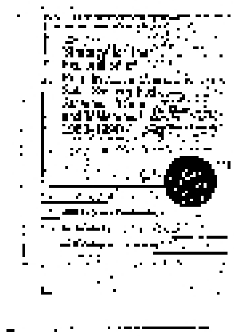

Strategy for the Exploration of Primitive Solar-System Bodiesâ€"Asteroids, Comets, and Meteoroids: 1980-1990

Committee on Planetary and Lunar Exploration, Space Science Board, Assembly of Mathematical and Physical Sciences, National Research Council

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Foreword

This document is one of a series prepared by committees of the Space Science Board (SSB) that develop strategies for space science over the period of a decade. Several reports in this series have been completed: *Report on Space Science 1975* (Part II, Report of the Committee on Planetary and Lunar Exploration, which covers the outer planets); *Strategy for Exploration of the Inner Planets: 1977-1987* (1978); *Strategy for Space Astronomy and Astrophysics for the 1980's* (1979); *Life Beyond the Earth's Environment* (1979); and *Solar-System Space Physics in the 1980's: A Research Strategy* (1980), which was developed as a continuation of the Board's assessment of future objectives of space-physics research that was begun with the Colgate Study (*Space Plasma Physics: The Study of Solar-System Plasmas*, National Academy of Sciences, Washington, D.C., 1978). Other reports are in preparation in earth sciences, relativity and gravitational physics, and planetary biology and chemical evolution.

With the publication of this document, the Space Science Board's Committee on Planetary and Lunar Exploration (COMPLEX) has completed a three-part series of science strategies for exploration of the solar system. The level of effort required for this task dictated that it be done in a series, each part devoted to a natural division of solar-system bodies, i.e., the outer planets, the inner planets, and the primitive bodies. Each strategy covers a period of approximately ten years, and collectively they should be regarded as an integrated plan for exploration of the solar system for the period 1975–1990.

Like its two predecessors, this document takes the position that the strategy will be stated in terms of science objectives to be achieved over the prescribed period, rather than a series of recommended missions. For the fifteen-year period covered by this series, the strategies provide a scientific baseline for guiding and evaluating new or changed mission approaches and plans. They have been used repeatedly for this purpose over the past five years when severe budget restrictions and related development problems have had a significant impact on planetary mission planning.

The Board adopted this report as its policy position for the exploration of the primitive bodies of the solar system at its February 1980 meeting. It takes this opportunity to express appreciation to COMPLEX members, past and present, for their commitment to see this long task to completion.

A. G. W. Cameron, *Chairman*
Space Science Board

Preface

This report is built on all earlier recommendations and policies of the Committee on Planetary and Lunar Exploration (COMPLEX) and the Space Science Board (SSB). The report forms the third of a unit consisting of it and the COMPLEX reports for 1976 and 1978.

COMPLEX would like to thank the members of, and participants in, its 1978 Summer Study on the Exploration of Asteroids, Comets, and Extraterrestrial Dust. The recommendations contained in this report, though finally formulated by COMPLEX, are built in no small measure on their efforts.

Contents

1
Introduction

PREMISES OF THIS REPORT

The Committee on Planetary and Lunar Exploration (COMPLEX) submitted to the Space Science Board (SSB), in 1975 and 1978, respectively, two reports proposing decadal strategies for exploration of the outer-solar-system planets and exploration of the inner-solar-system planets. These reports were approved and adopted by the SSB and constitute a statement of its policy on exploration of the solar system's planets. In 1978, the Board requested that COMPLEX extend its consideration to asteroids, comets, and meteoroids, for the purpose of assessing their relative significance to our understanding of the solar system and proposing an appropriate approach to the investigation of these bodies.

In addition, the SSB authorized COMPLEX to conduct for it a summer study aimed at gathering the necessary foundation of information on which to build its recommendations. Accordingly, during August 1978, the Committee meet for two weeks in Snowmass, Colorado, with some 30 experts on asteroids, comets, and meteoroids and related scientific subjects. It also heard a variety of presentations and received advice from various technical experts, including representatives of the National Aeronautics and Space Administration. On the basis of this accumulated information, and additional deliberations during 1978 and 1979, COMPLEX has formulated and submits this report to the SSB, which

1. Assesses the significance of asteroids, comets, and meteoroids for our understanding of the solar system and its relation to the broader cosmos;

2. Proposes a long-term strategy for the exploration of asteroids and comets for approximately the decade of the 1980's;

3. Assesses important programmatic elements that support and implement the strategy;

4. Examines the experimental capabilities available to carry out measurements needed to fulfill the scientific objectives; and,

5. Examines the role played by the study of meteoroids--meteorites, meteors, and interplanetary dust--in an overall program of primitive-body investigations.

In formulating this strategy, we have adopted the approach of our previous reports and propose long-term objectives that are independent of the scientific missions that may be chosen to implement them. We do this for reasons that have been enunciated in our 1978 report, and still with the realization that the strategy will come to fruition only through specific missions.

OVERVIEW OF PLANETARY EXPLORATION

This report was formulated during a time of enormous scientific achievement in planetary exploration. The Voyager encounters with Jupiter added impressively to our knowledge of that planet's atmosphere and magnetosphere, while at the same time it made spectacular discoveries of the properties of the Jovian satellites. The United States achieved the first spacecraft encounter with Saturn, recovering important information about that planet, its rings, and its magnetosphere. The United States and the Soviet Union carried out an array of penetrations of the atmosphere of Venus as well as orbiting the planet, answering a number of important questions and posing others.

In its earlier reports, COMPLEX reviewed the major questions that can be addressed to inner- and outer-planet exploration over a decadal time scale. In this report, COMPLEX concludes that exploration of asteroids and comets promises to illuminate important questions concerning the origin and evolution of the solar system and contribute to our grasp of important physical processes. In sum, we believe it is evident that solar-system exploration is, and will continue to be, of profound scientific value. We believe that it offers challenges to the United States that are within reach of our national capabilities and resources and that should be vigorously pursued.

In the face of this, we are alarmed by the apparent near-term prospects for continuation of a vigorous program of planetary science. The pace of planetary new starts has slowed to a rate totally inconsistent with achieving recommended objectives. Only one mission is in progress at present--the Galileo Orbiter and Probe to Jupiter--and its integrity is threatened by problems that have arisen in development of the Space Shuttle transportation system. The anticipated, near-term rate of planetary new starts is not responsive to the challenges and opportunities that this exploration presents to us; the level of initiative is not responsive to the stated national commitment to leadership in space science as set forth in the National Aeronautics and Space Act and as reiterated in 1978 by the President of the United States.

COMPLEX believes that the case in support of a vigorous national program of planetary exploration is patent and has been made repeatedly. We recommend that the stated national commitment to this endeavor be renewed and that the program necessary to realize this commitment be undertaken.

2
Origin of the Solar System/ the Primitive Bodies

Star formation in our galaxy is believed to have begun at least 10 billion y
ago and to be continuing at present. Although the conditions under wh
our own sun formed, approximately 4.5 billion years ago, are not known,
can infer that conditions were similar to those where star formation is p
occurring—in dense interstellar gas clouds. Molecules are observed in al
these dense clouds, and complex organic species with over eight atoms
seen in the larger clouds; the presence of dust in these clouds is inferred fr
infrared emissions. It is generally believed that our solar system formed w
such a cloud underwent gravitational contraction, some fragment of it fo
ing, because of its rotation, a gaseous disk, which we call the solar neb
During this early phase of its evolution, temperatures and pressures
thought to have been highest near the center of the nebula.

The sun, the planets, and the smaller objects formed from the solar neb
through a series of complex, but rather rapid, processes. The larger bod
contained large amounts of internal energy that fueled further evolution
processing, which continues, in many objects, to the present day. This pl
etary evolution has largely obliterated evidence of the original states of th
bodies. In contrast, because of their small sizes, asteroids, comets, and me
oroids apparently have undergone substantially less evolution than have
planet-sized bodies. For this reason they are collectively referred to here
primitive bodies. Some of these may have formed in the cooler, outer regi
of the solar system. Some early evolution appears to have taken place in
least several of the larger asteroids, so that not all asteroids are thought to
composed of the unaltered, primordial material that existed prior to t
events of planet formation. In any case, because they are too small to ha

sustained long-term planetary evolution of the kind that occurred on larger bodies, these primitive objects should retain evidence of the earliest evolutionary processes that shaped solar-system material.

The initial dust component of the presolar nebula is important to the nebula's subsequent evolution because it probably contained a large fraction of the elements heavier than helium. There are many possible sources of the initial dust, including, for example, the outer envelopes of carbon-rich red giant stars and novae, the expanding shells of supernovae, and planetary nebulae. Since the elemental and isotopic composition of dust from each of these sources is different, the composition of presolar dust carries information about the origin of the elements in the solar system. Some of this original dust may be preserved in comets and asteroids formed in places in the solar nebula where the temperatures never rose high enough to evaporate it.

It is believed by many students of meteorites that the undifferentiated chondritic meteorites formed in the dense gas and dust nebula surrounding the proto-sun and have undergone little further alteration. Comparisons between theoretical studies of chemical equilibrium in a gas of solar composition and the characteristics of these meteorites indicate that the chondritic material condensed from such gas while in approximate equilibrium with it and was then chemically isolated from the gas at moderate to low temperatures in the range 600 to 300 K. Thus, the compositions and structures of the chondrites tell us about composition, temperatures, and pressures in their place of formation. Studies of these meteorites alone, however, cannot reveal their precise points of origin, and we are thus unable to associate these conditions with any particular environmental location within the nebula. Investigations of other primitive bodies will help to remove this ambiguity.

The collapse of interstellar clouds to form new stars is thought to be a result of dynamical and thermal instabilities in the interstellar gas. The detailed sequence of events that precipitated the formation of the solar system is not known. If, for example, the collapse was initiated by a large-scale hydromagnetic instability, by shock fronts associated with H II regions, or by density waves in the galactic disk, then the solar system probably formed from a relatively homogeneous mixture of the interstellar gas and dust. If, however, star formation was triggered by shock fronts accompanied by injection of material from a nearby supernova, the initial presolar cloud may have been chemically and isotopically heterogeneous. Some of this heterogeneity may well have survived the later evolutionary stages of condensation and accretion.

Indeed, evidence for *in situ* decay of the short-lived isotope ^{26}Al in carbonaceous chondrites suggests that the explosion of a nearby supernova may have initiated the collapse. A variety of isotopic anomalies occur in some meteorites. These anomalies are clearly important, out of all proportion to their size, as tracers of heterogeneity within the nebula and thus as indicators of dynamical and nucleosynthetic processes that occurred only a short time before its formation. The meteorite evidence leaves large uncertainties regarding the distribution of isotopic species in the solar system. It is possible that presolar grains, having exotic isotopic compositions, are preserved in greater abundance at greater distances from the sun, where heating effects apparently were small, and, therefore, it is possible that the outer solar system is more isotopically heterogeneous than the inner solar system. This provides one important impetus for investigating the composition of primitive bodies from the outer parts of the solar system.

Since some collisional debris from asteroids undoubtedly reaches the Earth and is recovered as primitive meteorites, it is widely thought that some asteroids contain relatively unaltered nebula condensates. In addition, spectroscopic studies of asteroids indicate that some contain material that is completely different from that in meteorites, suggesting that currently unknown types of primitive materials exist on those bodies. These factors make the asteroids, like the comets, bodies of great scientific interest for the information they carry about solar-system formation processes.

If there was a close approach to equilibrium during the formation of meteoritic components, there must have been intimate contact between gases and solids for considerable lengths of time during the evolution of the solar nebula. However, removal of the uncondensed nebular gas must have occurred without blowing away the solids necessary to make the bodies of the present inner solar system. The process of growth of the solid bodies toward planetary size must have begun early, and a detailed treatment of the accumulation and growth processes must be developed to account for the vast range of sizes between meteorite-sized and planet-sized bodies.

Various mechanisms have been proposed for this accumulation into larger bodies. These can be divided fairly well into two classes. According to some ideas, gravitational instabilities of the solar nebula itself produced giant gaseous protoplanets. In these theories formation of the terrestrial planets requires stripping of massive atmospheres from their protoplanets, whereas the outer planets are formed by nearly complete gravitational contraction of the protoplanets. Smaller bodies could have been formed either from material that escaped incorporation into a protoplanet or from material torn from a protoplanet through tidal disruption. The time scales suggested for the major stages of planet formation in these theories are generally short, less than 10^6 years.

According to other ideas, accumulation of planetesimals and planets proceeded through the continual sweeping up of small bodies by larger bodies. In some forms of these theories, the initial formation of kilometer-size objects is a consequence of local gravitational instabilities in a dust layer formed as condensed matter settled onto the central plane of the nebula. According to these ideas, the terrestrial planets formed by gravitational accumulation of these small bodies in the gas-free inner region of the nebula, while the outer planets formed by accretion of residual nebular gas onto solid cores after these cores became sufficiently massive to retain gas. The small bodies are thought, in this context, to be planetesimals that escaped the accumulation process. In these theories, time scales for the formation of small bodies were about 10^6 years, whereas most planets seem to have required about 10^8 years for their formation.

Although accumulation theories can be separated into these two broad classes, both kinds of processes could have occurred during the solar system's formation. For example, the major planets may have formed from giant protoplanets, whereas the terrestrial planets and small bodies may have formed the gravitational accumulation.

Investigations of comets, asteroids, and their fragmentation products will provide essential information about these early processes in the solar system. This information is different from that found in investigations of planets and their satellites and therefore represents a necessary complement to studies of the planets and satellites. Comets are generally believed to have formed in the outer portion of the solar system, at least beyond the orbit of Saturn. Temperatures at those distances may have been low enough to preserve, in the condensed phase, species such as N_2, CH_4, CO, CO_2, and ^{36}Ar, which are usually considered to be volatile nebular constituents. The composition of comets, therefore, represents an important boundary condition for models of solar-system evolution. As a second example, asteroids usually are thought to have formed within the orbit of Jupiter. Their present positions range from the vicinity of Mars, where presumably water would be retained in condensed material only as hydrous minerals, out to regions near Jupiter, where water ice is expected to become a dominant constituent of the condensed material. Asteroids, therefore, appear to span a region of the solar nebula in which a complex transition between volatile-poor and volatile-rich material occurs. Determination of the nature and location of this transition will be an important addition to our understanding of the history of the solar system.

3
Scientific Rationale and Goals for the Study of Comets, Asteroids, and Meteoroids

The Space Science Board has defined the primary goals for investigation of the solar system. The primary scientific goals are "to determine the composition, structure, and environment of the planets and their satellites in order to define the present morphology and dynamics of the solar system and with the purpose of making major steps in understanding the processes by which the planets formed from the solar nebula and how they have evolved with time and how the appearance of life in the solar system is related to the chemical history of the system. The investigation of the interplanetary and interstellar medium is considered an intrinsic part of such an endeavor."

This report addresses the goals, objectives, and strategy for investigation of asteroids, comets, and small particles or meteoroids that pervade the solar system. This is done with the conviction that such investigations will provide understanding of a kind that is qualitatively distinct from that provided by studies of the planets and their satellites, which were the subject of the earlier 1975 and 1978 COMPLEX reports. Every object in the solar system exhibits a combination of current processes and relics left over from its origin. The largest bodies have mainly destroyed these relics by their geological evolution. In comparison, small bodies generally retain far more information about their origin and earliest history.

Like the planets and their satellites, as a collective group, comets, asteroids, and meteoroids are enormously diverse. In size they range from submicrometer particles to solid objects, 1000 km in diameter. Comets produce diffuse gas and dust envelopes up to 10^8 km long. The range of compositions of primitive bodies seems to encompass ice-rich dust and carbonaceous and silicate-rich material, as well as metal-rich material. Some of the larger objects may be differentiated, while many of the smaller ones are probably largely unmodified. Their orbits range from circular to highly eccentric. Many are highly inclined to the ecliptic plane. They are distributed over a large volume of space and may range inward to inside the orbit of Mercury and outward to 50,000 A.U. from the sun.

As a group, these objects provide an important link in our understanding of solar-system evolution. This conclusion is not based simply on their existence and diversity, but rather it reflects the general belief that many are composed of condensed material from the primitive solar nebula, which is either essentially unaltered or at least has not been altered to the extent of material on planetary and large satellite surfaces. This belief is firstly derived from the fact that these bodies are for the most part too small to have undergone significant internal heating and subsequent differentiation as a result of long-lived radioactivity and gravitational potential energy. What thermal alterations these objects have undergone was driven by peculiarly primordial energy sources, possibly including the decay of radioactive ^{26}Al and solar-wind induction, and they are thus thought to preserve a record of these very early processes. Secondly, observations of comets indicate that they have been stored at sufficiently low temperatures to retain the low-temperature condensates expected in the coolest parts of the nebula. Thirdly, studies of meteorites show that they formed during the earliest period of solar-system history about 4.5 billion years ago. There is little doubt that meteorites are derived from asteroids, comets, or both and that a much more complete picture of the early solar system will emerge from studies of these bodies.

COMPLEX recommends that the primary goal of investigation of asteroids, comets, and dust, during approximately the next decade, be to determine their composition and structure and to deduce their history in order to increase our knowledge of the chemical and isotopic composition and physical state of the primitive solar nebula and to further our understanding of the condensation, accretion, and evolutionary processes that occurred in various parts of the solar system before and during planet formation. This is the primary goal for study of the minor bodies and as such it is unique to asteroids, comets, dust, meteorites, and possibly the smallest planetary satellites.

We have defined three additional goals.

The minor bodies far outnumber the planets and their satellites and exhibit a rich diversity. The extremely small fraction of comets and asteroids that have been observed from earth already includes some 5000 objects. It is important to gain full understanding of the detailed range of diversity of asteroids, comets, and dust and the reasons for their similarities and differences. Some of this diversity can be studied by carefully chosen spacecraft missions, but it is clear that an important role will have to be played by Earth- or near-Earth-based observations of these bodies. We must, therefore be able to interpret, for example, the morphology, emission spectrum, and variable activity of comets, and the mass densities and reflection spectra of asteroids, in terms of the actual compositions and structures of these bodies. To understand their diversity it is also desirable to obtain carefully chosen, representative samples of these bodies for detailed study in earth laboratories. It is important, therefore, to recognize that fragments of asteroids, comets, and interplanetary dust regularly impact the earth where they can be observed or recovered. Classification of the relationship of these fragments to their sources in the solar system and to one another could elevate meteors, meteorites, and extraterrestrial dust to the status of returned samples of the primitive bodies. Therefore, *a goal in the study of primitive bodies is to determine their diversity of composition and structure.* By establishing the relationship between their remotely observable properties and their detailed compositions and structures and the relationships between these bodies and the material that reaches Earth in the form of meteoroids, Earth-based techniques can be used to extrapolate our detailed knowledge to the larger population of asteroids, comets, and meteoroids.

Through capture and surface impacts, asteroids and comets have played, and continue to play, a direct role in terrestrial planet and satellite evolution. In particular, comparative studies of Venus, Earth, and Mars rest heavily on a comparison of the elemental and isotopic compositions of the volatiles in their crusts and atmospheres. The contribution of cometary and volatile-rich asteroidal material to the atmospheric inventory is, for example, probably important for several volatile elements on Venus and on Mars. Quantitative assessment of this contribution to the atmospheres of Venus, Earth, and Mars requires knowledge of the detailed composition and mass distribution of comets and asteroids and their rate of capture by the planets throughout geological time.

Furthermore, the cratered surfaces and regoliths of the moon and terrestrial planets have been formed by the impacts of comets and asteroids and provide the primary basis for relative dating and stratigraphic correlation of these surfaces. The effects of these impact processes may reach far below the surface. On the moon such processes may have resulted in early melting, differentiation, and redistribution of the outer several hundred kilometers. Similar processes most likely occurred on all the terrestrial planets. The interpretation of these effects requires determination of the mass distribution, strength, orbital evolution, rate of capture, and physics of atmospheric entry of comets and asteroids.

The extent to which external bombardment has contributed to the evolution of the terrestrial planets, after their initial formation and early differentiation, is of considerable importance. Therefore, *a goal for investigation of the minor bodies is to understand the role played by accretion of these bodies* *in the evolution of the crustal and atmospheric composition and the crustal structure of the terrestrial planets.*

Of the minor bodies, comets are unique in that they exhibit dynamical processes involving ejection of gas and dust and production of low-density plasma as they approach the sun. These processes appear to begin with the rapid evaporation of volatiles and ejection of dust from the cometary surface as a result of solar heating. This is followed by an outflow of gas at roughly sonic velocities, which accelerates the dust along with it. Complex photochemical reactions and ionization processes in this gas and dust mixture give rise to the visible cometary coma or atmosphere in which a number of ions and radicals are seen in emission. Interaction of this low-density plasma with the solar wind produces an often readily visible cometary tail. These phenomena, which produce the spectacular visual displays associated with comets, are interesting for their own sake. Even with our currently meager knowledge of comets, they pose major challenges to our understanding of the behavior of diffuse assemblages of gas and magnetized plasma. For example, the flux of far-ultraviolet sunlight is apparently insufficient to account for the energy required to ionize the cometary gas; the ionization processes are not understood at present. The release of large amounts of energy is a common feature of diffuse systems of gas and magnetized plasma in objects as diverse as planetary magnetospheres, the solar corona and chromosphere, and star systems. These phenomena generally depend on the large physical scale and low density of the gas in which they occur and are, therefore, not amenable to investigation under controlled laboratory conditions. Direct study of these processes where they do occur, in a few accessible solar-system bodies, is a valuable stimulus and guide to our imaginations and enlarges our ability to decipher the natural behavior of the world around us. An understanding of the dynamical processes that shape the behavior of solar-system objects is a fundamental part of solar-system research. Therefore, *a goal in the study of minor bodies is the understanding of the dynamical processes responsible for the production, maintenance, and behavior of the gas, dust, and plasma envelopes of active comets.*

The four scientific goals enunciated above have emphasized our own solar system. However, the sun is only one of some 10^{11} stars in the galaxy, and it is important to consider it in the longer astrophysical context. Numerous links and interrelationships exist between the observations of, and inferences we can make about, our own solar system and the observations and inferences we can make looking out at other astronomical objects. For example, one explanation of certain isotopic anomalies in meteorites, some of which are clearly due to nuclear effects, is that freshly produced nuclei from a nearby supernova explosion were injected into the presolar nebula shortly before its collapse and subsequent chemical isolation from the galaxy. This raises the intriguing possibility that a supernova was responsible for trigger ing the collapse; indeed, recent astronomical observations have shown tha certain stars are formed in association with supernova remnants. As anothe example, inferences that we draw about the time-temperature profile in th primitive solar nebula can be compared with astronomical observations, prin cipally in the infrared, of objects that are thought to be newly forming stars The existence of these and other similar links qualitatively extends our in tellectual horizons and provides a crucial stepping stone between ou solar system and the larger universe outside.

4

Strategy for Exploration of Primitive Bodies and Its Relation to the Strategies for the Inner and Outer Planets

Comets, asteroids, and their fragments are an integral part of the planetary system. Exploration of these primitive bodies is thought to hold special promise for elucidating those early solar-system conditions and processes that eventually resulted in the accretion of planets and influenced early planetary evolution, a goal previously identified by the Space Science Board (SSB) as a primary scientific motivation for solar-system exploration. *Thus exploration of asteroids and comets constitutes an essential element of a balanced program of solar-system exploration designed to address fundamental scientific questions concerning the nature and early history of the system.*

In addition, asteroids and comets undergo a variety of processes that are, by themselves, of intrinsic scientific interest in the areas of space physics and comparative planetology. These include, for example, certain physical phenomena in plasmas and geological processes on low-gravity bodies. Study of such physical processes involving small bodies is of high scientific merit and a desirable element of a balanced program of planetary exploration.

The past decade has seen remarkable advances made in learning about asteroids, comets, and meteoroids from ground-based observation, laboratory measurements, and theoretical analysis. Improved telescopic instrumentation applied to increasing numbers of small bodies has led to significant, but still limited, characterization of many of these bodies. The laboratory study of meteorites, in particular, has advanced substantially, aided in large part by the vigor of the lunar sample program and the discovery of many new meteorites in Antarctica. Recently, the collection and analysis of extraterrestrial dust has begun. In summary, we believe that these scientific fields have matured, that significant questions are posed about these objects that may be important to our understanding of the early solar system, and that to answer these questions will require scientific exploration of these objects with spacecraft. *Thus COMPLEX recommends that investigation of comets and asteroids be conducted by spacecraft missions, which combine elements of both the reconnaissance phase of study and the exploratory phase of study in those areas for which specific and fundamental questions have been raised.* The Committee's detailed recommendations on these topics are given in Chapters 5 and 6.

The Committee has been informed of the prospective availability of low-thrust propulsion systems ideally suited to exploration of comets and asteroids. Thus, a well-developed scientific rationale will be matched in the 1980's by a transportation system able to deliver appropriate instruments to the vicinities of representative members of this important class of bodies.

Asteroids and comets are broadly diverse in composition, physical state, and associated processes. The chief compositional differences between asteroids and comets are thought to result from their formation in different locations and under different physical conditions, asteroids primarily in the inner solar system and the comets primarily in the outer solar system. Both groups of bodies are expected to contain primitive materials from their places of origin, although both have suffered several kinds of subsequent alteration, which must be deciphered if their record of primordial conditions is to be fully understood. The alteration processes, orbital changes, physical disruption by tidal splitting and impact, as well as fractionation and differentiation processes contribute to diversity. *Elucidation of the diversity of comets and asteroids and its relation to variations in the conditions of formation and evolutionary modifications is an essential aspect of their exploration.* Elucidation of this diversity will require a coordinated program including both *in situ* measurements and remote observations.

In its earlier strategies for planetary exploration, COMPLEX recognized the likelihood of a constrained budget over the next decade and accordingly recommended achieving at least a limited set of goals of the highest scientific importance that could be attained only through planetary encounter by spacecraft. For both the inner and the outer solar system, selected planets were identified as principal targets for investigation over the next decade in order to fulfill the primary scientific goals. At the same time, it was the committee's recommendation that, on a time scale of two decades, the general level of exploration for all the inner planets, the level of exploration for the outer planets, Jupiter and Saturn, and the level of reconnaissance for Uranus be brought into approximate balance.

Asteroids and comets are both important classes of objects that are complementary in the type of information that they may potentially yield about conditions in the early solar system. Fragments of both classes of objects may exist in earth laboratories in the form of meteorites, and the firm establishment of a close generic link between a meteorite class and specific comets and asteroids would represent a substantial scientific achievement. The primary objectives for exploration of both comets and asteroids developed in this report are in equal measure of the highest scientific importance.

Asteroids and comets can be distinguished at present, however, in the level of our knowledge about their solid fractions and in the variety of information and processes capable of being addressed by spacecraft encounter. Whereas there exist sufficient earth-based measurements of asteroid surfaces to infer some compositional information and to classify asteroids into different classes that may be related to various meteorite classes, the solid nucleus of a comet has never been resolved, and little information on the composition of the solid fraction of comets is available. A major difference between comets and asteroids is the relative content of volatiles. These volatiles can be directly and readily sampled by spacecraft in the cometary coma and characterized chemically. We have no intact sample of this material available. In addition, there are important dynamical processes that arise from the interaction of the comet with radiant solar energy and the solar wind that are of intrinsic scientific interest. Comets may have formed far from the sun in the outer solar system, at or beyond our present reach with spacecraft, and may retain materials not preserved elsewhere in the solar system, including possible presolar grains in addition to materials formed in the primitive solar nebula. *Therefore, COMPLEX views reconnaissance and initial exploration of comets by spacecraft encounter as a goal of high priority and recommends that it be accomplished in the period 1980–1990.*

Existing knowledge of asteroids allows us to pose fundamental scientific questions about the early solar system. Approaching the answers to those questions will require spacecraft encounters with asteroids. The apparent chemical variation of asteroid surface material with solar distance within the main asteroid belt suggests that asteroid exploration offers a promise for elucidating conditions of solar nebula condensation between the orbits of Mars and Jupiter. Investigation of apparently differentiated and undifferentiated asteroids will address the important question of early heat sources in solid objects of the solar system. Geological processes on small bodies, recently glimpsed by images of the moons of Mars and Jupiter, are also of significance to the field of comparative planetology. *Therefore, COMPLEX views reconnaissance and initial exploration of asteroids by spacecraft as a goal of high priority and recommends that it be undertaken within the next decade and a half.*

The three documents setting out the strategy for exploration of the outer planets, of the inner planets, and of primitive bodies were developed separately over a period of several years. This separation, however, exists only for reasons of time and schedule. None of the strategy statements should be regarded outside of the broader context of the overall strategy represented by all three. Nor should a more recent document be thought to carry greater weight than an earlier one, except in so far as a recommendation clearly and explicitly differs from previous SSB policy. *The three strategies for outer-planet exploration, for inner-planet exploration, and for the investigation of primitive bodies together constitute a coherent and comprehensive strategy for scientific exploration of the planetary system over approximately the next decade.*

There are clear scientific reasons for linking the inner and outer planets and primitive bodies within a single, integrated exploration strategy. The planets in the solar system divide naturally into the large, low-density, outer planets and the smaller, high-density inner planets. The outer planets have large components of volatile materials and well-developed satellite systems and collectively contain most of the mass and angular momentum of the planetary system. The inner planets, including earth, are dominantly rock and metal and are, by comparison, volatile poor. Both sets of bodies are the products of broadly common processes of solar nebular condensation and planet formation. Comets, asteroids, and meteoroids are comparatively primitive objects that may still record conditions and processes in the early solar nebula, near the time of planet formation. Main-belt asteroids provide this record in an orderly distribution over a range of solar distances from the orbit of Mars to that of Jupiter and thus constitute a key link between the inner and outer planets. Comets apparently provide a complementary sample of primitive volatile-rich material from the outer solar system perhaps beyond the orbit of Uranus and thus are products of the outer reaches of the solar nebula near to or beyond our present ability to explore by spacecraft.

The Committee affirms its recommendation that a significant program of exploration of the solar system by spacecraft should be maintained during the coming decade. This report, together with the two previous COMPLEX reports, sets forth the strategy for such a program, which is conservatively paced, in concert with the expectation of severe fiscal constraints over the foreseeable future and which recommends only those objectives that are of the highest scientific importance and that can be achieved only by spacecraft encounter.

For the outer planets, COMPLEX has recommended that in-depth exploration of Jupiter and its satellites and reconnaissance of Uranus are goals of the highest priority during 1975-1985 and that NASA be in a position to initiate exploration of the Saturn system by the end of that time. For the inner planets, COMPLEX has recommended that the triad Venus, Earth, and Mars receive the major focus of exploration during 1977-1987. In the present strategy, COMPLEX recommends that reconnaissance and initial exploration of comets is a goal of high priority for the next decade and that reconnaissance and initial exploration of asteroids is a goal of high priority, which should be achieved within the next decade and a half.

The program of solar-system investigation should be balanced. It should move forward on a broad front to the outer planets, the inner planets, and the small primitive bodies in a manner consistent with the scientific objectives.

5
Comets

THE PRESENT STATE OF KNOWLEDGE

Comets have generated a deep impression and much public interest over many centuries. The familiar and generally visible heads (comae) and tails of comets, though spectacular, are ephemeral and transient phenomena. A large tail persists typically for 3 to 6 weeks during a comet's passage in the inner solar system and is composed of gas and dust emitted by a small and difficult to observe object called the nucleus. Comet nuclei can be seen sometimes as pinpoints of light in the comae of comets, but they evidently are much too small to be resolved from Earth even with the largest telescopes. A comet's emission is maximum at perihelion passage—its closest approach to the sun. After that, the visible phenomena diminish. The tail usually disappears first, typically near 1.5 astronomical units (A.U.), and the fuzzy remnant of coma usually disappears when the comet reaches 3 to 4 A.U. At large distances from the sun, where they reside for most of their lifetimes, comets consist of bare nuclei.

It is commonly thought that cometary nuclei are conglomerates of dust and ices or snows, that they are among the most primitive remnants from the condensation of the presolar nebula, and that they have been preserved for aeons in a pristine state in the deep cold of space at very large distances from the sun. Occasionally gravitational perturbations from passing stars or interstellar clouds dislodge a comet and send it careening into the inner solar system, where heat from the sun boils off gas and dust to produce the spectacular displays normally associated with these bodies. Some of these comets are trapped near the solar system by gravitational attraction of the planets and remain periodic comets until their gas is depleted. Cometary comae and tails are evidence of a permanent loss of gas and dust, produced by solar heating, and thus for the dissipation of the nucleus.

Several schools of thought hold that cometlike objects were among the fundamental building blocks of some larger planetary bodies and that they may also have played a role in later states of planetary evolution, perhaps by providing volatile constituents for some atmospheres. It has been speculated that some of these cometary constituents were essential to the origin of life.

As a result of their small sizes, and their large average distances from the sun, evolutionary processes that differentiated the planets are thought to have been insignificant for many comets. After a comet enters the inner solar system, its decay is rapid, taking typically less than 100,000 years. Comets observed from Earth are in varying states of dissipation.

A bright comet consists of a roughly spherical coma or atmosphere comprised of dust, neutral gases, and ions; a curved, relatively featureless dust tail whose axis lies in the plane of the cometary orbit; and a narrower plasma tail directed almost exactly away from the sun and showing considerable temporal and spatial structure. Depending on a comet's distance from the sun and the light in which it is observed, its coma can be quite large, in the range of 10^5 to 10^7 km when a comet is at 1 A.U. The plasma and dust tails are even larger in the case of a bright comet, some 10^7 to 10^8 km in extent. All of these phenomena result from the gas and dust that emanate from the nucleus; the nucleus itself is thought to be small, of the order of 1 to 10 km in diameter for typical comets.

Approximately 630 different comets have been discovered so far, and the new discoveries number roughly 5 to 10 a year. These comets can be classified into four groups according to their orbital periods:

1. Short-period comets with periods ranging from 3 to 25 years. There are approximately 80 of these, and most have been observed repeatedly. Among the shortest periods are those of Encke, whose orbital period is 3.3 years and whose return has been observed more than 50 times, and Tempel 2 with a 5.3-year orbital period and whose return has been observed more than 20 times.

2 and 3. Intermediate- and long-period comets, with periods in the range of 25–200 years and 200 to 10^6 years, respectively. Approximately 470 such comets have been observed, of which only about 20 have intermediate periods. A few of the latter have been observed repeatedly in historical times, Halley's comet being the best known example, with a period of 76 years.

Long-period comets have elongated elliptical orbits extending as far as 10,000 A.U. from the sun; they approach the sun more or less isotropically and with random inclinations. This is in sharp contrast to the motions of the short-period comets, which all orbit in the same sense as the planets and have small inclinations. Among the intermediate-period comets are some that orbit in the retrograde direction.

4. About 80 comets have orbits that are quasi-parabolic. Their original orbits, before entering the solar system, have aphelia that seem to cluster too close to 50,000 A.U. to be random. Most of them apparently have never been through the planetary system before, since gravitational perturbations from the giant planets would already have scattered their aphelia over a much larger range. Because these comets apparently come from distances at which gravitational disturbances produced by passing stars or molecular clouds are significant, it is believed that they come from a population of comet nuclei stored at large distances in loosely bound orbits about the sun. This swarm of comets is usually called the Oort cloud. As noted earlier, bodies near the margins of the cloud are sometimes perturbed by stars and provide a steady supply of "new" comets to the inner solar system. Since comets decay fast, this source of new comets evidently maintains the present steady state among decaying "old" comets.

When all planetary gravitational perturbations on cometary motions are taken into account, the differences between computed and observed positions usually grow as the square of time, implying that an acceleration has been neglected. This nongravitational force is thought to be a reaction to the nonsymmetrical emission of gas from the surface of the nucleus. In some comets, for example, Encke, this rocket effect produces pronounced perturbations of the orbit. This same phenomenon often makes the orbit of a newly discovered comet impossible to predict with great accuracy.

The ice and snow in comet nuclei is thought to be composed of condensed gases and other volatile materials, including H_2O and probably CO, CO_2, HCN, CH_3CN, as well as unidentified complex organic molecules. The nonvolatile material is believed to be in the form of grains ranging from submicrometer-sized dust to sand grains and perhaps pebbles and boulders, containing silicates and possibly metals, oxides, sulfides, and organic compounds among others. These agglomerations were described picturesquely by Whipple as "dirty snowballs." When solar heat vaporizes the volatile material, the outflowing gas carries smaller solid particles with it. Since the comet's gravity is finite, though weak, any larger pebbles and boulders are likely to remain bound on the surface of the nucleus. Also since many comets show evidence of directional emission of gas and dust, it is apparent that their nuclei are inhomogeneous and may have localized active regions. The emission of material is often sporadic, suggesting further that comet nuclei are generally inhomogeneous.

Our knowledge of the comet nuclei is limited and, to a large extent, indirect. (Indeed, a minority view holds that cometary nuclei are not monolithic objects at all but rather are loose aggregates of material.) The masses of comet nuclei are not known with any certainty. Upper limits of about 10^{21} g are implied by their lack of gravitational influence on passing objects; but this number is too large to be a significant bound. Estimates of mass lost by comets in a single solar passage are in the range of 10^{13} to 10^{14} g. Active comets survive for more than 100 solar passages, implying nuclear masses in excess of 10^{15} g. Assuming that the density of a conglomerate of ice and nonvolatile material is 1 or 2 g/cm^3 and using the diameters of a few bright comets established from their production rates and the magnitudes of the inactive nuclei, it appears that most comet masses lie in the range of 10^{15} to 10^{18} g. The corresponding diameters are 1-10 km. The material that makes up comet nuclei may be relatively fragile in view of the tendency for some comets to split as they pass close to the sun. This is consistent with a low-density, perhaps nonspherical, icy conglomerate. Comet nuclei seem to rotate with periods typically of the order of 10 h.

With reasonable assumptions about the albedos of comet nuclei, the variation of their temperature with distance from the sun can be estimated. On this basis it is possible to give a plausible account of the appearance of comet comae by assuming that sublimation of H_2O, or sometimes CO_2, is the controlling process. With further assumptions concerning the thermal response of the surface as it rotates, it is possible also to give a reasonable account of the nongravitational forces. Those models that agree best with observed cometary orbits assume that sublimation of water snow dominates the gas emission in short-period comets. These ideas also account reasonably well for the formation of dust tails.

We are confident that our general ideas about comet nuclei are correct on the whole. However, many observations do not fit easily into familiar patterns, indicating that the actual state of affairs is more complicated than we have described. Comets show evidence of their widely different ages and progressive loss of material. Indeed, some comets that have been observed many times show direct evidence of aging through secular changes in their activity during successive solar passages. In addition, there may be important differences, from one comet to another, in initial structures and compositions. However, no comet characteristics observed so far point clearly to significant variations among the structures and compositions of young, unevolved comet nuclei. Observations made so far are unable to resolve this important question. New comets are more luminous and more homogeneous in luminosity, as a class, than old, evolved comets. Unusual emissions of CO^+ or dust seen in some comets may be an evolutionary effect.

As a comet approaches the sun its surface temperature rises and consequently the rate of sublimation of the volatile material increases. The temperature of the surface and the depth to which the solar heat penetrates depend on the physical characteristics of the surface material, especially the albedo and the thermal conductivity. However, as a rough guide we can expect CO_2 to sublime rapidly at distances from the sun less than about 3 A.U. and H_2O at distances less than about 1.5 A.U. from the sun.

Gas leaves the surface at about the speed of sound, which corresponds to the surface temperature and expands into the interplanetary medium. Thermal energy of the gas is converted to kinetic energy of radial outflow—a cometary wind similar to the solar wind but produced without the decelerating effects of gravity. For most comets, gas densities near the nucleus (within about 10^3 nuclear radii at 1 A.U.) are large enough for collisions and fast ion-molecular reactions to alter the chemical composition of the gas. However, the time available is relatively short (10^2 to 10^3 sec), and the densities are very low (about $10^{12}/cm^3$ at the surface of a vigorous nucleus near 1 A.U.). Farther from the nucleus the gas chemistry is fixed, except for alterations due to photodissociation, photoionization, and perhaps ionization by locally accelerated energetic particles. Photodissociation leaves hydrogen atoms with large random velocities (10–20 km/sec), resulting in an extensive hydrogen cloud, seen in Lyman-alpha radiation.

The composition of the coma is determined by the so-called parent molecules, which make up the volatile components of the nucleus. These have yet to be identified. Most of the parent molecules are unobservable or difficult to observe through the use of earth-based spectroscopic techniques. So far only HCN and CH_3CN have been tentatively identified as parent species through the detection of microwave lines. The presence of water in the nucleus is inferred on the basis of a number of circumstantial arguments, some of which were mentioned earlier. Other parent molecules that may be present include CO, CO_2, CH_4, and N_2. Most of the radicals observed in comets are observed also in the interstellar medium. Thus, it is tempting to search in comets for those more complex molecules that have already been found in interstellar molecular clouds. However, the basis of any such analogy is not now understood. We should not expect that all the volatile elements are emitted from comet nuclei, since very complex organic polymers or tars may be retained and may be detectable only through *in situ* techniques or by means of a sample return.

The species that have so far been identified in cometary atmospheres are the following:

Organic: C, C_2, C_3, CH, CN, CO, CS, HCN, CH_3CN
Inorganic: H, NH, NH_2, O, OH, H_2O
Metals: Na, Ca, Cr, Co, Mn, Fe, Ni, Cu, V, Si, K

Ions: CO^+, CO_2^+, CH^+, Ca^+, N_2^+, OH^+, H_2O^+

Dust: The presence of silicate material is suggested by infrared spectral measurements; carbon may be present also.

Most of the early identifications were made from spectra at visible wavelengths, because these species flouresce efficiently in sunlight. The dissociated neutral atomic constituents should be detectable from telescopes in space through ultraviolet flourescence; H, C, and O have been found so far.

The ionization of the neutral gas is not understood at present. The flux of solar far-ultraviolet radiation is too small by an order of magnitude to account for the apparent rate of ionization. An unknown ionizing process seems to be at work, and this poses an important challenge to our understanding of comets. Several mechanisms have been suggested, but no one generally accepted, quantitative model exists. One important possibility is ionization by fast electrons accelerated by the interaction of the solar wind and the magnetized cometary plasma. Such energetic electrons might, for example, be produced by field-line reconnection in a magnetized comet tail. This would be a cometary analog of the process that produces terrestrial auroras and that seems to accelerate energetic particles in other astrophysical environments.

A tentative estimate of the volatile fractions of four recent comets has been made from their apparent production rates of C, O, and N. Although the parent molecules are uncertain, they seem to be composed mainly of H, C, N, and O. The mass ratio of the dust to gas liberated from a nucleus has been estimated in two cases to be 0.5 and 1.7, within a factor of 2. By comparison, the ratio of volatile to nonvolatile components is about 100 for solar material. These tentative results imply that hydrogen and helium are depleted in comets. Nevertheless comets seem to contain 3 to 10 times as much volatile material as the most volatile-rich meteorites, and CI chondrites. Thus comets seem to have solidified out of the solar nebula at temperatures much lower than characteristic meteorite condensation temperatures, at about 150 K as opposed to over 400 K. This suggests that cometary material is the least differentiated and best preserved condensation product of the preplanetary solar nebula that is known to remain in existence.

As noted above, the mass of emitted dust seems, within a factor or 2, to be approximately equal to the mass of emitted gas. The flow of gas carries dust grains to a several-hundred-meter-per-second terminal velocity within a few nuclear radii. Subsequently, the grains move in orbits that depend on the ratio of solar radiation pressure to solar gravity. Some grains are blown almost directly away from the sun by radiation. The larger grains move in Keplerian orbits, with their gravitational attraction to the sun effectively reduced because of radiation pressure, and produce a broad, curved dust tail. The very largest grains have orbits much like the comet's and lie in a thin sheet in comet's orbit plane, sometimes visible in an "anti-tail" or sunward spi The very smallest cometary dust particles are probably swept from the so system by the solar wind.

Sunlight scattered by dust particles is responsible for the continuum li from the coma, tail, and anti-tail. The particles are heated by sunlight a emit thermal infrared radiation with a superimposed silicate spectral feat near the wavelength of 10 μm, probably because of silicates. The infra observations show that in addition to silicates the dust contains a bla material presumed to be carbon. The silicate signature is strikingly sim to that seen in circumstellar shells around giant and supergiant oxygen-r stars, and the black, sootlike material appears to be similar to dust surrou ing carbon-rich stars. The silicate signature is also seen through absorption dust in the interstellar medium between Earth and the galactic center. T interstellar dust may be produced by red giant stars, novae, and supernovae

New comets appear to emit dust grains copiously, and these form sp tacular dust tails. Periodic comets have some dust in their comae but do have pronounced dust tails. The dust in the comae of comets Encke Kohoutek had thermal emission spectra, which suggests the presence of la grains. These large grains give thermal radiation without the silicate signatu which requires grains to have radii of less than 10 μm.

Altogether, observations in visible light and at infrared wavelengths se to indicate that comets emit dust particles ranging in size from less tha micrometer to more than a centimeter. In addition, fragmentation of nucleus observed in some comets suggests that "particles" as large as h dreds of meters can be produced by splitting of the nucleus. The rec comet West broke into four large pieces of similar brightness and with sim dust production. It appears that the dust-ice mixture is not a surface p nomenon but prevails throughout the cometary nucleus.

Comet grains left in interplanetary space may make a significant contri tion to the zodiacal light, a glow produced by sunlight reflected from in planetary dust grains. These grains probably originate largely from aster fragmentation and cometary dust, as well as from interstellar dust ente the solar system. The zodiacal cloud must be continuously replenished cause the larger grains spiral into the sun in a relatively short time as a re of the Poynting-Robertson effect, and the smaller grains are blown ou the solar system even more quickly.

Large pieces of cometary debris follow orbits closely associated with parent comet. When this debris impacts Earth, it produces the familiar met showers. For example, comet Halley's debris is responsible for two show one in early May and one in late October. Halley's showers last only abo week, demonstrating a strong concentration of the orbiting debris.

Light from the resulting meteor trails can be observed spectrosopically, and it shows the lines of common elements, such as sodium and magnesium, in roughly solar abundances. It is thought that small meteoroids, including those associated with meteor showers, provide the metallic ions that are observed to make up ionospheric sporadic E layers. *In situ* observations of the ionic compositions of these layers have revealed the presence of Na, Al, Si, Ca, Fe, and three Mg isotopes with relative abundances that approximately follow the solar abundance pattern. It should be noted that extraterrestrial dust grains have been collected on airplane flights in the upper atmosphere. The origin of these grains remains uncertain.

It is speculated that some fraction of comet dust may be unaltered interstellar material. It may be possible to illuminate this question by establishing some elemental isotopic ratios. Relative isotopic abundances of the elements reflect their formation processes. Carbon is a good example. Bodies within the solar system, including the sun, the moon, terrestrial planets, meteorites, and Jupiter, exhibit a common value of about 90 for the $^{12}C/^{13}C$ isotopic ratio. Red giant stars show a range from 12 to 50 for this ratio. In carbon stars the ratio falls in a wide range from 2 to 100. Although observed values in the interstellar medium also span a wide range from 13 to 105, some investigators have argued that a value of 40 is representative.

The measured $^{12}C/^{13}C$ isotopic ratios in the gas of comets Ikeya (70 ± 15), Tago-Sato-Kasaka (100 ± 20), Bennett (greater than 50), Kohoutek (115^{+30}_{-20}), and Kobayashi-Berger-Milon (100^{+20}_{-30}) are consistent with a solar-system origin for volatiles in these bodies. However, laboratory studies and model calculations of ion-molecule reactions indicate that mass kinetic effects can yield rather large isotopic fractionations, which may obscure the true values of $^{12}C/^{13}C$ in the interstellar medium; similar reactions may influence the cometary ratios. These important problems point to the need for a better understanding of isotope fractionation effects in nature.

The gas emerging from a comet nucleus is ionized to increasingly higher levels as it travels out through the coma. It has already been mentioned that an energy source sufficient to account for the observed ionization is unknown at present. Because of its ionization, cometary gas is expected to interact strongly with the solar wind even though classical, interparticle collisions are negligible. Collective phenomena, in which many particles interact electrically and coherently over large distances, dominate the behavior of ionized plasmas. These should prevent the comet and solar-wind gases from flowing freely through one another. The solar-wind magnetic field further inhibits intermingling of comet gas with the interplanetary medium, and charge-exchange interactions also are thought to transmit solar-wind momentum to the comet gas efficiently.

Altogether, to a first approximation, it is thought that the solar wind and the comet gas behave largely as immiscible fluids. Because mass loading of the solar wind by charge exchange with comet gas rapidly slows the solar-wind flow, a standoff shock wave forms some 10^4 to 10^5 km in front of the comet (that is, on the sunward side); behind this shock, solar-wind gas flows around the comet. The spherically symmetrical flow of comet gas is stopped by solar-wind pressure; the gas flow is turned and swept around behind the comet to produce the ion tail. The appearance of extended linear features in comet ion tails suggests that at least some interplanetary magnetic field lines are snared by comets, draped around the comae, and stretched back through the ion tails. Reconnection of these tail field lines, in a cometary analog of the geomagnetic substorm, may provide a source of energetic particles to produce the bulk of the comet's ionization, although plasma turbulence in other parts of the interaction region may also accelerate particles.

These qualitative ideas about the comet-solar wind interaction have existed for several decades. Indeed, the behavior of comet ion tails, specifically the appearance of accelerating motions too rapid to be produced by the pressure of sunlight, led to the earliest notions of a continual corpuscular solar radiation. Nonetheless, a firm and detailed understanding of the interaction is inhibited by our lack of hard information. There is significant uncertainty about even the gross aspects of these phenomena. For example, the formation of a standoff shock wave in the solar wind ahead of the comet depends on the rapid deceleration of the wind flow. If mass loading of the solar wind is diffuse and extended over a large region of space, the deceleration may be gentle enough to deflect the wind around the comet without generating a shock. In this case the interaction may involve substantially smaller amounts of energy conversion from the solar-wind flow into, say, fast particles. Resolution of fundamental questions about the comet-solar wind interaction will require *in situ* measurements of the plasma, energetic particles, and electromagnetic fields in the inner and outer coma and the near tail.

Many of the visible characteristics of comets, including the dynamic behavior of cometary structure, are produced by these plasma phenomena. Disruptions, kinks, and waves in comet tails may result from instabilities associated with the tail magnetic field and the streaming motions of plasma along the lines of force. Large-scale magnetized plasmas and assemblages of dust and gas are ubiquitous in the universe. These behave in unexpected ways that depend on physical conditions and scales that are unique to astrophysical systems. Dynamical phenomena in comets are manifestations of processes with much wider generality in astrophysical plasmas. Thus the study of comets may influence our ideas about physical processes in natural objects that are well beyond our reach for *in situ* investigations.

We have already noted that some 80 comets have been observed to follow very extended, weakly bound orbits with aphelia clustering about 50,000

A.U. We have also noted that these objects appear to be following their first traverse through the inner solar system and that they apparently come from the edge of an extensive cloud of cometary bodies surrounding the solar system. The size of the cloud is limited sharply by gravitational perturbations from passing stars. The existence of this "Oort cometary cloud" is established with reasonable certainty. However, we have no direct information either as to its age or its origin. No reasonable mechanism for the formation of comets *in situ* in the distant cloud has been proposed. The characteristic times for particles to aggregate to macroscopic dimensions in regions of such low density are apparently too long.

It is generally thought that comets formed at about the same time as the rest of the solar system, some 4.5 billion years ago. Their high volatile content suggests that comets condensed and accreted in cool regions of the presolar nebula. Beyond that we have no knowledge of the details of the formation of comets and their subsequent transfer to storage in extended orbits in the Oort cloud. A number of ideas have been put forward, including ejection through gravitational interactions with the giant planets and orbit expansion following rapid loss of material from a massive presolar nebula. According to some of these speculative ideas, cometary bodies are part of the population of planetesimals that accreted to produce the giant planets.

A possible clue to the origin of comets is the size distribution of new comets, which, however, is inferred only indirectly and is poorly known. Their diameters appear to cluster near 5 km. The masses of such objects are in the range that characterizes bodies that may result from gravitational instabilities in the dusty, icy, preplanetary disk nebula.

Comets spend only a small fraction of their lives in the inner part of the solar system. An active comet is thought to lose some 1 percent of its mass during each orbit, so that the active life of a periodic comet is short on a cosmic time scale. Evidently, the observed population of comets is in a roughly steady balance between the supply of new comets from the Oort cloud that are captured into the inner-solar system, the loss of cometary bodies ejected from the solar system, and the depletion of comet volatiles with the consequent decay of activity.

As noted earlier, gravitational perturbations from passing stars are thought to precipitate the initial entry of a comet into the inner solar system. The subsequent capture of these bodies into tightly bound orbits of short, intermediate, and long periods is evidently a result of the gravitational influence of the planets, predominately the massive planets Jupiter and Saturn. The general features of the capture process appear to be understood, although some details remain to be elucidated. Many of the cometary bodies that initially enter the inner solar system are thought to be ejected by the planetary perturbations, with only a fraction captured into stable, bound orbits.

The rapid decay of comets in the solar heat suggests the existence of a population of inert, residual cometary bodies, largely depleted of their volatile material. It is speculated that inert comet cores may be found among the Apollo-Amor asteroids, which move about the sun in elongated Earth- and Mars-crossing orbits.

In this brief summary of the present knowledge of comets we have stated our ideas about these objects, and our motivations based on these ideas, for undertaking more detailed and intensive study. Our ideas about comets are constructed from limited remote observations as well as from our more general notions about solar-system bodies. This fabric of preconceptions, tentative though it is, allows us to pose significant questions on which to base more detailed studies and ensures that such studies will be scientifically rewarding.

COMET SCIENCE OBJECTIVES

The primary scientific objectives of comet exploration during the next decade are, in order of priority:

1. To determine the composition and physical state of the nucleus (determination of the composition of both dust and gas is an important element of this objective);

2. To determine the processes that govern the composition and distribution of neutral and ionized species in the cometary atmosphere; and

3. To investigate the interaction between the solar wind and the cometary atmosphere.

In view of the apparent diversity of comets, it is important that comparative measurements be made, including measurements of objects in different stages of evolution. Furthermore, it is important to observe the changing state of the nucleus and coma of a comet during perihelion passage.

A secondary objective is to determine the physical state of the cometary dust for the purpose of relating it to interplanetary and interstellar dust.

The nucleus is the fundamental part of a comet, having survived, presumably in a relatively unaltered state, from the early epochs of solar-system formation. Through detailed understanding of comet nuclei, including both their bulk compositions and their physical and chemical structures, we can address the primary overall goal of comet and asteroid studies enunciated earlier: to understand the solar nebula, its origin, and its evolution. Determination of the composition of comet nuclei also helps to address the thir overall goal: to assess the role played by comets and asteroids in the evolution of the atmospheres and crusts of the terrestrial planets.

Through 4½ aeons in deep-freeze at the fringes of the solar system, comet nuclei have preserved volatile-rich materials and structures that would normally be transitory in our part of the solar system. Indeed the distinguishing features of comets, their comae and tails, provide dramatic evidence of the essential evanescence of cometary material near the sun. By determining the nature of volatiles and particulates released from comets during their brief sojourns in the inner solar system and by establishing the processes of cometary luminescence and decay, we address the second and fourth overall goals for the study of small bodies. In particular, an understanding of the diversity of comets requires that we be able to relate the remotely observable emissions from active comets to their nuclear structures and compositions. Manifestations of solar-wind interaction, including the plasma tails, provide special opportunities for studying space physics; many questions are before us, including the existence of an upstream bow shock, the character of the surface of contact between cometary atmospheres and the space environment, the degree of particle acceleration, and the nature of cometary outbursts.

Knowledge of the composition of both volatile and nonvolatile components will establish an important reference point for theories about early-solar-system processes, including the relationship of cometary and meteoritic material, and the possible cometary contribution to planetary atmospheres. The surfaces of comet nuclei that are accessible to remote sensing may have concentrated massive nonvolatile phases due to preferential vaporization of volatiles and ejection of dust during previous perihelion passages. In addition, the emitted gas is expected to be fractionated as a result of differential volatility of the various constituents. This emphasizes the importance of separately characterizing the compositions of all three components—the nuclear surface, the atmosphere, and the dust—in order to meet the objective of the first priority.

MEASUREMENT REQUIREMENTS

The scientific objectives for comets mandate measurements that will characterize the nucleus, the dust, and the atmosphere of one or more comets. The current state of ignorance of the nature of cometary matter dictates an approach in which the requirement for reconnaissance is not compromised by attempts to achieve a degree of detail or precision that would be more appropriate to subsequent phases of cometary exploration. At the same time, it is essential that the quality of measurements be sufficient to carry our understanding of these bodies forward in a significant way. In the following paragraphs, we outline these measurement requirements.

The Nucleus

The decadal objective of determining the chemical and physical states of cometary nuclei will require measurements of the elemental and mineralogical composition, the surface morphology and temperature distribution, and the structure and mass of a comet nucleus.

COMPOSITION

Measurements of the elemental composition of the surface of a comet nucleus should establish its chemical state and make possible meaningful compositional comparisons with the atmosphere and dust surrounding the comet as well as with other solar-system objects. *The Committee recommends that the measuremeents should be sufficiently sensitive and accurate to establish the abundances of all chemical elements that are expected to be present in amounts greater than a few percent by atom with an accuracy of the order of 1 atom percent.* It is expected generally that these elements will include H, C, O, Na, Mg, Al, Si, S, Ca, Fe, and Ni. The accuracies called for are adequate to distinguish between the principal classes of known extraterrestrial materials if the nonvolatiles represent at least 10 percent of the surface material. In addition, it is highly desirable to determine abundances of the radioactive elements potassium, thorium, and uranium.

Measurements providing information about the heterogeneity of the chemical composition are also desirable, especially if it proves possible to relate these to regions of active evolution of gas and dust.

If the concentrations of more than 90 percent of the atoms are determined to an accuracy of the order of 1 atom percent, the identities and fractions of common volatile constituents, such as water and carbon dioxide, present to more than 10 percent of the surface will probably have been established. If the nonvolatile constituents are present at only a few percent by weight, then only their fraction and a crude characterization will be revealed by the recommended levels of sensitivity and accuracy. If the nonvolatiles are present in amounts of the order of 50 percent or more by weight, the recommended measurements will distinguish between the gross classes of meteorites as well as between granitic, basaltic, and ultrabasic types of terrestrial rocks.

It is desirable to measure with increased sensitivity and accuracy the values of certain selected element abundances and abundance ratios—for example S/SI—in order to ensure that the gross classes of nonvolatile materials can be distinguished in the case that they comprise less than 10 percent of the surface material. This may also permit classification of the nonvolatile materia in a more detailed way, at the level of distinguishing between the various classes of carbonaceous chondrites.

Measurements of the major mineral components of the surface of a comet nucleus, including regional variations, should be made. Mineralogical information can be used to infer the physicochemical conditions under which the constituents of the nucleus formed, as well as the alteration processes to which the material has been subjected. It is particularly important to detect and, if possible, to measure the concentrations of water and carbon dioxide ices, high-temperature refractory silicates that are commonly found in meteorites, layer-lattice silicates such as those found in the matrices of carbonaceous chondrites, and minerals such as gypsum, which might be formed by the volatile leaching of the nucleus. The success with which mineralogical components can be distinguished and identified depends on the context in which they are found, including the specific character of the mineralogical mixture. *It is desirable that the concentrations be established of all minerals comprising more than 5 percent of the surface material of comets, with a spatial resolution of better than 10 percent of the diameter of the nucleus.*

We do not anticipate that isotopic, trace-element, or complex molecular compositions of cometary nuclei can be measured in a substantial way during the first phases of comet exploration. But the measurements—especially of isotopic composition—are important. Accomplishing them should be a goal that helps to shape even the earliest phases of exploration. For example, determination of the mechanical properties of the surface of the nucleus will help to define conditions in order to facilitate eventual *in situ* measurements or sample acquisition for laboratory analysis. The elements for which isotopic composition should eventually be determined include those that reflect the preaccretionary compositional mix of the solar nebula and those that have been useful in understanding the chronology of thermal evolution and outgassing history of the planets. Molecular components may be an especially important constituent of a volatile-rich, low-temperature body such as a comet, and those accounting for more than 1 percent of a comet should eventually be identified. Abundances should eventually be measured for those trace elements that have proven useful in the past in characterizing processes of condensation, (e.g., the platinum metals), volatile fractionation (e.g., In, Tl, and Pb), geochemical differentiation (the rare earths), and generation of heat (K, U, and Th). Such measurements should aim at elucidating processes of fractionation that occur in a volatile-rich environment.

PHYSICAL CHARACTERISTICS

The nuclear surface features should reveal information about the processes of comet decay and thus, by extention, about the primordial comet. In addition, the surface may reveal a cross section of the object if it has partially ruptured or otherwise decayed in an asymmetric fashion. *We recommend that most of the nuclear surface of comets be mapped to a resolution of a few meters and that selected regions be photographed at higher resolution to examine texture and structure.* Detection of structural changes during perihelion passage is desirable.

The temperature of the nucleus plays a large role in governing the manner in which a comet sheds material from its surface and in determining the overall heat budget of the body. *We recommend that the temperature distribution over the surface of comets be measured on both the day and night sides with a resolution better than 10 percent of a nuclear diameter.* Coupled with measurements of the surface albedo, this will provide important information about the thermal properties of the surface material. It is desirable to measure the temperature of selected regions, especially those associated with localized activity, to considerably higher resolution.

The density of the comet nucleus provides an important constraint on its bulk composition. *The mass and shape of the nucleus should be measured with sufficient precision to yield a bulk density accurate to 10 percent.* It is also desirable to measure any remanent magnetism of the nuclear material as well as its bulk electrical properties.

Cometary Dust

The nonvolatile portion of comets may consist of particles that are a mixture of solar nebular condensates, reworked solar-system materials, and interstellar grains. The significance of comet-dust composition is further enhanced by its possible relationship to other bodies of the solar system such as asteroids, meteorites, and the meteoroid complex. Establishing the composition will help to elucidate the nature of this material and the character of preaccretionary physical processes in the region of comet formation.

We recommend that the principal chemical elements of the dust, those expected to be present to more than 1 percent by atom in the nonvolatile portion, be measured with an accuracy of better than ½ atom percent. It is expected that these generally will include, as in the case of the bulk nucleus, H, C, O, Na, Mg, Al, Si, S, Ca, Fe, and Ni. Coupled with appropriate measurement strategies, these data should make possible meaningful deduction about the mineralogy, state of oxidation, and state of hydration of the material, as well as significant comparisons with the compositions of other solar-system bodies. Some of these comparisons would be made more significant, and more detailed information relevant to comet history would be available, if measurements could be made of certain less abundant or trace elements; among these are K, Th, U, and one or more of the rare earths.

It is important to determine the mineralogy and textural relationships of mineral groups within the dust particles. In favorable cases, this information can be used to infer the conditions under which the nonvolatile fraction of the comet formed and alteration processes to which this material has been subjected. Identification of all minerals present with an abundance greater than 5 percent is desirable. Particular emphasis should be placed on the measurement of refractory silicates (such as pyroxenes) commonly found in meteorites, layer-lattice silicates such as those found in the matrices of carbonaceous chondrites, and volatile leaching products. It would also be useful to measure the grain sizes of different mineral phases as well as the textural relationships among various minerals. In addition to providing a basic characterization of the nonvolatile material necessary to infer its origin, comparison of these properties with laboratory measurements of recovered meteoroids might provide decisive links between comets, meteorites, and interplanetary dust.

Cometary Atmosphere

Our ignorance of comet atmospheres dictates an exploratory approach in which a comprehensive inventory be made of all the species within the range of detection. *COMPLEX recommends that the abundances of all those atmospheric species with molecular weights in the range of 1-150 and which are present at relative concentrations by number in excess of 0.1 percent of the total be determined.* The accuracy of the abundance measurements should be better than 10 percent. In addition, accurate isotope ratios for specific volatile elements can provide unique information concerning nucleosynthesis and solar-system and comet formation and evolution. For this purpose, isotope ratios for those isotopes of O, C, N, Ar, and Ne that are detected should generally be determined to be better than 5 percent, and in the case of $^{16}O/^{18}O$, to 1 percent. A significant increase in scientific return could result from an extension of the mass range to at least 250 and to a partial concentration of 0.01 percent or less.

Measurements at the recommended level should differentiate over a range of important but diverse possibilities for the volatile inventory of comets. For example, if cometary atmospheres contain all the volatile elements, except H and He, in the ratios believed to exist in the primitive solar nebula, then $^{16,18}O$, H, $^{12,13}C$, ^{14}N, $^{20,22}Ne$, ^{32}S, and ^{36}Ar would be present at levels exceeding 0.1 percent. At the 0.01 percent level, ^{34}S, ^{38}Ar, ^{15}N, ^{17}O, ^{21}Ne, ^{33}S, ^{31}P, ^{19}F, and ^{35}Cl would be detected. Finally, if HDO is the major deuterium-bearing constituent, then D becomes detectable at the 0.001 percent level. If, as a contrasting case, cometary atmospheres contain volatile elements in the abundances expected from outgassing of Cl carbonaceous chondrites, then all of the elements O, H, C, S, N, and P would be present at levels exceeding 0.1 percent, but the rare gases Ne and Ar would be very minor constituents.

The chemical compounds in which the volatile elements occur may come out of the nucleus at different distances from the sun. *Therefore, we recommend that measurements of cometary atmospheric composition be made over a range of activities of the comet, including its most active stage.*

In order to elucidate the physical and chemical processes that control comet atmospheres, it is necessary to determine the nature and spatial and velocity distribution of the important dissociated and ionized constituents. As discussed earlier in this chapter, a number of atoms, free radicals, and ions have already been remotely detected in comets. They are, undoubtedly, additional but as yet undetected species. Measurements of the variations in constituent abundances with distance from the nucleus are required to establish the relationship of products to parent molecules. *Therefore, we recommend that the abundances of the major radicals and ionized species be determined to better than a factor of 2 uncertainty and that sufficient measurements be taken to determine their radial distribution.* In order to assess the contribution from fast electrons to the dissociation and ionization of atmospheric components, *we recommend that the flux, spectrum, and distribution of electrons in the range from thermal energies to several thousand electron volts be determined.*

The Solar-Wind Interaction

The general objective is to determine the overall structure, distribution, and dynamics of the cometary and solar-wind plasmas and magnetic fields. *We recommend that measurements of the plasma, electromagnetic fields, and energetic particles, as well as neutral and ionized particles, be made in a volume of space surrounding the nucleus and encompassing the major solar-wind interaction areas.* These areas include the undisturbed solar wind, the hypothetical shock front, postshock plasma flow, contact discontinuity between the solar wind and cometary plasmas, and the outflowing cometary gas and plasma. For an active comet, this requires that intensive plasma physical measurements be made to a distance extending some 10^7 km in front of the comet. It is desirable to carry out measurements in regions to the side of and behind the comet, where the ion and dust tails are connected to the comet's coma. This will provide important information about the inner boundaries of the tails and will reveal to us the gases, particles, and fields of which the tails are composed. It is also desirable to measure the energetic neutral particles produced by charge exchange between the solar wind and cometary gas. The measurements should be carried out over an extended period of time and with sufficient temporal continuity and time resolution to monitor transient and periodic behavior; these may include sudden changes in ionization, energetic particle flux, and magnetic field, among other phenomena. Measurements of the neutral and ionized thermal gas composition are discussed in detail elsewhere in this report and complement the additional measurements discussed here. It is desirable that the ion flux composition measurements be sensitive to low partial densities, of the order of 0.1 cm^{-3}, in the solar-wind interaction region.

The solar-wind plasma measurements should be sensitive to the density and flow of ions throughout the solar-wind interactions region. This requires the capability to measure the plasma flow in a hot, postshock solar-wind, where temperatures may range near 10^7 K with low flow speeds. Measurements should also be made of the plasma electron distribution function throughout the comet.

The thermal gases and plasma that flow from a comet have particle energies that range up to about 10 eV; this is the range of energies typically available from dissociation and ionization reactions. Plasma particles that are part of the solar-wind have kinetic energies that correspond to the solar-wind flow speed, that is, up to about 10^3 eV; these are addressed by the measurements described above. It is a common feature of nonequilibrium assemblages of plasma and magnetic field that they accelerate energetic particles as a consequence of their sometimes violent attempts to reach equilibrium. In a comet, energetic particles may be accelerated in a number of regions, including the ion tail, especially if it contains a strong entrained magnetic field. From the tail, these particles may move into the inner coma by streaming along magnetic field lines. Particles may also be accelerated by plasma turbulence produced from the direct interaction of the solar-wind and comet gas flows. The flux of the energetic ions and electrons should be measured. The sporadic and transient nature of these energetic dynamical phenomena dictates that the measurements have a time resolution of the order of 1 sec. Sufficient angular resolution and coverage should be obtained to determine anisotropies in the energetic particle fluxes. The range of energies covered in measurements aimed at the solar-wind interaction should extend to a value that corresponds to the solar-wind electric field potential across the comet; the energy range should extend up to about 100 keV.

The magnetic field may play a controlling role in many of the cometary plasma dynamical phenomena. The magnetic field structure should be determined in the extended coma and solar-wind interaction regions as well as in the vicinity of the nucleus. Measurements of the magnetic field should be sensitive over a range that includes the weak interplanetary field insensitities at several astronomical units from the sun—of the order of 100 gammas. The magnetic field measurements should encompass a range roughly from 10^{-1} to 10^{+3} gamma. The three components of the vector field should be measured with a frequency response from dc to several cycles per second, to allow identification of transient and sporadic phenomena as well as low-frequency hydromagnetic waves.

The plasma turbulence wave spectrum resulting from the solar wind–comet interaction should be measured in the interaction region and in the upstream solar wind. Wave turbulence is an important feature of the behavior of natural, nonequilibrium plasmas. In a comet it may play a dominating role in coupling the cometary gas to the solar-wind flow, and it may also accelerate energetic particles. The frequency range for these measurements should begin at a few cycles per second and should extend high enough to include all plasma modes having frequencies up to the highest electron plasma frequency expected to occur in the dense cometary ionosphere.

STRATEGY RECOMMENDATIONS

Based on the preceding considerations of the present state of knowledge of comets and of the investigations needed to carry our understanding forward, COMPLEX has formulated a strategy for the exploration of comets. The known comets encompass a broad range of activity levels. Generally speaking, the most active comets appear to be those that have most recently entered the inner solar system; those less active apparently have resided for longer times near the sun in relatively tight short-period orbits and already have lost a large fraction of their volatile components. Cometary bodies that have exhausted their volatiles may ultimately become members of the population of Earth- and Mars-crossing asteroids, which are discussed later. The best preserved samples of primitive cometary material are therefore thought to reside both in new comets making their first traverses from the Oort cloud through the inner solar system and in long-period comets that have made only a small number of passes near the sun. In addition, these young, active comets, with their vigorous outpouring of gas and dust, interact strongly with the solar wind and with sunlight. Thus, these comets also provide the best opportunities to explore the full range of dynamical processes associated with the comet phenomenon.

The Committee is informed that, for practical reasons, these young, active comets are effectively beyond our present reach for detailed, *in situ* study. Their orbits are poorly known, and there is rarely sufficient time between the discovery of these comets and their close solar passage to mount a well-targeted mission, even if a spacecraft is kept prepared and waiting. The comets that are accessible for spacecraft investigation, in intermediate- or short-period orbits, are generally among the older and more evolved comets. Nevertheless, *in situ* studies of the composition and structure of these evolved comets, combined with the knowledge that will be obtained about their modes of evolution, should allow significant reconstruction of the primitive character of these planetesimals. The more active of the short- and intermediate-period comets also provide good opportunities to explore the physical processes associated with cometary atmospheres and with their interaction with the solar wind.

An understanding of the range of diversity of comets is an important scientific goal. The differences between one comet and another may be caused either exclusively by the process of aging—loss of mass during solar passages—or they may reflect differences in primordial state and composition. The detailed composition of condensates formed in the outer regions of the primitive solar nebula, where we believe comets originated, is unknown. Reliable deductions concerning the actual range of diversity of bulk cometary material are hampered by our lack of knowledge of comet nuclei. The Committee has concluded, therefore, that a detailed *in situ* study of any one active comet has a high probability of providing a significant increment in the information about the general nature of low-temperature condensates in the primitive solar nebula. Any *in situ* comet investigation must, however, include as an essential element a determination of the relationship between its remotely observable characteristics and its detailed composition. This determination should include simultaneous remote observations of the comet. In this manner, the similarities and differences between the explored comet and other observable comets can be investigated.

After assessing the present understanding of comets, the Committee concludes that studies of cometary nuclei and their emitted atmospheres are in an early reconnaissance stage and constitute the highest priority objective of *in situ* cometary investigation. However, significant observational information is in hand for the coma and solar-wind interaction regions, including the tail. These observations pose specific questions about cometary processes; consequently, the Committee judges the present level of study of these parts to be at a more advanced exploratory stage.

It is the Committee's view that while Earth-based and Earth-orbital observations of comets will continue to make important contributions, they will not substantially improve our understanding of comet nuclei during the time addressed by this report. *In order to elucidate the composition and structure of comet nuclei and atmospheres, and to explore the range of cometary phenomena, COMPLEX concludes that spacecraft studies of comets must be undertaken.* High-activity comets provide the opportunity to explore the physical processes that produce the widely known, and spectacular, extended comet phenomena; these also provide examples of some of the least evolved volatile-rich material remaining from the solar system's formation. Low-activity, short-period comets provide the most accessible targets for detailed study of the nucleus and coma regions. It is desirable that *in situ* studies be undertaken of more than one comet, including specimens with widely different levels of activity to facilitate disentangling of the evolutionary processes. Ground-based and earth-orbital observations of comets interpreted in the light of *in situ* measurements can also make valuable contributions to our understanding of the evolution and diversity of comets.

The Committee has been informed of a range of mission modes that can currently be brought to bear on comet exploration, including both high-velocity flyby and extended-period rendezvous. *COMPLEX concludes that a response to the comet science objectives will require the use of rendezvous-mode investigations and that during the next decade the minimum appropriate increment in our knowledge of comets will require a rendezvous with at least one active comet.* Investigation of the nucleus, atmosphere, and solar-wind interaction region requires the high spatial resolution and coverage over an extended time that can be realized only in the rendezvous mode. Our present lack of knowledge of the close-in comet environment and the anticipated modest level of improvement in this knowledge prior to a spacecraft mission dictates that a rendezvous mission be operated in an adaptive mode that allows the measurement tactics to be tailored to avoid hazards and maximize the science return.

Rendezvous-mode investigations provide long stay-times in the near vicinity of a comet nucleus. This capability should be exploited to study the variation of comet behavior during at least a substantial part of a full orbit for a short-period comet. Ideally, measurements should be made during both pre-perihelion and postperihelion phases of the orbit and should follow the comet at least until the emission level has fallen to 1 percent of its maximum value.

In order to realize the further goal of understanding the factors that produce diversity in the population of comets, a balanced and economical program of cometary exploration could incorporate flyby in addition to rendezvous-mode investigations. Flyby investigations may be especially useful for extending our understanding of comet diversity to the young, vigorous objects that may contain the best preserved samples of primitive material but that generally follow orbits least accessible to rendezvous modes. Flyby investigation of a comet, with suitably developed instrumentation targeted to study the gas, dust, and magnetic plasma, should provide valuable independent information as well as data useful for comparison with the detailed investigations of cometary nuclear and extended regions undertaken from rendezvous spacecraft.

In the Committee's judgment, the science objectives can be met during the next decade without undertaking to land on or penetrate a comet nucleus. In the absence of any information about the physical constitution of comet nuclei, we consider that mission modes should not be attempted that rely on either landing or penetrating to meet the basic science objectives. In looking ahead to comet investigations, beyond the decade specifically addressed in this report, COMPLEX envisages measurements of greater technical sophistication, including those that demand landing on or penetrating a comet nucleus, as well as the eventual *return of a surface sample to* Earth for laboratory analysis, to meet the overall goals of solar-system science. In keeping with the policy of the SSB, we consider that planning for such an endeavor will require precursory studies to enable proper selection, acquisition, and handling of a sample, and we consider that such planning is an intrinsic part of a *program of cometary science.*

6
Asteroids

THE PRESENT STATE OF KNOWLEDGE

The asteroids are a collection of small bodies that orbit the sun, predominantly in a main belt at distances of 2 to 3½ A.U. Thus the main belt of asteroids resides in the transition region separating the rocky, terrestrial planets of the inner solar system from the giant gaseous planets of the outer solar system. Calculations suggest that most of the asteroids have remained near their present relative positions in the solar system since their formation. Telescopic spectral measurements made of these bodies show that they vary in their mineralogical compositions. The spectroscopically defined classes of asteroids resemble, in a general way, some of the classes of meteoritical materials. The distribution of asteroid types in the main belt apparently is not random. Near the inner edge a large fraction of the asteroids have spectral reflectance properties similar to those of the rocky, silicate-rich meteorites. Farther from the sun, in the outer parts of the main belt, most of the asteroids have reflection spectra similar to volatile-rich carbonaceous chondrite meteorites; these meteorites are thought to be the least-altered early solar-system materials for which we have samples. Altogether, the asteroids seem to constitute an ordered assemblage of primitive planetesimals and their fragments in which there is preserved important information about the structure of the protoplanetary nebula and the processes that produced the planetary bodies of the solar system. Elucidation of the formation and evolution of the solar system will require detailed knowledge of the asteroids. In this chapter we summarize our knowledge of asteroids that leads to these perceptions and outline the investigations aimed at gathering the needed information.

Everything we know about the properties of asteroids is derived from measuring the positions of these bodies in the sky and by analyzing the time variability and spectral content of the reflected and emitted radiation from unresolved, starlike images. Such data provide knowledge that is meager with respect to that needed to answer fundamental questions about the nature, origin, and evolution of these bodies. Asteroids move along modestly inclined and eccentric orbits, most of which are in the main belt, but some of which are found inside Earth's orbit, others beyond Jupiter's orbit. Jupiter has had a clear effect on the distribution of asteroid orbits as evidenced by gaps within the main belt and clusters of asteroids beyond the main belt. Asteroids have collided often with each other at typical velocities of 5 km/sec. About half the catalogued asteroids are clustered according to their orbital semimajor axes, eccentricities, and inclinations; these groups, which may be the products of collisional fragmentation, are known as Hirayama families.

The largest asteroid, Ceres, is 1000 km in diameter, and there are more than 30 others larger than 200 km. The population grades in a roughly power-law-like distribution down to bodies of 1 km in diameter and perhaps much smaller. Asteroids are generally irregular in shape, although the largest ones tend to be spherical. They spin with rotation periods ranging from a few hours to several days but most commonly with periods of about 9 h. The orientations of asteroid spin vectors are poorly known but may be random. Masses and densities are known for only three asteroids and with only poor precision. Ceres's mass of about 1.2×10^{24} g constitutes about one third of the total mass of the asteroids. Its density is about 2.2 g/cm^3, significantly less than Vesta's density of about 3 g/cm^3.

Optical properties, including, for example, albedos and reflectance spectra, have been measured for many asteroids and exhibit considerable diversity. Frequency histograms of various optical parameters show bimodalities (or half-a-dozen clusters in a multiparameter space) that have been used to define several broad classes. The main classes are designated C, S, M, and E. Some asteroids, including many Hildas and Trojans, which are in resonant orbits beyond the main belt, and a few main-belt asteroids, such as Vesta, do not fall into any of the defined classes and are referred to as "unclassifiable." Statistics indicate that among the 500 to 600 main-belt asteroids larger than 50 km diameter, the black C types account for about 76 percent of the asteroids, the brighter S types about 16 percent, and the others less than 10 percent. But the proportions vary with distance from the sun; over 50 percent of asteroids at the inner edge of the main belt are S types, while at the outer edge, where C types overwhelmingly predominate, only 6 percent are of the S type. Some Hirayama families exhibit a variety of optical types, while others have members with similar optical properties.

It should be emphasized that despite the clustering into broadly defined types, asteroids exhibit considerable diversity within the types. For instanc reflectance spectra of S-type asteroids exhibit an absorption band in t near infrared that varies considerably in both depth and central waveleng from asteroid to asteroid. Perhaps two dozen recognizably different spect are all broadly classed as S type, and much diversity exists within oth classes as well. Despite the considerable variation among asteroid types, in plying a variety of surface compositions, individual asteroids usually sho considerable homogeneity in optical properties, although the data pertai only to hemispherically averaged measurements as asteroids rotate. A fe cases are known of modest heterogeneity on single asteroids.

Among the most influential thrusts of asteroid research has been the inte pretation of the optical surface properties, as indicated by the optical type but measured more precisely by reflection spectroscopy, in terms of mineral ogical assemblages. Spectra of S-type asteroids reveal absorption band believed to be due to pyroxene, olivine, or mixtures of both; these importan silicates are probably mixed with substantial amounts of metal. The C-type asteroids, which have optical similarities to carbonaceous chondrites, contai at least several percent of opaque materials that serve to partially mask spectral features of silicates. Indeed, in terms of the major minerals to which reflection spectroscopy is sensitive, including pyroxenes, olivine, metals, and opaques, it appears that most asteroids may have compositions similar to some classes of meteorites. But the unique identification of metals and other opaques may not be possible through these remote techniques, so the compositional similarity of asteroids to meteorites remains a working but tentative hypothesis. This hypothesis is bolstered by dynamical studies that suggest that many meteorites may be derived from the main asteroid belt.

Most asteroids are in orbits that appear to be relatively stable. Thus, unlike comets, most asteroids probably condensed and accreted from the solar nebula somewhere near their current locations with respect to the planets. Since these locations, for most asteroids, span the region separating Mars from Jupiter, one might expect initial asteroidal compositions to vary from rocklike bodies near Mars to volatile-rich, icy, perhaps cometary, objects near Jupiter. The possibility that an initial distribution of composition has been at least partially preserved in the main belt is suggested by the monotonic increase with heliocentric distance in the fraction of asteroids with optical similarities to carbonaceous chondrites. Some other asteroids, beyond the main belt, are even more likely to remain near their relative heliocentric formation distances. These are the Hildas, Trojans, and Thule, which are locked in orbital resonances with Jupiter, preventing close approaches to Jupiter, thereby preserving their orbits. (Their original neighbors were presumably destroyed or ejected by close encounters with Jupiter.) The asteroid region may be the dumping ground for some bodies originally formed elsewhere in the inner solar system, but it is thought that most asteroids originally formed between Mars and Jupiter. Thus one of the most important reasons for studying the asteroids is that they give us insight into processes of condensation, accretion, and evolution of bodies formed in the transition region between rocky terrestrial planets and the gaseous outer planets.

Data obtained from ground-based measurements suggest that most asteroids are of a primitive composition. This hypothesis is unproven, but the close similarity between spectral–albedo curves for many C-type asteroids and for carbonaceous chondrites suggests compositional similarity. This notion is reinforced by such specific observations as the 3-μm H_2O band of Ceres and some other C types. Furthermore, the relatively small sizes of asteroids is likely to have protected many of them from most processes of thermal and chemical evolution that have affected the moon and larger bodies. Since asteroids have suffered an extensive collisional history, many of the smaller asteroids may be relatively recent fragments from the interiors of primitive precursor bodies, where primitive material has been protected throughout much of the history of the solar system.

Such primitive material in meteorites has given us important information about the behavior of the elements during condensation of the solar system, the chemical composition of the solar system, and the physiochemical conditions and processes in the solar nebula around the time of condensation. Meteorite material also shows a variety of isotopic anomalies, clearly of nucleogenetic origin, that give important information about the processes of element formation. Finally, meteorites contain evidence, including temporal information, about subsequent processes of accretion and interaction with the interplanetary environment; this information includes magnetization, radiation effects, embedded solar gases, and petrographic features. Detailed examination of an asteroid of such primitive composition may provide the best chance of studying primitive, undifferentiated material formed in a known part of the inner solar system. Some of the other asteroids, such as the Trojans, may have preserved low-temperature, primitive materials even better than have the short-period comets, which repeatedly approach the sun.

The spectra of some asteroids show substantial evidence for thermal evolution. The clearest example is the asteroid Vesta, which exhibits a reflection spectrum clearly incompatible with primitive composition. The spectrum, which is similar to that of basaltic achondrites, has been interpreted as being due to pigeonitic pyroxene and plagioclase with virtually no olivine, suggesting that this 500-km body has differentiated geochemically. Indeed minor compositional variations have been observed on different sides of Vesta, perhaps similar to the variety of basalt flows on the lunar maria. Other asteroids are less certain to have undergone thermal evolution, but three optical types may be of stony-iron (S), metallic (M), and enstatite achondritic (E) composition, all of which are usually interpreted as being highly evolved mineral assemblages. The S and M types may turn out to be the metallic cores of differentiated bodies, like Vesta, from which the original stony mantles and crusts have been stripped away by subsequent collisions.

Differentiated bodies of such small size are important to our understanding of geological, geophysical, and geochemical evolution of larger bodies. Because of their large area-to-mass ratio, small bodies require a rapid release of energy (e.g., by radioactive decay) if their internal temperatures are to increase significantly after formation. Hence, if any small bodies are found to have melted this will establish a stringent constraint on early solar-system thermal processes that may also have affected the moon and the terrestrial planets. The subsequent thermal and geological evolution of such small bodies may have been more rapid and simpler than the more extended evolution of the larger planets, but the character of such evolution remains unexplored.

Altogether, while some asteroids may have melted and evolved thermally, the majority of asteroids apparently have not, including Ceres, which, although larger than Vesta, is thought to have an undifferentiated primitive surface. The asteroids, then, appear to span the range of initial conditions that caused some to melt and evolve and others not to do so; their study thus sheds light on the sources of heat in the early solar system and on thermal evolution of planets and satellites.

The storage of many asteroids near their locations of formation in the inner solar system has had an important consequence. Because of their numbers and relative velocities of 5 km/sec, asteroids within 3.5 A.U. of the sun have undergone extensive collisional evolution. The distributions of asteroid spins and shapes have been interpreted as being due to collisions. The Hirayama families provide further evidence of the importance of collisions. In some cases the shattered bodies apparently were homogeneous, whereas in other cases they apparently were differentiated. The extensive collisional evolution of asteroids probably provides the chief impediment to reading the evidence of the very earliest solar-system processes from these bodies. But the impediment is not nearly so great as for the moon. On larger bodies, collisional impacts, including the very largest events, rain ejecta down over the surface of the body, forming regolith or blanketing layers that hide the materials beneath. But the smaller asteroids, and perhaps all but the largest ones, are thought to be fragments of precursor bodies whose gravity fields were too small to hold them together against violent collision-induced disruptions. Thus asteroids may present unique possibilities for studying the interiors of relatively large precursor bodies. As previously mentioned, the interiors of unevolved asteroids may contain well-preserved primordial material. Layering observed in such bodies would give direct information about their accretion histories and possibly about the condensation sequences in regions of the nebula where they formed. Furthermore, study of zonal layering on evolved asteroids would provide powerful information about the differentiation of small bodies.

Although we have no direct observations of asteroid geology, the Viking imagery of Phobos and Deimos hints at the surprises that may be in store for us. The morphologies of asteroidal surfaces will undoubtedly indicate both the extensive cratering and collisional histories and provide evidence for internal processes. The great range of asteroid sizes, and hence gravity fields, will sharpen our understanding of planetological processes, such as impact cratering, that are affected by gravity. If inferences from asteroid spectra are correct, some asteroids may be composed largely of nickel-iron and thus may undergo unusual geological processes. Beyond helping us to disentangle the physics of basic planetological processes, the morphology of asteroid surfaces provides a geological record that will reveal to us some of the past history of these bodies.

The Earth-approaching asteroids, of which there may be 1000 or 2000 larger than 1-km diameter, are in short-lived orbits. Few, if any, have remained in such orbits throughout solar-system history, and, instead, they are believed to have come, in relatively recent times, from the main asteroid belt and from the comet population. Perhaps half of these bodies are extinct comet nuclei. Most investigators strongly believe that many meteorites are fragments of such Earth-approaching asteroids. Reflection spectra suggest that some of these objects have the major mineralogy of ordinary chondrites, the largest class of meteorites.

We have already noted that many of our ideas about the formation and early evolution of the solar system have been derived from study of the meteorites, which represent the only nonlunar extraterrestrial samples available for detailed laboratory investigation. A significant limitation in interpreting the meteorite data is our ignorance of where these objects originated. The dynamical mechanisms that bring these fragments to Earth are not well understood, but it is widely conjectured that many meteorites originate from parent bodies within the main asteroid belt. Spectral similarities between meteorite types and asteroid classes exist, particularly for carbonaceous chondrites, stony irons, nickel irons or enstatite chondrites, and basaltic and enstatite achondrites. But the specific identifications are uncertain, and the apparent frequency distribution of main-belt asteroid classes is different from that of the meteorites. For instance, analogs of the most abundant meteorite class, the ordinary chondrites, seem to be rare or absent in the main belt. As we have just observed, it is virtually certain that some meteorites are derived from some of the small Earth-approaching asteroids, a few of which do seem to have the major mineralogy of the ordinary chondrites. But it is uncertain, in turn, whether the Earth-approaching asteroids are derived from the main belt, the comets, or perhaps from elsewhere. Our inability to place the meteorites in a geologic or cosmogonic context limits the interpretation of meteorite data. For example, the isotopic anomalies found in inclusions in Allende cannot at present be identified with a location within the solar nebula, even as far as specifying the inner or outer solar system. From the point of view of the asteroids themselves, it is almost certain that existing meteorites already provide samples from many more asteroids than are likely to be acquired through sample return missions. If specific relationships are established between these meteorites and their asteroidal sources, the meteorites will be elevated to the status of returned asteroid samples. If such identification is made, it will then be possible to utilize the meteorites to explore diversity within the asteroid population in ways not otherwise practical. Thus, a significant motivation for exploring the asteroids is to determine what relations exist between meteorites and asteroids, thereby establishing links between available extraterrestrial samples and the nature and location of their parent bodies.

Asteroids are bombarded continuously by energetic particles from the solar wind, from solar flares, and from the galactic cosmic rays. The record of this long-term bombardment is carried in the surface through enrichment of volatile material, activation of radioactive species, ionization damage, and loss of constituents as a result of sputtering as well as outgassing. Lunar material has been subjected to similar influences, and important information already has been gleaned from these records in lunar samples. The information carried in asteroidal material is thought to be different from and complementary to the lunar data because asteroids reside in different parts of the solar system, are thought to have much more volatile-rich compositions, are thought to undergo generally different surface processes because of their small size and weak gravity, and have impact histories substantially different from that of the moon. Further, a record of the temporal and spatial variation of energetic cosmic rays as well as a record of solar activity is carried in asteroid material. These records can be disentangled, and information of high scientific importance regarding the evolution of asteroid surfaces can be extracted by laboratory analysis on returned samples.

The above motivations for asteroid research are based on a relatively limited data base that reveals some asteroidal properties but that does not address many other properties. Our ideas are also shaped by plausible but unproven hypotheses, such as the one that links meteorites to asteroids. Our understanding of asteroids is now sufficient, we believe, to list reasonable and important goals and objectives for future study. But as long as our data are derived solely from measuring starlike asteroidal images from Earth, we must regard the asteroids as essentially uncharted worlds to explore that hold the potential for great surprises. Every previous occasion on which a first spacecraft reconnaissance mission procured a leap in knowledge of a planet, our preconceptions have been found wanting, and major areas of scientific inquiry were initiated. Thus a significant motivation for exploring the asteroids is the potential for many important, unexpected discoveries that we may anticipate when exploring virtually unknown worlds for the first time. Our approach must be sufficiently flexible to meet that challenge.

ASTEROID SCIENCE OBJECTIVES

The primary scientific objectives for the exploration of asteroids are, in order of priority:

1. *To determine their composition and bulk density;*
2. *To investigate the surface morphology, including evidence for endogenic and exogenic processes and evidence concerning interiors of precursor bodies; and*
3. *To determine the internal properties, including states of magnetization of several carefully chosen asteroids selected on the basis of their diversity.*

Significant aspects of both 1 and 2 must be addressed together by any program of asteroid exploration. Measurement of asteroid composition and morphology must be carried out together, because the interpretation of compositional variations and morphology of an asteroid are intimately connected with each other. The asteroids selected for exploration should include representatives of the common and of several unusual spectral classes. It is also desirable to explore asteroids over a range of semimajor orbital axes from Earth-approaching asteroids to the Trojans, to explore members of a Hirayama family, and to explore objects of different sizes.

A secondary objective of asteroidal studies is to determine long-term variations in the space environment, including the solar wind, micrometeoroid, solar-flare particle, and galactic cosmic-ray fluxes, through the record left in asteroid surface material.

The primary scientific goal for asteroids, the determination of their composition, directly addresses the primary motivation for studying primitive bodies. The gradation of observable properties of bodies in the asteroid belt suggests that this region of the solar system contains a relatively unaltered record of the physical structure of the primitive solar nebula and the condensation and accretion processes that operated in the early solar system. Thus, measurement of the compositions of several bodies that are representative of the observable differences across the asteroid belt should provide important information on the chemical composition and physical conditions of the presolar nebula at the transition region between the rocky inner planets and the gaseous outer planets. In addition, the characterization of selected highly evolved asteroids will address the sources of heat and thermal evolution of planets and satellites as well as provide an opportunity to study planetary interiors exposed in asteroids by the many collisions that have altered them since their formation.

MEASUREMENT REQUIREMENTS FOR ASTEROIDS

Composition

The chemical composition of asteroidal material should be established with detail sufficient to determine its chemical state and to make possible meaningful comparisons with meteoritic data. *We recommend that the principal chemical elements present in asteroids to more than 1 percent abundance by atom be measured to an accuracy of about 0.5 atom percent.* It is expected that these will include the elements H, C, O, Na, Mg, Al, Si, S, Ca, Ti, Fe, and Ni. The required accuracies should distinguish between the principal known classes of extraterrestrial materials and provide information on the oxidation states and degrees of hydration.

These elements should be measured at at least one location on an asteroid with the above accuracy. Several diagnostic elements should be measured with sufficient global coverage to determine the scale and extent of chemical heterogeneity. The radionuclides, K, Th, and U, are important in estimating the present and past heat budgets of a body; the abundances of volatile elements (e.g., Pb or In) provide information on the temperature history of an object; the abundances of other trace elements such as rare earths, reflect certain magmatic histories. It is highly desirable to establish the amounts of Th and U with a detection limit of 0.01 ppm and an accuracy of at least 30 percent and K with a detection limit of 100 ppm and an accuracy of 20 percent. The measurement of at least some of the diagnostic trace elements with a detection limit of 0.1 ppm and an accuracy of 30 percent would also be desirable.

A less-comprehensive chemical analysis will lead to significant ambiguities in interpretation. For example, although determination of a few especially important elemental ratios (e.g., Mg/Al, Fe/Si, and O/Si to 10 percent accuracy) and the establishment of the presence of C and H at greater than the 0.5 percent by atom level would be an important addition to our knowledge of asteroids, it would leave the relationship of these bodies to some meteorite classes much less certain.

Experience with meteorites has shown that objects with similar elemental compositions may have different mineralogies. Knowledge of the mineral composition provides additional information about chemical composition and also provides information about the physical conditions under which asteroidal materials formed and were subsequently altered. For example, CI chondrites are dominated by hydrous iron magnesium silicates formed at low temperatures, whereas many ordinary chondrites, dominated by olivine and pyroxene, underwent high-temperature metamorphism. It can be expected that the asteroids will show similar mineralogical variations as a result both of solar-nebula processes that occurred before accretion and of evolutionary processes that occurred after accretion.

Mineralogical measurements should be sufficiently informative to distinguish between "primitive" and evolved materials. They should be able to recognize rocks that have melted and differentiated and should be able to discriminate between "equilibrated" and "unequilibrated" assemblages such as are found in the ordinary chondrites and minerals of hydrothermal or evaporitic origin. Because of the low temperatures of asteroids, it is important that the measurements be sensitive to water present as ice and in the form of hydrated minerals.

Significant constraints on mineralogy should be established for all asteroids studied. *We recommend that measurements be sufficiently diagnostic to distinguish among the mineral assemblages characteristic of the principal meteorite classes. Furthermore, it is necessary for at least some asteroids to identify minerals present at more than 5 percent of the surface material and to measure their concentrations on the surface to within a factor of 2.* These recommendations are intended to be consistent with the fact that some mineral assemblages are relatively easy to characterize while others are nearly intractable even in the laboratory.

The chemical characterization of an asteroid should also include identification of molecular components. The molecular component includes such relatively volatile species as CO_2, water in its various forms, simple organic and inorganic compounds, as well as complex organic compounds that vaporize or decompose only at elevated temperatures. Some of the meteorites that are considered to be most primitive contain several percent by weight of carbon, and, indeed, this is commonly thought to be a sign that a meteorite contains primitive, relatively unaltered material. Although an adequate elemental analysis will set limits on the maximum amounts of such species, because of their significance to our understanding of the nature and history of asteroids, they warrant special consideration. In the early stages of asteroid exploration, establishing the presence of 0.1 percent or more by weight of such molecular components, and establishing the character of those species that represent more than a few percent of the total, is desirable.

Isotope studies have provided some of the most detailed insights into processes that occurred in the early solar system. Pairs of nuclides, such as ^{40}K-^{40}Ar and ^{87}Rb-^{87}Sr, have defined the ages of formation of lunar and meteoritic materials. Studies of isotopes of Xe have helped to define, through measurements of the decay products of ^{129}I and ^{244}Pu, the history of nucleosynthesis. Spallation patterns in the isotopes of the rare gases, and the amounts of cosmogenically produced radioactive nuclides, have made possible the determination of the times at which various dynamic events, such as the formation of specific lunar craters and the fragmentation of meteoritic parent bodies, have occurred. Careful measurements of the variation in abundances of the three oxygen isotopes have established contributions of different nucleosynthetic processes to solar-system material. More recently, studies of the magnesium isotopes in certain meteorites have revealed the presence of ^{26}Al in the early solar system. The presence of this nuclide has implications both for the formation of some solar-system material and for the possible presence of potent heat sources at early times. Measurements have revealed the existence of isotopic heterogeneities in the early solar system and have opened up the possibility of gaining new insights into the nature of the interstellar material that formed our solar system. Isotopic anomalies that reflect a variety of physical and nuclear processes have recently been found in O, Mg, Si, and a number of heavier elements. The origin and interrelationships of the different anomalies are poorly understood, and further study will provoke our ideas about the formation of the solar system. If asteroids are to achieve their full potential in contributing to the understanding of the formation and evolution of the solar system, it will be necessary to make isotopic measurements with accuracies comparable with those currently possible in Earth-based laboratories. While such accurate isotopic measurements are at present beyond the scope of reconnaissance or exploration-level studies of asteroids, isotopic measurements are considered primary scientific objectives for these bodies.

Physical Properties

Knowledge of the density of an object facilitates important inferences about its bulk chemical composition. *We recommend that bulk asteroidal densities be measured to an accuracy of 5 percent.* This requires accurate measurements of the size, shape, and mass.

We have found distinctive geological units, craters, fractures, lava flows, volcanoes, and other striking morphological features on various bodies in the solar system. All of these features have provided important information on the processes that occurred in and on these bodies. Many such features may be found also on asteroids. The range of apparent compositions and sizes of asteroids suggests that surface manifestations of geological processes will be highly diverse, possibly revealing unexpected features. Determination of the characteristics of impact craters offers the opportunity to study fundamental processes of accretion and fragmentation during planet formation. Observation of asteroid shape, structure, and morphology will help to determine the sizes of impacts required to fragment such bodies, the effects of composition on cratering and fragmentation processes, and the characteristics of asteroidal regoliths.

Asteroids apparently vary from primitive to highly evolved bodies, reflecting processes such as accretion, melting, and differentiation. Various kinds of surface features such as volcanoes, lava flows, hydrothermal alteration zones, faults, and fissures may provide direct evidence of disparate evolutionary histories.

The sizes and distinctive fragmentation histories of the asteroids offer a potential opportunity to observe open cross sections of parent bodies. Freshly exposed surfaces may carry evidence for the homogeneous nature of some bodies or the differentiation or inhomogeneous accretion in the form of physical layering of others. Indirect evidence for compositional layering may be deduced from the characteristics of impact craters formed in materials of different composition.

The surface morphology of asteroids should be determined with sufficient resolution to establish the nature of endogenic and exogenic processes that have altered them. Based on experience with the pictures of Phobos and Deimos, together with speculations about possible asteroidal processes, *we recommend that full coverage be obtained with images having a resolution of 50 m and that images of selected areas be obtained with better than 5-m resolution.* Pictures should be made with a variety of lighting angles, and selected stereoscopic pairs should be obtained to allow unambiguous determination of the surface topography. We anticipate that in studying asteroids, adaptive mission modes will be important in guiding target selection and the extent of high-resolution coverage.

Remanent magnetization seems to be a property of nearly all meteorites. This magnetization may have been the result of a general nebular magnetic field early in solar-system history or the result of a field intrinsic to the meteorite parent body. The presence of magnetization would indicate a body formed in a magnetic field or, less likely, that active field generation is occurring. *We recommend that magnetic field measurements be capable of detecting global magnetism or local remanence at the level of a few gamma surface intensity.*

The importance of determining the internal structure and bulk composition of an asteroid by establishing its density with sufficient accuracy already has been discussed. Techniques to determine the details of the internal structure also exist, and others are likely to be developed in the future. Present methods include active and passive seismic techniques, electromagnetic sounding, measurements of the response of an object to fluctuations in the interplanetary magnetic field, and heat-flow measurements. Internal-structure measurements are important scientifically, though not essential for initial reconnaissance of asteroids.

STRATEGY RECOMMENDATIONS

The asteroids constitute an ordered assemblage of materials spanning a range of heliocentric distances from the middle of the inner-planet zone part way into the outer-planet zone. This orderly variation in composition across the asteroid belt is thought to reflect a variation in the primitive processes of condensation and accretion. The asteroids range in size from tiny meteoroids to small planets of the order of 1000 km in size. Apparently some of these bodies are primitive assemblages of low- and high-temperature condensates, lacking only the most volatile constituents. Others apparently reflect very early processes of planetary modification and differentiation that may have affected the larger planets as well. The characterization and understanding of the asteroid population requires exploration of representative bodies in order to elucidate its fundamental diversity and structure. The exploration strategy must include ground-based and earth-orbital remote-sensing measurements that can address the population as a whole. *COMPLEX recommends that spacecraft exploration of asteroids should be undertaken and considers that it will produce a qualitative increase in our understanding of these bodies.* Spacecraft measurements should be made of a sufficient diversity of bodies to elucidate the variations in composition and structure and so that Earth-based techniques can be usefully applied to extrapolate detailed knowledge of several specific objects to the larger population.

Our basic knowledge about asteroids is highly developed in some areas and totally lacking in others, as a consequence of the peculiar strengths and weaknesses of ground-based observations and inferences drawn from meteoritical data. From the study of meteorites, we can already postulate fundamental, sharply focused questions concerning the mineralogical, chemical, and isotopic character of asteroids that can be approached only through intensive studies. Ground-based, remote observations have yielded reliable classifications of asteroid diversity. Thus asteroid exploration requires both that selected asteroids be studied in detail and that the detailed studies be placed in context through reconnaissance and exploration of a greater diversity of asteroids. Sufficient information now exists about asteroids and their probable relationships to other planets and to the origin and evolution of the solar system that a program of study should be initiated that includes both reconnaissance and exploration phases.

Both flyby and extended-period rendezvous modes are available to the spacecraft exploration of asteroids. After assessing the quality of measurements that can be carried out in these modes and comparing them with the science objectives, *COMPLEX concludes that a response to the science objectives will require rendezvous-mode investigations of several selected asteroids.* The Committee is informed that spacecraft and propulsion capabilities currently envisaged will permit considerable flexibility in the design of an extended multiple asteroid mission. There exists the capability for multiple asteroid rendezvous, including about half a dozen bodies, with extended measurement times available at each object. In addition, for *in situ* analysis, there is the possibility of deploying landing or penetrating science packages to several bodies. Generally this involves a trade against the total number of objects that can be visited. The Committee considers that sufficient information is available, from remote observations and from theoretical considerations, so that *in situ* measurement may be a viable technique for use in asteroid investigations. *COMPLEX recommends that the use of in situ measurement techniques for asteroid investigations be assessed in detail in order to define the increment in measurement capabilities that would be realized, to determine the impact on the overall science objectives, and to assess the reliability of such an approach.*

Exploring the diversity of asteroids is essential to the elucidation of the origin and evolution of these bodies as a class. The variation among asteroids is a fundamental characteristic. Asteroids chosen as subjects for spacecraft investigations should be carefully selected to represent the range of variation. The selected asteroids should span the range of distinct spectral types, including both the most common types and a selection of several unusual bodies. In addition, there are several secondary criteria. Asteroids having a range of orbital distances, from 1 to 5 A.U., should be studied; asteroids of several sizes should be studied; it is desirable to study at least two members of a single Hirayama family.

COMPLEX considers that return of selected asteroid samples for laboratory analysis will be necessary to meet many of the more intensive objectives of continuing solar-system science. A program of asteroid investigation should include studies to guide selection, acquisition, and handling of asteroid samples.

7
Meteoroids: Meteorites, Interplanetary Dust, and Meteors

INTRODUCTION

The term meteoroid is used here to denote interplanetary objects larger than molecules and smaller than an arbitrary size of about 100 m, the approximate size of the smallest telescopically observable asteroids and comets. Meteoroids vary considerably in composition and structure. They range from friable aggregates of microscopic grains to solid iron meteorites. The meteoroid population is a dynamic system in which particles are continually destroyed by collisions or ejected from the solar system while fresh material is added at a rate sufficient to maintain quasi-equilibrium conditions. The orbital lifetimes of individual objects are in most cases considerably shorter than the age of the solar system; most present-day meteoroids are fragments liberated relatively recently from larger bodies. In almost all cases meteoroids are believed to be fragments of asteroids and comets. However, minor components of the meteoroid complex almost certainly include interstellar grains in transit through the solar system as well as particles ejected from Mercury, the moon, and other satellites.

Many meteoroids contain primitive matter. This includes material that may be older than the solar system as well as material that condensed from solar nebula gas. Some meteoroid material carries evidence of early solar-system processes that has been obliterated on large bodies. Although the identification of the sources of these materials is an important problem, extremely important results concerning the early solar system are being obtained even in the absence of such identification.

Because meteoroids are believed to be samples of asteroids, comets, and interplanetary dust, study of them provides a partial approach to the investigation of these primitive bodies. Direct study of comets and asteroids can be accomplished only by telescopic observation or by direct visitation with spacecraft. Meteoroids, however, are numerous and frequently enter the terrestrial environment, where they can be detected through atmospheric entry phenomena and collected for laboratory analysis. Impact effects on spacecraft can also be utilized. It is estimated that approximately 10^7 kg per year of comet and asteroid fragments enter the Earth's atmosphere and settle onto the Earth's surface.

Meteoroid analysis makes use of a wide range of measurement techniques available in earth-based laboratories and, in fact, has stimulated the development of new and sophisticated experimental techniques. Many meteoroids are heterogeneous objects that lend themselves to creative new approaches in separating them into their constituent parts. Measurements of the physical structures and elemental, mineralogical, isotopic, and molecular compositions of meteoroids of all classes are being used to investigate fundamental questions about the formation of the solar system such as the composition of the solar nebula, the role and sequence of condensation, mechanisms of accretion, and the chronology of various processes including solar activity.

Meteoroids provide samples from many more objects than can be visited by spacecraft. By the end of the century it is hoped that detailed investigation and sample returns will have been accomplished with spacecraft missions to several asteroids and comets. It is unrealistic, however, to expect that a truly representative sample of these bodies can be investigated directly even before the end of the next century. Optical reflectivity studies have demonstrated the existence of broad classes of distinctly different asteroid types. Comets, also, may prove to be compositionally diverse. A major motivation for meteroid studies, then, is to gather knowledge about a large number of asteroids and comets. However, a direct link from classes of meteoroids to the comets and asteroids can be constructed only through spacecraft studies of the latter.

An understanding of the physical properties and dynamics of the meteoroid complex is also important for the interpretation of the relationship between meteoroids and other small bodies in the solar system. Such an understanding is crucial to the interpretation of the impact record on planetary surfaces as well as to the question of whether small bodies have played a role in the evolution of planetary atmospheres. Furthermore, the meteoroid complex is the only astrophysical dust cloud in the universe that is accessible for *in situ* studies. Dust is a ubiquitous component of galaxies, and it plays an important role in star and planet formation. By studying the physical processes that influence the evolution of dust in the solar system, we may generalize our insight into similar processes that occurred in the solar nebula as well as in other astrophysical dust clouds.

It is possible that interstellar material is among the meteoroids already being studied in terrestrial laboratories or is a component of the interplanetary meteoroid complex. Identification and study of such material would likely result in a dramatic increase in our astrophysical knowledge.

Meteoroid studies fall into three basic categories: (1) meteorites, (2) interplanetary dust, and (3) meteors. These are distinguished primarily by the experimental or observational techniques employed and are discussed separately below.

METEORITES

Present State of Knowledge

Meteorites are meteoroids that survive passage through the Earth's atmosphere as discrete objects or associated fragments. Meteorites range in size from a few grams to many tons, hence producing a variety of observable effects at the Earth's surface. One dramatic example is the lunarlike Barringer Crater in Arizona, produced by the impact of a massive iron meteorite. Meteorites can be placed into two broad categories according to whether they are differentiated or undifferentiated. Undifferentiated meteorites, also called chondrites, contain nonvolatile elements in nearly their solar proportions, while volatile elements are depleted to variable extents. Those least depleted in volatiles are the carbonaceous chondrites, which are thought to have had the lowest formation temperatures and to have suffered the least thermal and chemical alteration of any solar-system materials so far available for detailed laboratory studies.

Differentiated meteorites–irons, stony irons, and achondrites–have chemical compositions distinctly different from the undifferentiated chondrites. In many cases the compositions indicate chemical fractionation resembling the processes by which igneous rocks were formed on the Earth and moon. However, isotopic studies show that in the case of meteorites most of the magmatic events occurred 4.5 billion years ago, soon after formation of the solar system. They therefore carry important information about heat sources in the early solar system and about the extent to which the planetesimals, which produced the planets, were differentiated prior to their accumulation.

These various meteorites can be further categorized according to a numbe of criteria including their bulk chemical compositions, their degrees of oxidation, their mineralogies, and their petrographies. Of the several thousand meteorites that have been recovered and that are currently available for laboratory analysis, only three have been observed during passage through the Earth's atmosphere with sufficient precision to establish their orbital parameters. All three were ordinary chondrites and had orbits extending into the asteroid belt.

Intensive laboratory investigations of meteorite origin, evolution, and history have been highly rewarding. Mineralogical and chemical studies of distinct inclusions of carbonaceous chondrites suggest that they are composed of material that condensed from, aggregated in, and underwent varying degrees of alteration in the gas of the solar nebula. Age determinations of other meteorites show clearly that some of the planetesimals that formed from such material underwent major differentiation processes shortly after they accreted. The results of many investigations of meteorites, too numerous to summarize, include studies of their mineralogical and petrographic characteristics, determination of their isotopic and major and trace element compositions both in bulk samples and separate constituents, identification of organic compounds, age determinations, measurements of isotope anomalies from extinct radionuclides and isotopic heterogeneities in the solar nebula, and studies of solar and galactic cosmic-ray effects. Remanent magnetization of meteorites points to the presence of strong magnetic fields in the early solar system.

In some meteorites, crystals removed from the interiors have impact craters and solar-flare tracks showing that the crystals were once exposed to free space. These crystals thus preserve a record of the dust and energetic-particle environment dating back, perhaps, to the early solar system. They potentially provide a unique opportunity to study the activity of the early sun.

Trace quantities of many organic compounds have been discovered in carbonaceous chondrites. These may have formed, for example, during condensation of the solar nebula or during electrical discharges in primitive atmospheres around parent bodies of carbonaceous chondrites. The original inventory of complex organic molecules on earth may have been significantly influenced by the influx of such carbonaceous material, and their presence may be intimately linked to the origin of life on earth.

Meteorites provide the most abundant and the clearest clues with which to disentangle early solar-system history; they formed the foundation upon which many fundamental ideas about the origin and evolution of the solar system are based. Much of our thinking about comets and asteroids is similarly based on meteorite studies.

Future Prospects

Laboratory investigations can be expected to continue to yield important results that will help to shape our future thinking about the nature and origin of the solar system. Among many others, investigations in the following areas will undoubtedly continue to be pursued:

1. The nature and extent of isotopic anomalies, the origin of the anomalies and the clues they reveal about origin of the elements, the precollapse state of the nebula, and the mechanisms of condensation, mixing, and accretion;
2. The origin of elemental and mineralogical differences between classes of meteorites, and within individual meteorites, and the clues that these reveal about condensation, accretion, and differentiation processes during the solar system's formation;
3. The deciphering of the record of solar and galactic particle effects as recorded in meteorites, particularly in the case of gas-rich meteorites, which potentially give information on the state of the sun in the early solar system;
4. The relationship between meteorites, asteroids, comets, and interplanetary dust.

Because of the continuing fundamental impact of meteorite studies on the basic scientific goals enunciated in this report and their intimate relation to the study of asteroids and comets, *COMPLEX recommends that a vigorous program of laboratory and theoretical investigations of meteorites be maintained.*

The most sophisticated techniques available for material studies are currently being used to investigate meteorites; indeed, many advances in technique owe their existence to the stringent demands of extraterrestrial materials research. *To realize the full promise of meteorite research it is necessary to maintain laboratory capabilities at the highest level of evolving technology and to encourage the development of even more sophisticated analytical methods.* It is desirable to develop improvements in the sensitivity and precision of isotopic, elemental, and mineralogical measurements. Much has already been learned from precise measurements on ever smaller bits of matter, and this progress should continue. The advent of the new accelerator methods for the direct measurement of radionuclides also gives new opportunities for measuring the radiation histories recorded in meteorites.

The discovery of large numbers of meteorites on the Antarctic ice cap, some of which apparently fell to earth more than 10^6 years ago, makes it now possible to address the question of whether the meteoroid complex arriving at earth and/or the cosmic-ray activity has changed during this period. The cosmic-ray record in the Antarctic meteorites may also provide new insights into the dynamics of meteoroid evolution. Continued collection, curation, and study of this important new source of extraterrestrial materials should be encouraged. Spherules collected in deep-sea sediments represent another, largely unexploited, source of extraterrestrial materials that could be important in extending the range of meteorite types available for analysis as well as addressing the question of temporal changes in the meteorite bombardment record.

INTERPLANETARY DUST

State of Current Knowledge

Interplanetary dust consists of microparticles derived from a number of independent sources including cometary and asteroidal debris, particles ejected from the atmosphereless planets and satellites, and interstellar grains. These microparticles are studied by *in situ* techniques with spacecraft, by sounding rockets that take instruments into the ionosphere, by laboratory studies of collected samples, and by astronomical observations.

Using *in situ* spacecraft techniques it has been possible to measure the dust distribution in the neighborhood of the Earth and the moon and also in deep space. The Helios spacecraft provided measurements on dust fluxes and number densities between 1 and 0.3 A.U. solar distance in the size range between 0.1 μm and 10 μm in diameter. Zodiacal light measurements on Pioneers 10 and 11 revealed the existence of small particles (1–10 μm diameter) beyond 1 A.U. Larger particles ($\gg$ 50 μm in size) have been found between 1 and 5 A.U. by the Pioneers 10 and 11 penetration experiments. At closest approach to Jupiter, an enhancement in the dust flux of up to 2 orders of magnitude was observed. The population of dust particles in the size range 0.1 μm and 10 μm and residing beyond 1 A. U., particularly within the asteroid belt and in the vicinity of Jupiter, is still largely unexplored.

An important recent development has been the collection of small dust particles (~10 μm) of likely interplanetary origin, in the earth's upper atmosphere. It is possible to make laboratory measurements of the elemental, isotopic, and mineralogical compositions and physical structures of individual particles even though such particles are extremely small. Several hundred particles have been collected and partially characterized. The elemental compositions show strong similarities to carbonaceous chondrites. However, the physical structures and mineral assemblages are different, indicating that the dust particles represent a previously unknown type of primitive solar-system material.

Microparticles impacting on solids at a high velocity ($v \gg 5$ km/sec) produce craters. These impact craters have been analyzed in lunar surface samples and in surfaces exposed on spacecraft. This has revealed important information about the size distribution of the past and present dust flux at 1 A.U. Although the question remains controversial, no significant differences between past and present dust fluxes have been proven. Impact craters found on the surfaces of crystals in some meteorites provide clues about interplanetary dust in the early solar system.

Directions for Future Research

Although at present the properties of interplanetary dust are poorly understood, there are a number of important directions for future research that should elucidate these properties and make it possible to relate the dust to comets and asteroids and, possibly, to the interstellar medium.

Several modes of investigation of interplanetary dust exist, and measurement capabilities differ in each mode. Particles recovered from sea sediments, Antarctic ice, and the upper atmosphere can be studied in detail in the laboratory, but no orbital information can be obtained. In contrast, dust detectors on deep-space missions can measure the spatial variation of dust density and can obtain orbital information while providing only limited information about chemical and physical properties. Dust experiments in near-earth orbit offer the possibility of recovering material for laboratory study and also obtaining orbital information.

Much of the interplanetary dust probably consists of primitive materials that can contribute unique and important insights into the formation and evolution of the solar system. Thus, for materials that can be studied in the laboratory such as particles collected in the upper atmosphere, the same philosophy that governs meteorite research applies. Determinations of the chemical and isotopic compositions, mineralogies, morphologies and textural relationships, and radiation histories should be made using the most sophisticated techniques available. While the analytical approaches to the study of interplanetary dust are parallel to those used for the study of meteorites, they currently lack the sensitivity and precision needed to extract the maximum information from minute individual particles. *COMPLEX recommends that the development of techniques to isolate, manipulate, and analyze small samples of extraterrestrial matter be vigorously supported.*

The advent of the Space Shuttle era will open exciting new opportunities for the study of interplanetary dust. The flux of dust particles is low, and the particles are very small. By using large-area, recoverable experiments in space with long exposure times it will be possible to recover significant amounts of material that could then be subjected to analysis in a number of earth-based laboratories. All methods of collection suffer selection biases, and such experiments should be considered complementary to collection of dust particles in the upper atmosphere and in sea sediments. Earth-orbital space collections of interplanetary dust that also established the size distributions, velocities, and directions of collected particles would provide samples that could be more precisely attributed to specific sources within (or outside) the solar system. *COMPLEX recommends that interplanetary dust experiments including collection, analysis, and orbit determination have high priority in the overall program of earth-orbital science.*

In defining the dynamics of the meteoroid complex, it is necessary to determine the flux, orbital parameters, and nature of dust as a function of location within the solar system. It is also desirable to determine the various processes that modify the structure and orbits of particles, including, for example, rotational bursting of small assemblages of particles.

Studies of high-velocity impacting dust particles have already been made on a number of spacecraft. Existing instrumentation can measure impact velocities to 30 percent accuracy or better in the range of 5-20 km sec^{-1}. For higher velocities, these data can at present be determined only within a factor of 2. The smallest detectable particles are 0.1 μm in diameter. Detectors involving thin-film penetration and time-of-flight measurements can achieve velocity accuracy better than 5 percent and can, in principle, achieve impact-angle measurements with an accuracy of 10 deg. These penetration detectors are somewhat limited in that fragile particles and particles smaller than 1 μm break apart in the detector and cannot be measured. Existing instruments can adequately measure mass, velocity, and flux of high-velocity particles in the 0.1-μm to 10-μm size range, but further development is needed for accurate orbital parameter measurements. Elemental and isotopic compositions of high-velocity dust particles can be measured in principle by time-of-flight mass spectroscopy of the plasma generated from high-velocity (>10 km sec^{-1}) meteoroid impacts. A laboratory prototype has demonstrated a mass resolution ($M/\Delta M$) of 80 for plasma generated by impacts of micrometer-sized particles. Element abundance determinations to better than 10 percent and isotopic measurements to better than 1 percent would be highly desirable.

METEORS

Present State of Knowledge

When a meteoroid larger than about 10^{-6} g enters the earth's atmosphere, a number of physical phenomena result. The term "meteor" refers only to these atmospheric phenomena. The most prominent meteor phenomenon is the emission of visible light, which can be used to photograph the atmospheric trajectory, estimate the mass photometrically, and make spectrographic measurements. These observations can be used to infer the heliocentric orbit of the meteoroid and some aspects of its chemical and physical nature. The production of ion pairs along the flight path permits trajectory and mass measurements of smaller meteoroids to be made by radar. Very large meteoroids can be detected at great distances by acoustical techniques. In three cases, as mentioned above, where a significant mass survived, meteorites have been recovered from the predicted geographical area of impact based on trajectory determinations.

Although meteorites form a subset of the meteoroids that appear as meteors, relatively little is known about the properties of the total range of objects that produce meteors. Application of photometric methods to meteoroids ranging in mass from 10^{-6} to 10^{11} g has provided information about their properties. Spectrographic data of limited precision have shown that within a factor of 2 most meteors have an average solar composition of nonvolatile elements. However, in some cases, several elements including, for example, sodium seem to be depleted with respect to solar abundances. Several mass spectroscopic measurements of the enhanced abundances of metallic ions in the upper atmosphere subsequent to meteor showers are consistent with terrestrial values to within 5 percent.

Many meteors come from orbiting streams that apparently are associated with specific comets. This is the only interplanetary material for which a definite source can now be identified. Other meteors occur in streams with orbits resembling those of comets but for which no currently active comet can be identified as a source. Still other meteors are not associated with streams and have orbital elements spanning a large range of values. Many of these latter objects have orbits that are similar to those of comets, while others appear to have evolved from earlier locations in the asteroid belt.

Considerable theoretical and experimental work has been done on the physical structure of meteors. Nevertheless this work has not so far achieved a satisfactory characterization of their properties. An important advance has been made possible by the three ordinary chondritic meteorites that were photographed by meteor networks and subsequently recovered. The calibration established in this way has called into question previous estimates of density, mass, and strength of individual meteors. This more recent work suggests that approximately 30 percent of the larger meteors (more massive than 100 g) have physical properties closely resembling ordinary chondrites and are probably, for the most part, members of this most abundant class of meteorites. Many of the remaining meteoroids are more fragile. These may well be carbonaceous meteorites as suggested by their spectra, but a calibration similar to that achieved for the ordinary chondrites has not yet been possible. Little attention has been given so far to large meteors that occur in showers or that in other ways have definite cometary associations. Insofar as such data have been analyzed, it appears that these bodies are among the more fragile of large meteors. However, it is also found that their physical properties vary widely, and there is evidence that their range overlaps those of the recoverable meteorites mentioned above.

Directions for Future Research

Partly because of their known relationship to some comets, meteors represent intrinsically interesting objects for future study. One basic objective of continuing meteor research is to establish better our understanding of the relationship between the atmospheric phenomena that characterize the entry of these objects into the earth's atmosphere and the initial sizes, structures, and composition of the bodies themselves. This may best be accomplished with an extensive meteor observation network situated so as to provide a reasonable probability of subsequently collecting meteoroids that have been tracked and that have survived atmospheric entry. This would allow a calibration from which the compositions and sizes of other meteors could be estimated. Then, together with measurements of orbital elements, this information could be used to establish the relationship between meteoroid properties and various source locations in the meteoroid complex. Semiquantitative measurements of elemental abundance ratios by remote observational techniques for those objects whose orbital elements can be established, but which do not survive entry as recoverable meteorites, would also be useful. In addition, improved measurements of the isotopic ratios, to better than 1 percent for ions introduced into the upper atmosphere by known meteor showers, would also constitute a significant advance in our characterization of these materials.

One interesting possible direction for continuing work is stratospheric collection of debris left by the passage of fireballs that fail to survive atmospheric entry. To link these fireballs with comets or asteroids would require that the meteors be photographed by a meteor network. It also appears feasible to collect atmospheric samples of cometary meteor showers. Showers with appropriately low-entry velocities and high mass fluxes are rare but do occur at a rate of roughly four per century. Collection of material from a known comet, such as Halley's would, of course, lead to a large increase in our understanding of both meteors and comets.

SUMMARY RECOMMENDATIONS

Much of what we know about the formation of the solar system is derived from studies of meteoroids that have impacted the earth and that have been analyzed with sophisticated laboratory techniques. We know that meteoroids are intimately connected with asteroids and comets, although the precise connections remain to be drawn by future research and exploration. Because of their number and diversity, analysis of meteoroids facilitates a much larger sampling of primitive bodies than will be achieved through any other approach. Furthermore, the knowledge gained through study of meteoroids is expected to continue to influence strongly the direction of comet and asteroid exploration. *COMPLEX considers that continued and intensive study of meteoroids is an essential and complementary element in the overall program of primitive-body investigations.* Realization of the potential of primitive-body investigations requires a multifaceted experimental approach involving meteoroid collection, laboratory analysis, ground-based observations, orbiting spacecraft, and deep-space missions. A vigorous program of theoretical research is essential to ensure that the conceptual implications of these investigations are fully developed.

Laboratory analysis of material collected from various sources is one of the most important aspects of meteoroid studies. Each collection technique suffers selection effects, and meteoroids collected in different ways contribute complementary information. The various sources include new meteorite falls, meteorites from Antarctica, meteor ablation debris from deep-sea sediments, and interplanetary dust collected from orbit and in the stratosphere. The study of interplanetary dust is an important part of the overall program of earth orbital science.

In many cases, penetrating laboratory investigations require development or refinement of analytical techniques beyond the level of sophistication already achieved for lunar sample and meteorite investigations. The rich scientific return from meteoroid studies is of fundamental importance; continued development of advanced techniques should be encouraged.

A balanced approach to the study of the smaller and more-abundant members of the meteoroid complex should take advantage of opportunities for *in situ* spacecraft measurements. Measurements of elemental and isotopic compositions and correlations of these with orbital parameters is highly desirable. In the attempt to identify and analyze interstellar grains, this approach is essential. Spacecraft measurements are complementary to Earth and moon-based measurements of impact phenomena. Impact phenomena on other terrestrial planets and other satellites record the temporal and spatial variation of the flux of large meteoroids. Disentangling this variation is important to an understanding of the history of the solar system.

8
Scientific Instrumentation for Asteroid and Comet Exploration

Space research over the past two decades has provided a legacy of measurement expertise without which the recommended strategy for primitive-body exploration would be impossible. A substantial arsenal of instruments has been brought to an advanced state of development in programs of earth and planetary exploration and by supporting laboratory studies. However, for exploration of both asteroids and comets, some crucial measurements will have to be extended into new domains. We have examined measurement capabilities required to meet the scientific objectives of primitive-body exploration; and on this basis we have assessed measurement capabilities and have formulated recommendations for instrument development.

Determination of the body's composition is the primary scientific objective for both comet and asteroid exploration. Near perihelion, comets evolve an atmosphere and dust envelope the analysis of which will facilitate determination of the nuclear composition. It is apparent that to meet the requirements to measure the composition of the nucleus of a comet will require use of remote-sensing techniques as well as analysis of the emitted gas and dust.

ANALYSIS OF SURFACES

Two techniques have been developed for remote sensing of surface elemental composition and, with suitable further development, appear to be adaptable to primitive-body exploration. These make use of gamma-ray emission and the x-ray flourescence phenomenon.

X rays excited in the surface material by solar radiation and gamma rays resulting from natural radioactivity and from cosmic-ray and solar-particle interactions with surface matter have spectra that depend on the composition of the surface material. Both x rays and gamma rays can be detected in the vicinity of a comet or asteroid. X rays provide information on the light elements, Mg, Al, and Si, for example, in the top few micrometers of a surface. Gamma-ray spectrometry has been used in lunar orbital application to map the K and U abundances and the variation of several element ratios such as Fe/Si and Mg/Si. Subsequent improvements in the technique raise the hope that it could measure abundances, probably to better than 25 percent accuracy, of many of the elements expected to be present in the surfaces of comets and asteroids including C and H and thus make substantial contributions to chemical analysis of such bodies. On a rendezvous mission with an extended close approach, the two techniques can provide qualitative and semiquantitative analyses for a large number of elements, including most of those of prime scientific importance. Their capability to provide quantitative information at the level of precision desired for all significant constituents has yet to be demonstrated. It is reasonable, however, to expect that continuing developments will improve the sensitivity and accuracy of both techniques.

The application of x-ray and gamma-ray analysis in primitive-body exploration requires a significant effort of instrumental and interpretational improvement. In the comet application, the presence of high concentrations of volatile low-Z elements has important implications for both techniques. It is important to study the moderation and attenuation processes and to determine the impact of these interferences on the sensitivity and accuracy of the measurements. For missions to both comets and asteroids, flight times are long; long-term radiation effects on the detectors should be studied, and the potential degradation due to accumulated induced radioactivity needs to be evaluated. The most advanced gamma-ray detectors operate at cryogenic temperatures. Engineering studies are required to implement this capability on a primitive body spacecraft.

Altogether, remote x-ray and gamma-ray techniques appear capable of providing important measurements of the composition of comet and asteroid surfaces. Because of the primacy of these composition measurements, however, we recommend that a vigorous program of further development be given a high priority.

Important improvements in surface composition analysis might be realized by instruments directly on or in the surface. Elemental composition determinations from landed experiments have been accomplished on the Surveyor lunar missions (1967–1968), on the Soviet Lunakhod (1971), and on the Viking Mars missions (1976–1977). The alpha-particle technique was used on Surveyor missions, and x-ray fluorescence techniques were employed in the other cases. An instrument that combines both approaches has been developed and has the advantage of the alpha-particle technique for light elements (C, N, O, F, Na) and the sensitivity and discrimination of the x-ray technique for elements in the region of Fe and heavier. In addition to providing a more complete analysis than might be possible from orbit, such a lander experiment could provide ground truth for the orbital results. The development of other promising techniques for composition analysis should be pursued so that as primitive-body exploration moves out of the reconnaissance phase, the levels of instrument capability will be commensurate with the measurement requirements.

Generally, the more intensive objectives of asteroid and comet investigations will eventually require measurements that depend on close interaction with surface material. Such measurements can normally be carried out either by *in situ* landed instruments or by analysis of returned samples. Sample return has been discussed earlier. It is important that development of instruments for landed investigations on small bodies be supported and that studies to ascertain the feasibility, costs, and potential scientific advantages of this approach be carried out.

Several important mineral components of asteroid and comet surfaces can be detected through the measurement of reflectance spectra from near-ultraviolet to infrared wavelengths. Some absorption features are highly diagnostic of mineralogy. The ices of H_2O and CO_2, iron-bearing pyroxene, olivine, and plagioclase have particularly distinguishing absorption characteristics. The measurements themselves present no great difficulty, but it cannot be assured in advance that the assemblage of phases in a given surface will give a spectrum that will yield to definitive interpretation. Despite these limitations, reflection spectroscopy should be capable of addressing reconnaissance-level objectives of primitive-body exploration. The technique has been used extensively in asteroid studies from ground-based telescopes and is being developed for flight application on the Galileo mission for measurements of the Jovian satellites. Reflection spectroscopy has the potential capability to establish, through use of a mapping mode, the presence of compositional heterogeneity on the surface. This is particularly important in addressing the question of whether specific asteroids represent fragmented residues of larger bodies that have evolved to produce interiors mineralogically different from surfaces. On a finer scale, such mapping could reveal subsurface differences in mineralogy exposed in deep craters.

Reflectance spectroscopy in the infrared appears to be the only technique currently available for remote sensing of molecular composition. In cometary exploration, the *in situ* analysis of evolved dust and gas in the coma can be expected to provide the important data on molecular composition, but on an asteroid without landed instruments or sample return these remote measurements will assume great importance.

Isotopic studies have provided some of the most detailed insights into processes that occurred in the early solar system. Clearly the exploration of primitive bodies will ultimately require measurements of isotopic abundances with accuracies comparable with those currently achieved in Earth-based laboratories. Such measurements appear to be beyond the scope of reconnaissance-level studies of primitive bodies, although the *in situ* analysis of cometary effluent should provide some contributions toward this crucial longer-term scientific objective.

Measurements of the density of cometary nuclei and asteroids permit important inferences to be made about bulk composition. The requirement to determine density to an accuracy of 5 to 10 percent places stringent requirements on the measurement of size, shape, and mass, which, however, can be met by careful application of existing instrumentation.

COMETARY DUST

The chemical and physical characterization of the nonvolatile component of comets is a goal of first-order importance to cometary science. An important approach to detailed analysis of this material is to acquire a sample of the emitted dust for analysis on board the spacecraft. For this it is important to acquire a sample of sufficient size and one that is representative of the material. Unless an adequate, representative sample can be delivered to the analytical instrument in a manner that largely preserves its character or, as a compromise, alters it in a predictable manner, the most sophisticated analysis is useless. Although considerable experience exists with low-velocity particle collection in Earth's atmosphere, there is little experience in collecting intact particles at velocities of several hundred meters per second.

Collection of cometary dust poses unique problems; the unknown physical nature of the dust, its distribution of velocities, and the possible presence of important volatiles in the dust are but examples of attributes to which the collection technique must be attuned. At the time of this writing, the Committee has not been apprised of any well-developed technique suitable for the collection of cometary dust. We are informed that work is under way in the development of dust-collection techniques, and we urge that this problem receive continuing vigorous attention.

The remainder of this discussion is directed at the analysis of a dust sample once it has been collected. The desired level of instrumental performance is to provide the capability for a complete elemental analysis of all chemical elements present in amounts greater than 1 percent.

At present, there are two analytical techniques that have demonstrated the capability of successful spacecraft operation. The x-ray fluorescence technique has the demonstrated ability to analyze, with the desired sensitivity and accuracy, elements heavier than magnesium. The alpha-particle backscatter technique has demonstrated adequate sensitivity and accuracy for elements at least as light as carbon. As noted earlier, an instrument combining the special capabilities of the two techniques has been laboratory tested.

There are both operational and interpretational problems with this approach to dust analysis on a cometary mission. To replace the low-resolution proportional counters previously used on the Viking spacecraft, high-resolution solid-state detectors are being developed that do not require extensive cooling; the long-term stability and performance of such detectors has yet to be demonstrated. Although analysis through both x-ray fluorescence and alpha-backscattering techniques with thin samples is understood in principle, it has not yet been studied in the laboratory. Problems in interpreting the data may be exacerbated by the fact that cometary dust may be formed under conditions very different from dust that has been studied in a meteoritical or terrestrial planet context.

Altogether if a sample of cometary dust of the order of 0.1 mg in a 1-cm^2 area can be collected with its character left intact, instruments exist that require relatively minimal further development to meet the accuracy and sensitivity required by our recommendations for chemical analysis. If the collected sample is smaller, the required instruments do not currently exist, although it is expected that they can be developed.

Several powerful laboratory techniques are currently in use for planetary material analysis, and their availability for spacecraft application would greatly enhance the scientific return from a primitive-body mission. An electron miniprobe, a miniaturized scanning electron microscope, can perform a fairly complete chemical analysis on individual dust grains. Mass-spectrometric analysis of vaporized dust is also capable of chemical and isotopic analysis. The development of these and other advanced techniques for spaceflight is strongly recommended.

COMETARY ATMOSPHERE

The objective, to obtain a comprehensive inventory of the neutral species present in a cometary atmosphere at relative concentration greater than 0.1 percent to a precision of ±10 percent cannot, in the opinion of the Committee, be met by any currently available single instrument. It is necessary, therefore, to consider that several instruments might collectively provide the needed measurements.

Many of the measurements of neutral composition needed to satisfy the scientific objectives can be provided through mass spectrometry. Its capability to cover the range of molecular weights from 1 to 150 and greater without specificity is a valuable attribute in meeting the objective of providing a comprehensive inventory of the neutral species present in the cometary atmosphere. The intrinsic nonspecificity of the technique is, however, vitiated by other characteristics, which impose important limitations in the cometary application. The sensitivity of electron-impact mass spectrometers is less than is desirable for this application, and gas–surface interactions present difficulties for several species believed to be important in a cometary atmosphere.

The typical sensitivity of mass spectrometers currently being used in spaceflight applications limits the detection level to about 10^4 particles/cc, a level which except very near the comet nucleus would preclude several important measurements. This limitation can be circumvented or at least mitigated by enrichment processes but generally with the sacrifice by nonspecificity. Measurements must therefore be made where the cometary atmospheric number density is equal to or greater than 10^7/cc if a mass spectrometer is to satisfy the objective of measurement of species present at a 0.1 percent level.

Measurement of isotope ratios to the required precision by a mass spectrometer will require integration times carefully matched to the local number density of the species involved. The less-abundant isotope must be present in a concentration of $10^4/cm^3$ or slightly greater to enable meeting the measurement requirement.

The application of mass spectrometry in the presence of large quantities of H_2O requires special attention. The tendency of H_2O to accumulate on instrument surfaces and induce a background that adversely effects subsequent measurements of H_2O must be recognized and accommodated. This general problem applies also, to a lesser extent, to other molecules of relevance, e.g., CO_2, CO, and CH_4, and the techniques used to minimize or eliminate the H_2O background should also minimize the backgrounds induced by other molecules. Techniques have been developed to minimize this induced background and are being applied in instruments for analysis of very wet atmospheres as, for example, submarine cabin environments and respiratory products in pulmonary medicine. Mass spectrometers have also been applied successfully in planetary atmospheres, including that of Venus where the CO_2 content is very high. The efficacy of these techniques in the cometary application must be carefully assessed, and the instrument must include provision for limiting this background.

Reactive atoms and radicals are generally not well measured by mass spectrometers. Such species undergo reactions on instrument surfaces, and the reaction products can obscure the presence of the same product in the ambient atmosphere. Although recent developments show promise in relieving this limitation in certain applications, it is important to enlist other techniques for the measurement of H, O, OH, NH, and SH.

Most of the molecular species of interest are infrared active and can, in principle, be measured by high-resolution spectroscopic methods. Oscillator strengths for the individual rotation–vibration transitions at near- and mid-infrared wavelengths are sufficient to be useful for measurements made in absorption against the sun (or possibly the illuminated nucleus) or in emission with state-of-the-art instrumentation. However, this approach is viable only for those regions of the atmosphere where the molecular density is high enough to allow a significant level of collisional de-excitation.

The more abundant volatiles (H_2O, CO, CO_2) have strong infrared bands and will be detectable at ranges from the nucleus where the tangential line-of-sight column density exceeds 10^{14} cm^{-2}. Column densities two or three orders of magnitude greater than this are estimated to occur in the central region of the atmosphere for even relatively small comets in the active phase. Such measurements, with a spectral resolution of a few tenths of a wave-number would be useful; however, to fully resolve potential ambiguities in spectral regions where bands of different gases, or isotopic transitions of the same gas, overlap a higher spectral resolution near 10^{-2} cm^{-1} is desirable. Quantitative interpretation of spectral measuremens made either in absorption or emission must, of necessity, involve assumptions regarding the relative population of the levels from which the measured transitions occur and that may be far from thermodynamic equilibrium. Simultaneous measurements of several bands of the same species will be advantageous in resolving possible ambiguities.

Ultraviolet spectroscopy has been applied extensively in planetary exploration and has, in fact, mapped the Lyman-alpha envelope of comet Bennett from an earth-orbiting satellite. Its intrinsic sensitivity to emission, absorption, and scattering by reactive atoms and radicals is particularly relevant to cometary atmospheres. Spectral lines or bands excited by resonance fluorescence or resonance scattering of solar-ultraviolet radiation that can be observed in emission and are of interest include He, N, H, N_2, O, C, H_2, CO, OH, NH, and CN. Many of these species present problems for mass spectrometry because of their reactivity, and thus ultraviolet spectroscopic observations provide an important complement.

In the occultation or absorption mode, either the sun or a suitably chosen star can be used as a source of radiation. As in emission spectroscopy, this method of determining the composition of atmospheric constituents is a proven one. Detectable species, which are of interest for comets, include CO and CO_2, provided their densities at the cometary nucleus are 3×10^{11} cm^{-3} or greater, and H_2O, NH_3, and CH_4, provided their densities at the nucleus are at least 10^{10} cm^{-3}. At a distance of 10^5 km the spatial resolution achievable is 10 km, while during rendezvous a resolution of less than 1 km can be achieved by viewing absorption against a star.

Modern array detectors permit the attainment of high spectral and spatial resolution with short integration times by eliminating mechanical stepping of optical elements to perform spectral or spatial scanning. The detection thresholds of modern flight spectrometers range from 0.03 Rayleigh (R) at 130.4 nm to 0.1 R in the region from 160 to 320 nm if the integration time is 20 min. When comet Halley is at 1 A.U. from the sun the predicted emission rates from its coma are 100 R at 130.4 nm (O) and at 165.7 nm (C). These emissions may be as low as 0.1 R at Encke or Tempel 2.

Active resonance fluorescence techniques can measure local abundances of important atoms and radicals, e.g., H, O, C, and OH. This technique complements, in an important way, mass spectrometry, which has particular difficulty with these active species. Moreover, obtaining the local abundances of these species greatly enhances the value of remotely determined column densities of the same species by enabling an interpretation of the latter in terms of their variation as a function of distance from the cometary nucleus.

A careful assessment of the correct approach to ion abundance measurements is necessary. It is desirable to measure ion composition where the partial density is as low as 0.1 cm^{-3} and as high as 10^5 cm^{-3} and to determine also the plasma velocity distribution. Both thermal ion mass spectrometers and instruments developed for solar-wind measurements offer promise in the cometary plasma regime. Ion mass spectrometers capable of measuring characteristics of thermal ion distributions and instruments designed to analyze more energetic ion populations (10 eV to 100 keV) are well developed. Ultraviolet spectroscopy can provide several complementary measurements of ions: He^+, C^+, CO^+, CO_2^+, and N_2^+ are all observable in emission, and line-of-sight column densities of these ions can be determined.

The velocity distributions of both the neutral and ionized components of the cometary atmosphere can be measured with mass spectrometers. The variation of neutral density in a mass spectrometer, as a function of angle between the normal to its inlet orifice and the nucleus, is related to the neutral velocity distribution. The ion and electron velocity distributions are determined by ion mass spectrometers, retarding potential analyzers and various forms of Langmuir probes.

Atmosphere measurements in the fast flyby of a comet pose several problems not encountered in a rendezvous. Remote spectroscopic observations are generally similar but limited by lack of a very close approach to the nucleus by short observation times and by less flexibility in observational geometry. Neutral mass spectrometry can take considerable advantage of the flyby velocity, which effectively increases sensitivity and makes possible the separation of the incident flux from the background because of the large velocity difference. With suitable development, mass spectrometers that operate in the high-velocity flyby mode could be built and could play a significant role in cometary exploration in the coming decade.

Altogether it is anticipated that a combination of *in situ* and remote measurements will be needed to elucidate the composition and behavior of the atmosphere. The value of neutral mass-spectrometry measurements can be enhanced in the cometary application through developments aimed at improving capability to measure reactive species and in reducing the residual and induced backgrounds of molecules such as CO, CO_2, and H_2O. Ion mass spectrometers will be required to measure a wide range of ion densities and velocity distributions. Developments of the capability to determine the velocity distribution associated with constituent abundances over wide ranges will increase the value of ion composition measurements. Both ion and neutral mass spectrometry require major development efforts before application in a high-velocity encounter mode.

Infrared and ultraviolet spectroscopy can make important contributions to the characterization of a cometary atmosphere. Both techniques require development to tailor them to the comet specific application. The most desirable instrument types, particularly in the infrared, tend to be large, and development of smaller, lighter versions of these sophisticated instruments would provide substantial scientific return.

For several of the experiments required to explore the solar-wind interaction, existing instruments or modifications of existing instruments may be used, and the cometary environment poses no significant problem. Generally these instruments, like the magnetometer or plasma-wave detector, rely on antenna sensors for which the cometary gas and dust pose no hazard. The remaining instruments—mass spectrometers and particle analyzers—require admission of particles into internal analysis chambers. For these, although the technical basis for the instrumentation exists and appropriate instruments have been flown on spacecraft, the cometary environment may pose new and significant hazards. These hazards, at the time of this writing, have not been adequately assessed, and dust-protection techniques and strategies that do not compromise the adequacy of the scientific measurements have not been demonstrated.

The ion-drive propulsion system, which is proposed for use on comet spacecraft, is a new concept, untested for use on scientific missions. The large solar arrays, magnets, electric field, and energetic plasma exhaust, while on, will perturb the surroundings in a way that will preclude or interfere with many important measurements. It is essential that strategies to circumvent these problems be devised.

DUST HAZARD

The potential hazard, to spacecraft and instruments, of the cometary dust presents a particular problem because of the rather great range of uncertainty of the dust-flux magnitude and its physical and chemical nature.

To some extent the problem can be overcome by operating the spacecraft in an adaptive mode to avoid hazardous situations. However, this may interfere with measurements that require relatively close approaches to the nucleus during active phases; these include atmospheric measurements as well as collection of dust for analysis. Instruments, such as neutral mass spectrometers, which require controlled admission of a sample for analysis may potentially be seriously impaired, or disabled, by cometary dust. It is important that instruments and spacecraft operation protocols be developed that permit these important measurements to be carried.

SUMMARY

The assessment of instrument technology for primitive-body exploration has exposed both significant strengths and weaknesses in existing capabilities. In many cases, instruments, virtually off the shelf, are suitable; in other cases, substantial further development is needed. In the preceding paragraphs the more noteworthy examples of measurement requirements for which instrumental solutions must yet be found are discussed.

In its *Strategy for Exploration of the Inner Planets: 1977-1987* COMPLEX expressed its serious concern that adequate Supporting Research and Technology funds be made available for "maintaining a vigorous scientific capability in both experimental and theoretical areas of space sciences." This concern must be reiterated in the context of the exploration of primitive bodies. Most measurement techniques that have been developed for planetary atmospheric exploration face special problems in a cometary environment. The success of primitive-body exploration will depend crucially on the extent to which innovative solutions to these and other measurement problems are found. Such circumstances are a normal and even desirable aspect of space science. These technical challenges call out for the extraordinary effort that must distinguish successful advanced endeavors.

9
Means of Investigation and Research

EARTH-BASED AND EARTH-ORBITAL OBSERVATIONS

In the report *Strategy for Exploration of the Inner Planets: 1977–1987* COMPLEX and the Space Science Board set forth recommendations for the use of ground-based and Earth-orbital observational capabilities in planetary investigations. In its charge to COMPLEX for 1980, the Space Science Board has asked the Committee to examine the degree to which optimum use is being made of these capabilities to ensure that planetary investigations are carried out in the most effective way, consistent with other demands on observing facilities. The approaches to earth-based and earth-orbital solar-system investigations are multifarious and will expand rapidly with advent of the Space Shuttle transportation system. These approaches include the use of ground-based telescopes and radar devices, balloon platforms and high-flying aircraft, and earth-orbiting satellites including such large devices as the Space Telescope, Spacelab, and the Long Duration Exposure Facility. The techniques that can be used include remote observations over a wide band of wavelengths as well as more active collection and analytical experiments applied to interplanetary dust.

In the exploration of asteroids and comets, remote observations undertaken from earth and from earth orbit play an especially important role. These bodies are numerous and diverse; it is evident that a large part of the diversity reflects variations in the conditions of formation and in the processes of planetary evolution that are important to our understanding of the solar system. Since the number of bodies that will be visited by spacecraft in the foreseeable future is limited, ways must be found to extend detailed knowledge obtained about a few objects, and knowledge obtained from laboratory analysis of available material, to the larger population. *Thus COMPLEX recommends that a detailed program of remote observations be undertaken of those primitive bodies selected for spacecraft investigation and that support be continued for remote observations of the larger population of primitive bodies.*

There is much potential to expand our knowledge through more detailed observations of asteroid and comet populations. Ground-based techniques that could be usefully applied to asteroids include phase-angle dependent photometry and radiometry, Fourier-transform infrared spectroscopy, and radar. Densities of some selected asteroids may be usefully measured by combining the results of occultation measurements with careful determinations of the asteroids' influence on the orbit of Mars. In the case of comets, it will be particularly important for the study of the physics of the cometary coma and tail to apply the full range of Earth-based remote-sensing techniques during the course of a comet rendezvous mission. Because of the extended dimensions of comets, some kinds of Earth-based observations of comet tails will often be of higher quality than equivalent observations obtained from spacecraft. The comparison of such observations with the *in situ* measurements of the comet's space environment and close-up observations of the nucleus and atmosphere of the comet should prove important for understanding the processes that shape the more distended features of comets.

Ground-based observation programs are also important for the planning stages of missions to comets and asteroids. Astrometric programs are required to determine the orbits of these bodies. A variety of ground-based observations must be employed to select important and accessible targets.

With the advent of Earth-orbital observatories and facilities carried by the Space Shuttle, many additional opportunities for physical studies of comets, asteroids, and interplanetary dust will be available. High-resolution observations of comets will be possible from the Space Telescope, and a variety of orbiting instruments will be able to probe otherwise inaccessible portions of cometary spectra. The Infrared Astronomical Satellite (IRAS) will observe thousands of previously unknown asteroids, and an even greater capability may exist in the Spacelab Infrared Telescope Facility (SIRTF).

In summary, we strongly endorse support of programs for Earth-based and Earth-orbital observations of comets and asteroids and recommend that as new facilities become available each is assessed to ensure that most efficient use is made of its potential for these investigations.

SAMPLE RETURN FROM PRIMITIVE BODIES

In its 1978 report, COMPLEX analyzed the use of extraterrestrial sample return as an approach to accomplishing objectives of planetary exploration.

We concluded that sample return is an important, integral part of a program of exploration, capable of yielding vital information that cannot otherwise be obtained. We have recommended that maximum advantage be taken of the complementary, interactive, and mutually supportive natures of various program components and mission modes, including precursory missions, *in situ* studies, and sample return. COMPLEX recommended criteria that need to be applied in planning for selection, acquisition, and handling of extraterrestrial samples.

COMPLEX has further considered the role of sample return in the investigation of primitive solar-system bodies and concludes that, for these objects also, realization of the scientific objectives will require returned sample modes of investigation. The considerations that lead to this conclusion are included in the later discussion of the objectives. Nonetheless, there are significant differences between primitive bodies and the larger planets that need to be addressed.

Meteorites that are commonly recovered on the surface of Earth, and subjected to detailed laboratory analysis, are thought to be fragments of asteroidal and cometary bodies. Thus, primitive-body investigations already rely on the use of extraterrestrial samples. Indeed, many of the scientific objectives enunciated in this report owe their detailed form to knowledge and conceptions already gained from the study of meteorites. However, meteorites are thought to be a biased sample of extraterrestrial primitive material. It is expected that biases result from the dynamical and fragmentation processes that deliver meteoroids to Earth-intersecting orbits and from differences in physical properties of meteoroids, including their ability to withstand, intact, the stress of atmospheric penetration to Earth's surface. Thus many important types of cometary and asteroidal material may not be represented in laboratory collections. Indeed, even on the basis of crude spectral reflective information, some asteroids seem to be made of material not seen in laboratory collections; recovery of such material might be an important accomplishment. In general, samples returned with sufficient documentation to allow contextual inferences about their origin and history will facilitate interpretation of laboratory analyses with more incisive implications for our understanding of the origin and evolution of primitive objects. *Thus COMPLEX views return of samples from carefully selected primitive bodies as an important part of a program of investigation of these bodies.* Attention should be paid to acquiring samples distinctly different from those known to be in terrestrial laboratories and to techniques that would make possible sample selection with adequate documentation as to their context and relevance to important questions of primitive-body origin and evolution.

There is considerable experience with operation of spacecraft on the surfaces of planet-sized objects, and indeed automated acquisition of surface material has been accomplished by both the United States and the Soviet Union. The Soviet Union has succeeded in the complete automated return, to Earth, of lunar samples. Acquiring and returning samples from small, primitive bodies is in many cases a substantially different undertaking, with which there is no present experience and for which there so far has been little detailed analysis. Indeed, some aspects of the endeavor may be much simpler than for the moon or Mars because of the weak gravity and the inferred regolithic character of the surfaces of some of these objects.

The role of precursory missions prior to sample return may be different for some small bodies than for planets. For example, the widely dispersed characteristics of the orbits of the numerous small bodies may preclude precursory missions to all bodies from which subsequent sample return may be desired. Some flexibility is required. It is premature to rule out completely the future possibility of designing an adaptive mission that could perform essential reconnaissance and exploration tasks as well as limited sample return from some classes of small bodies. But, at the present time, too little is known about these bodies and about sample return technology to select targets for sample return and to ensure acquisition and return of samples. Thus, we believe that the major consideration of sample return from small bodies in the decadal strategy should be in the context of ensuring that the first reconnaissance and exploratory missions are sensitive to the needs of follow-on sample return missions. In addition, *we recommend that studies be carried out to determine the feasibility and costs of automated sample acquisition from asteroids and comets and of their return to Earth in a manner that preserves their integrity.*

THEORY, DATA ANALYSIS, AND SUPPORTING RESEARCH

The goal of planetary exploration, and of space science in general, is to expand our knowledge and understanding of the world around us and of the processes that have brought it to its present state and that continue to drive its evolution. Scientifically oriented, deep-space missions carry us toward that goal. However, if the full intellectual potential of these missions is to be realized, it is essential that they take place in a broad, balanced scientific context. This requires that support be made available to permit full utilization of the returned data and that support be made available for a vigorous program of theoretical research, which is crucial for constructing the conceptual framework of our understanding. To these ends, we have recommended in earlier reports that "missions contain, as part of the original mission cost, sufficient funds for data reduction and analysis beyond the flight mission stage in order to ensure that the scientific return is reasonably exploited" and "that NASA establish a vigorous and ongoing program of data analysis and synthesis, which is designed to foster interdisciplinary and comparative planetological research," including both theoretical and experimental research concerning the past and present states of the solar system.

As planetary exploration moves from early reconnaissance to more intensive stages of investigation the need to maintain a strong general scientific context becomes all the more pressing. It is important that this be accomplished in a stable manner that is insulated from the large fluctuations that have characterized the level of activity in direct support of major planetary missions.

We welcome the implementation of programs, such as the Mars Data Analysis Program, designed to serve some of these functions. However, in order to be effective, these programs must be implemented at the same time that the spacecraft data become available to the scientific community. Furthermore, adequate resources should be expended to ensure not only that the longer-term research objectives of spacecraft Principal Investigators can be carried out but also to foster a substantial involvement of the larger scientific community. If the support is too late or too little, the essential dissemination of the data sets and their characteristics to the larger community will be impeded.

Much of the data gathered from space missions retain continuing value beyond the analyses that are carried out immediately after the mission. As our ideas and theories evolve in new directions, there is need to use these data, sometimes in ways not conceived of earlier. Therefore, we recommend that NASA establish suitable active archives of data gathered through planetary exploration in order to make these data available to qualified researchers. NASA already has moved in this direction by establishing several space imagery centers. We note here that the mechanics of storage and utilization of data from space exploration is a pressing one for many of the disciplines. A separate committee of the SSB (Committee on Data Management and Computation) is charged to address this question in detail.

In addition to maintaining strong programs of theoretical studies and data analysis, it is essential to support a strong program of laboratory research. Some aspects of the contributions and necessity of strong laboratory research programs were touched on in Chapter 7. In addition, there is a major need for laboratory studies in direct support of interpretation of spacecraft measurements made during solar-system exploration. As just two examples, we cite the necessity for laboratory determinations of atomic and molecular reaction to facilitate the interpretation of measurements of comet atmospheres and laboratory studies of reflectance spectra of solid materials to enable more incisive interpretations of remote asteroid observations.

LAUNCH CAPABILITIES FOR PLANETARY EXPLORATION

During the time in which the three parts of this solar-system exploration strategy were written, the United States has been developing a new approach to the launching of spacecraft, which relies on a reusable Shuttle, instead of disposable rockets, for insertion into earth orbit. The capabilities of the Space Shuttle are not directly usable for launching spacecraft for planetary exploration. These spacecraft require the use of additional launch vehicles to carry them from earth orbit to interplanetary trajectories. Thus, for purposes of maintaining a launch capability adequate to carry out an appropriate program of planetary exploration, it is essential that the combined launch system—Shuttle plus upper stage—meet certain minimum levels of performance. Consequently, the Board previously recommended that the combined launch system have adequate performance to *"launch 500-kg payloads with a C3 of 150 km²/sec², payloads of 2000 kg at a C3 of 90 km²/sec², and payloads of more than 7000 kg for low C3."* The Space Science Board based these broad recommendations on estimates of spacecraft configurations needed to realize the planetary-science strategy over the next decades and judged these to be "the *minimum* necessary to carry out the exploration of the solar system as recommended by the Space Science Board (1976) without consideration of those missions that require low thrust and high payload." The Board recognized that the nominal schedule for the first operational flights of the Space Shuttle and the high-energy Interim Upper Stage (IUS), in conjunction with NASA's decision to discontinue the capability of direct-launch, high-energy missions, would impose a hiatus of several years on possible new planetary exploration initiatives. At the same time, the Board recognized that development of a new high-technology propulsion system is a difficult and demanding endeavor and that difficulties in adhering to a preconceived development schedule were foreseeable. Since such additional delays would clearly jeopardize the continuation of a vigorous program of planetary exploration at the very time that a large number of challenging scientific opportunities lay before us, the Board recommended *"that every effort be made to keep development of the Shuttle orbiter and a high-energy IUS on its nominal schedule."*

At the time of this writing, the Shuttle and IUS development have suffered a sequence of major delays, performance deficits, and cost overruns. We are informed that present plans call for a Shuttle with a 60,000-lb payload capability by 1984 and with a full 65,000-lb payload capability after that. The general capabilities of these projected performance levels are indicated in Figure 1. The delays are making a significant impact on the ability of the United States to realize the SSB's recommended strategy for solar-system exploration and on the country's ability to carry out its stated policy of maintaining a vigorous program of space science. As a result of delays in

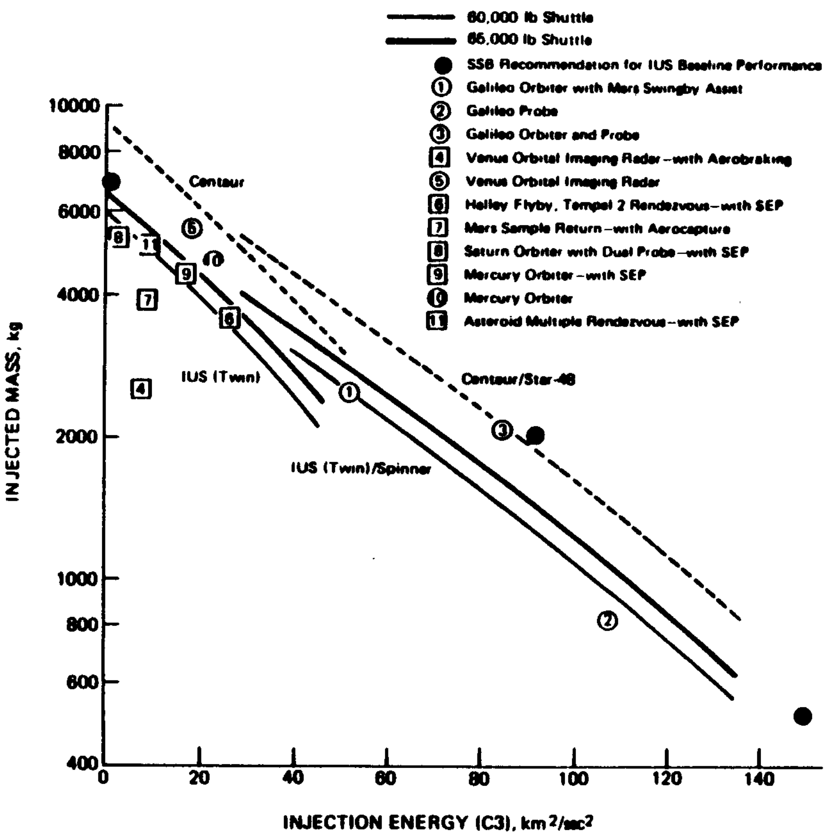

FIGURE 1 The heavy line indicates the capability of the nominal Shuttle-IUS performance, due to be available after 1984; the light line indicates performance planned for 1984. Also shown are performance requirements for several selected mission possibilities with indicated assumptions about technological developments. Numbered circles rely on present technology used with Shuttle-IUS; numbered squares assume new technological development in spacecraft propulsion.

the Shuttle-IUS schedule and reductions in anticipated performance levels, the Galileo orbiter and probe mission to Jupiter has been delayed—originally scheduled for launch in 1982, the mission is at present planned with a launch in 1984—and a split configuration, with separate launches for the orbiter and the probe is currently planned. This reconstruction of the mission has added substantially to its cost. In addition, key elements of the decadal strategy are threatened with postponement, perhaps beyond the near-term launch windows accessible to present technology. *We recommend that steps be taken to minimize the adverse impacts of the Shuttle-IUS development problems on continuing solar-system exploration. These steps should include augmentations to science budgets sufficient to carry out reconstruction of missions needed to offset Shuttle-IUS delays and performance deficits, while still allowing orderly progress toward realization of the decadal science strategy.*

NASA has chosen to pursue development of an additional, low-thrust propulsion system powered by solar electricity and launched in conjunction with the Shuttle-IUS. This Solar Electric Propulsion (SEP) system has the potential to facilitate a major enhancement in our ability to explore the planets, as was discussed in the previous SSB/COMPLEX report (1978). In terms of the present strategy for exploration of primitive bodies, the Committee concluded that, in order to meet the science objectives for asteroids and comets, it will be necessary to use rendezvous-mode investigations in which spacecraft are brought nearly to rest in the frame of these objects for extended periods of time. The Committee is informed that such mission trajectories are available with the use of SEP. *Accordingly, we endorse the decision to undertake development of a Solar Electric Propulsion System.*

In 1978, the Committee recommended that a comparative assessment be carried out of SEP design options in terms of feasibility, cost-effectiveness, and ability to meet the scientific objectives of solar-system exploration over the next two decades. The Committee is also informed of a number of potential additional technological developments that may be useful to produce substantial improvements in our ability to mount planetary missions. These improvements include use of the Centaur rocket as a high performance Shuttle upper stage, aerobraking or aerocapture techniques where planetary orbital encounter is accomplished with the use of atmospheric drag, and space-storable fuels and on-orbit assembly of vehicles. Preliminary assessments of some of these have been carried out, as indicated in Figure 1. In view of continuing uncertainties about Shuttle-IUS performance levels and the importance that these hold for the ability of the United States to carry out the decadal strategy and to continue with a significant program of planetary exploration through the remainder of the century, COMPLEX *recommends that analysis of potential technological developments in the area of spacecraft propulsion be carried out so that these may be assessed in* *terms of their feasibilities, capabilities, and costs and so that the full range of available mission options and techniques may be understood in terms of the overall science objectives of solar-system exploration.* The Committee requests that it be kept informed of the results of these analyses.

INTERNATIONAL COOPERATION

Planetary exploration is a large undertaking, which has captured the imaginations of many of the world's people. It is an undertaking that is significant, in historical proportions, to the expansion of human knowledge. Planetary exploration by spacecraft has to date been carried out only by the United States and by the Soviet Union, each of which has the independent capability to undertake major programs of investigation. Cooperation between the United States and the Soviet Union, because of separate national interests and the other elements of nationalism that understandably pervade such large endeavors, presents special problems. The 1978 SSB/COMPLEX report treated the question of U.S.-U.S.S.R. cooperation in detail. The recent meeting of the "U.S.-U.S.S.R. Working Group on Near-Earth Space, the Moon, and the Planets" in Moscow, to exchange information derived from Venus exploration, is a welcome step toward substantial cooperation.

Participation of other nations in planetary exploration has been limited largely to involvement in the separate national programs of the United States and Soviet Union. However, we are now looking forward to a future in which both the international European Space Agency and Japan will achieve the independent capabilities to launch planetary-class spacecraft and thus will be within reach of substantial and independent programs of space exploration. We are encouraged by these developments and look forward to the important contributions that can be made by the Japanese and European space-science programs.

We believe that it is important to bring a significant level of international coordination and cooperation to bear on the formulation of long-term space-science objectives, especially with those nations capable of achieving independent space-science programs. This will lead to an optimum utilization of complementary capabilities in the exploration of space. COMPLEX has accepted, from the SSB, a charge to explore possibilities for international cooperation in formulating planetary-science objectives and in carrying out planetary exploration.