. The most intensive study proceeds to active experimentation, including the possibility of return of samples for laboratory analysis.

Not all solar-system objects fit smoothly into one level of investigation. Knowledge derived from Earth-based telescopic observations varies in magnitude and character from one class of objects to another. Thus, for some objects, we may conclude that spacecraft investigation is justified only if the initial science return is at a more advanced level than could be expected from, say, an exploratory fly-by. As an example, exploration strategy for the small, primitive bodies of the solar system—comets and asteroids—is now under consideration. The burdens placed on a program to explore these objects are different from those placed on much of planetary exploration. To begin with, meteorites recovered on Earth provide us with samples of solar-system debris, which are surely related to asteroidal and cometary material, even if in an unknown way. Also, these objects are numerous and are interesting as members of classes that may represent different degrees of primitive evolution. Further, as mentioned earlier, asteroids reveal a range of spectral characteristics to telescope observations; these spectral characteristics bear a loose relationship to the properties of meterorites. We also know that some meteor showers are associated with orbits of comets, suggesting the possibility of a relationship between some recovered meteorite samples and some component of the nonvolatile comet material. These facts raise questions, even at our present level of knowledge, that cannot be addressed by the usual fly-by reconnaissance investigation. A judgment must be made about what kind and level of investigation is necessary to return information that will address these questions and provide a significant increment in our knowledge. Thus, for example, since we already have established, from telescopic observations, the existence of wide variation in the types of asteroidal material, we may conclude that to justify exploration with spacecraft requires chemical and mineralogical measurements of a quality sufficient to distinguish among the major known meteorite types.

A Strategy for the Next Decade

COMPLEX has formulated a stragegy to guide solar-system exploration over approximately the next decade. It has been convenient and conceptually useful to divide the recommendations into three parts: the planets of the inner solar system (Mercury, Venus, Earth and its Moon, and Mars); the outer solar system (Jupiter, Saturn, Uranus, Neptune, and Pluto); and comets and asteroids. One reason for the utility of this division can be seen by summarizing the salient characteristics of these three classes of objects, which were described earlier. Most of the outer solar-system planets apparently formed at low temperatures and trapped large quantities of volatile material from the preplanetary nebula. The four rock and metal planets of the inner solar system consist primarily of minerals that condense at relatively high temperatures and that apparently accreted to form planetary bodies without carrying along large quantities of highly volatile substances. The planets of both the inner and outer solar system have in common the qualities of being large and formed with enough internal energy to drive continuing planetary evolution, which has erased evidence of the formation processes and altered the character of planetary material since the time of formation. By contrast, the smaller solar-system objects—especially comets and asteroids—did not contain enough internal energy to drive continuing planetary evolution. Thus, in these bodies, the character of solar-system material at the time of formation is relatively well preserved; also, evidence of early energy sources and metamorphic processes, which has been obliterated on planets, is apparently preserved in some of these primitive bodies.

For the decade running through 1985, COMPLEX has recommended that outer solar-system exploration not extend beyond Uranus. The targets for investigation in this time period are Jupiter, Saturn, and

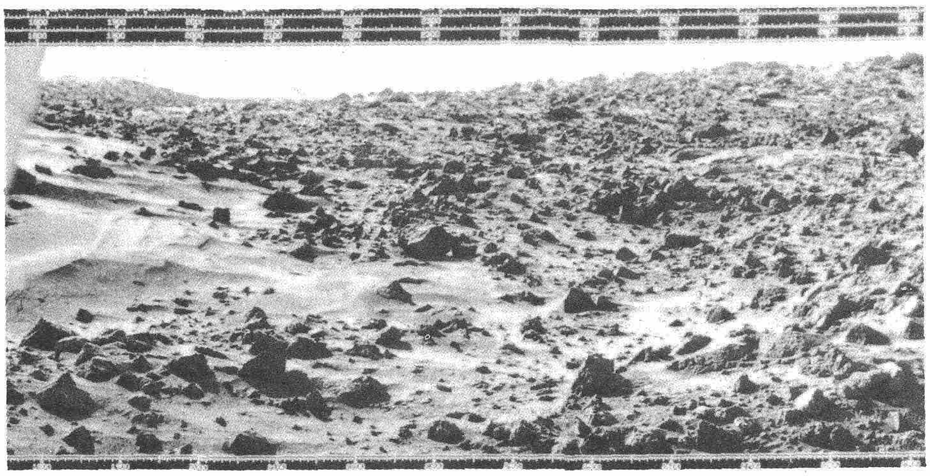


Martian landscape

Uranus, along with their satellite systems. A reconnaissance of Jupiter was accomplished by the Pioneer and Voyager spacecraft and the committee recommended that a major undertaking during the decade be an exploratory investigation of Jupiter, its satellite system, and magnetosphere. The primary recommended objectives are to determine the chemical composition and physical state of Jupiter's atmosphere and satellites and to explore the planet's magnetic field and energetic particle fluxes. The Galileo mission, being developed to accomplish these goals, will employ an atmospheric entry probe as well as a Jupiter orbiter that will explore the magnetosphere and make numerous close passes to several satellites, enabling investigations through remote-sensing techniques.

The committee has also recommended that reconnaissance-level investigations of both Saturn and Uranus be accomplished during the decade. Aspects of these recommendations are expected to be satisfied through planetary fly-bys involving the Pioneer and Voyager spacecraft. Looking forward, COMPLEX regards exploratory investigation of Saturn as the next step in continuing study of outer solar-system bodies beyond 1985.

For the inner solar system, reconnaissance-level investigations are completed, and COMPLEX has recommended that the decadal strategy



have as its major focus the triad of planets—Venus, Earth, and Mars. This choice is based on the belief that these three bodies pose a fundamental and well-defined challenge to our understanding of planets. As noted earlier, the atmospheres of these bodies span a factor of 10^4 in density; Mars' atmosphere is about one percent of Earth's; Venus' atmosphere is about one hundred times that of Earth. These differences are very apparent from our anthropocentric viewpoint and are very large in comparison with other variations in the planetary properties as we currently perceive them. The "air"-less bodies of the inner solar system are relegated to a lower priority for the decade. This recommendation also takes into account anticipated propulsion capabilities.

At this time, Venus is being subjected to investigations of its atmosphere and solar-wind interaction by the Pioneer–Venus mission, which employs several atmospheric probes and an orbiting spacecraft. The major science objectives recommended to carry Venus investigations through the decade to 1987 are to ascertain the composition of the planet's surface material and its interaction with the atmosphere and to explore important photochemical processes in the atmosphere that are analogous to processes in the Earth's atmosphere.

Maps of planetary surfaces have had a profound impact on our understanding; they contain records of the dominant processes that have shaped the terrestrial bodies. For example, maps of Mars reveal the earlier episodes of erosional processes that are not understood in terms of the current Martian climate. This suggests that conditions on Mars may have been very different in the past and raises important questions about the stability of planetary environments. Venus is shrouded in a dense layer of clouds, its surface hidden from us except for a few coarse, but tantalizing, sketches drawn by Earth-based radar; these vaguely show a number of large features spread on the planet's surface. An important goal for the next decade of studies on the inner solar system is construction of a detailed map of Venus' surface. It appears that techniques employing radar from an orbiting satellite are applicable to this task.

Since the Viking mission to Mars, studies of that body have advanced to a more intensive level than have studies of any other planetary object save the Earth and Moon. Our investigations of Mars have posed new questions that challenge our understanding in important ways. Approaching the answers will involve major scientific efforts. The recommended primary objectives include establishing the composition and chemical and physical character of the surface in its diverse domains, determining the nature and chronology of surface-forming processes and the inventory and distribution of volatile substances, exploring the structure and circulation of the atmosphere, exploring the structure and dynamics of the interior, and establishing the planet's state of magnetization and its solar-wind interaction.

CONCLUSION

The Committee on Planetary and Lunar Exploration has designed a decadal strategy for scientific exploration of the planetary system and is now formulating a strategy for exploring the small, primitive, and relatively unevolved solar-system bodies—the comets and asteroids. This will complete a task begun some five years ago and will provide the framework for a coherent approach to solar-system exploration through most of the 1980's.

The recommended program of exploration is vigorous within the confines of an anticipated restricted budget for these activities, is conservatively paced, and, for the most part, reflects a level of activity near the minimum that is perceived necessary to keep the research efforts viable and healthy.

When the explorations are completed, we will have reached all the known planets of the solar system save two—Neptune and Pluto. We will have achieved a gross understanding of the morphologies and environments of Uranus and Saturn and their satellite systems. We will have plunged into Jupiter to test its composition directly, and we will have explored its satellites. In the inner solar system, we will have begun to unravel the profound mysteries that will be the legacy of our earlier exploration of the terrestrial planets. We will have focused on the triad of close sister planets—Venus, Earth, and Mars. Disentangling their similarities and differences will provoke and test our ideas about planetary evolution and the behavior of terrestrial environments. And we will have undertaken to study the primitive bodies of the solar system, which, we expect, have most faithfully recorded conditions during the early years of the solar system.