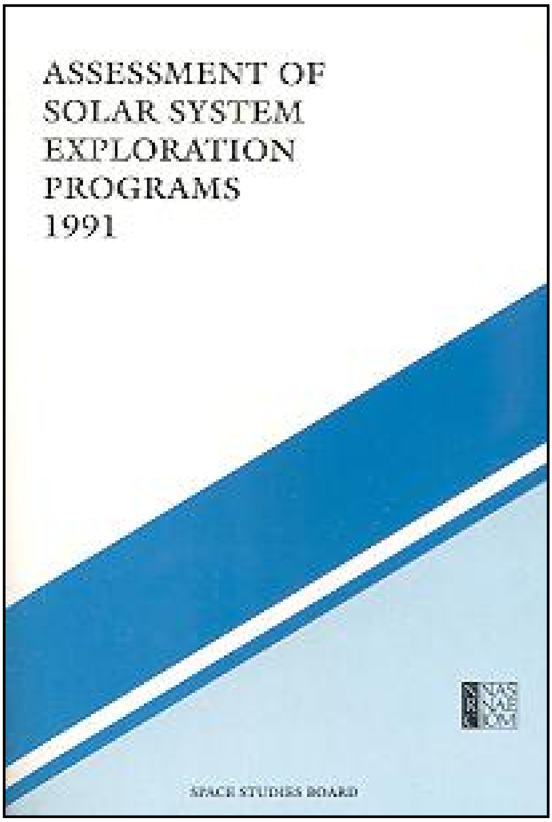
Assessment of Solar System Exploration Programs 1991



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

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

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Foreword

This report is one in a series written by the standing discipline committees of the Space Studies Board. The purpose of this new series is to assess the status of our nation's space science and applications research programs and to review the responses of the National Aeronautics and Space Administration and other relevant federal agencies to the Board's past recommendations.

It is important, periodically, to take stock of where research disciplines stand. As an advisory body to government, the Space Studies Board should regularly examine the advice it has provided in order to determine its relevance and effectiveness. As a representative of the community of individuals actively engaged in space research and its many applications, the Board has an abiding interest in evaluating the nation's accomplishments and setbacks in space.

In some cases, recurring budget problems and unexpected hardware failures have delayed or otherwise hindered the attainment of recommended objectives. In other cases, space scientists and engineers have achieved outstanding discoveries and new understandings of the Earth, the solar system, and the universe. Although the recent past has seen substantial progress in the nation's civil space program, much remains to be done.

These reports cover the areas of earth science and applications, solar system exploration (and the origins of life), solar and space physics, and space biology and medicine. Where appropriate, these reports also include the status of data management recommendations set forth in the reports of the Space Studies Board's former Committee on Data Management and Computation. The Board has chosen not to assess two major space research disciplines—astronomy and astrophysics, and microgravity research—at this time. Astronomy and astrophysics was recently surveyed in a report under the aegis of the Board on Physics and astronomy, *The Decade of Discovery in Astronomy and Astrophysics* (National Academy Press, Washington, D.C., 1991); the Space Studies Board is currently developing a strategy for the new area of microgravity research.

On completion of the four reports, the Board will summarize the contents of each volume and produce an overview. The Space Studies Board expects to repeat this assessment process approximately every three years, not only for the general benefit of our nation's space research program, but also to assist the Board in determining the need for updating or revising its research strategies and recommendations.

Louis J. Lanzerotti
Chairman, Space Studies Board

Assessment of Solar System Exploration Programs 1991

Summary

The advisory base for the Committee on Planetary and Lunar Exploration (COMPLEX) is made up of a series of documents published over the last 15 years. These documents provide a rationale for planetary exploration, a strategy for carrying out scientific study of the solar system, and a series of recommendations to NASA for implementation of this strategy. This report reviews the recommendations of the committee and the status of the field of planetary exploration relative to those recommendations.

NASA's planetary exploration program has made great strides in the past few years. Much of the strategy for exploration of the planets proposed by COMPLEX has been implemented. Other areas await the arrival of planned or approved space missions at their targets. The rate at which the proposed scientific objectives would be achieved was in some cases overestimated by COMPLEX; these objectives still await fulfillment.

Significant scientific objectives have been achieved in exploration of the outer planets and comets. U.S.-European cooperation is proceeding well. Further exploration of Venus is under way and of Mars is imminent. In contrast, little progress has been made in more intensive study of the Moon and Mercury and in preliminary reconnaissance of asteroids and Pluto. Exploration on the surface of Venus, in the inner Jupiter magnetosphere, and in the deep atmospheres of the outer planets requires significant technical developments that should be undertaken. These developments include high-temperature and high-pressure instruments, radiation-hardened spacecraft, and development of low-thrust propulsion. The recommendations in the areas of detection and study of other solar systems and in exobiology research are so recent that it is premature to evaluate the status of current activities.

Areas of concern to the planetary science community include the absence of a plan to carry out the extended mission for Magellan, the lack of reserves in approved flight missions, and the inappropriate use of research and analysis funds as a reserve for mission overruns. The committee views positively the proposed planetary Discovery mission line and NASA's efforts to encourage interdisciplinary research.

Assessment of Solar System Exploration Programs 1991

1
Introduction

The Committee on Planetary and Lunar Exploration (COMPLEX) advises the Space Studies Board (SSB) on the entire range of planetary studies that can be conducted from space, in addition to ground-based activities that support space-based efforts. The disciplinary scope of the committee's advice includes the geosciences, atmospheres, exobiology, particles and fields, and planetary astronomy. As a standing committee of the Board, COMPLEX assists in carrying out studies, monitoring the implementation of science strategies, and providing recommendations to NASA and other government agencies.

In the past, the advice of COMPLEX was directed primarily at NASA's Solar System Exploration Division and the Office of Space Science and Applications (OSSA). Although these entities within NASA continue to be the principal recipients of the committee's advice, the scope has been broadened as a result of the SSB reorganization in 1988-1989.

Specifically, COMPLEX advice now overs the exobiology branch of the Life Sciences Division of OSSA, as a result of having assumed most of the advisory responsibilities previously performed by SSB's recently disestablished Committee on Planetary Biology and Chemical Evolution (CPBCE). A particular responsibility of CPBCE that has not been assumed by COMPLEX is advice regarding planetary protection issues. In the future, matters relating to those issues will be handled *ad hoc* by SSB.

More generally, the advisory purview of COMPLEX and the other standing committees of the Space Studies Board corresponds to all relevant portions of the agency, including those involved in the science activities related to the presidential Space Exploration Initiative. The Board has also sought to expand its contacts outside NASA. The advice of COMPLEX is therefore directed to others working on planetary exploration policy and programs, whether in the executive or legislative branch of the federal government, in private industry, or in the university research community. This advice has also been used in the past by those planning foreign space programs.

The scientific goals that motivate planetary exploration have been outlined most recently in the volume *Planetary and Lunar Exploration* of the 1988 SSB study *Space Science in the Twenty-First Century* (SSB, 1988b). These goals are:

- to understand the origin of the solar system;

- to understand how the Earth, the planets, and the planetary satellites evolved from birth to the present;

- to learn what conditions lead to the origin of life; and

- to learn how physical laws work in large systems.

This report assesses the current status of NASA's planetary exploration program with regard to the science strategies and recommendations published in documents by the committee, in related reports by *ad hoc* SSB committees, and in the advisory documents of the former CPBCE. Exploration of the inner planets, outer planets, and primitive bodies of the solar system is discussed in Chapters 2, 3, and 4, respectively. The detection and study of other solar systems are reviewed in Chapter 5. The relevant science strategy documents include, in chronological order, a "Report of the Committee on Planetary and Lunar Exploration" in *Report on Space Science 1975* (SSB, 1976), *Strategy for Exploration of the Inner Planets: 1977-1987* (SSB, 1978), *Strategy for Exploration of Primitive Solar-System Bodies—Asteroids, Comets, and Meteorites: 1980-1990* (SSB, 1980), *A Strategy for the Exploration of the Outer Planets: 1986-1996* (SSB, 1986b), *1990 Update to Strategy for Exploration of the Inner Planets* (SSB, 1990b), and *Strategy for the Detection and Study of Other Planetary Systems and Extrasolar Planetary Materials: 1990-2000* (SSB, 1990d). These reports form the core of the committee's advice and are the principal reference base for assessing NASA's progress in solar system exploration.

The updated CPBCE science strategy, published in *The Search for Life's Origins: Progress and Future Directions in Planetary Biology and Chemical Evolution* (SSB, 1990c), is briefly reviewed in Chapter 6. Recommendations for the management of space science data, which were established by SSB's Committee on Data Management and Computation in the report *Data Management and Computation, Volume 1: Issues and Recommendations* (SSB, 1982), are discussed in Chapter 7. Aspects of international cooperation are discussed in Chapter 8. Reports relevant to the latter issue that were written by SSB *ad hoc* committees include *United States and Western Europe Cooperation in Planetary Exploration* (SSB, 1986d), and *International Cooperation for Mars Exploration and Sample Return* (SSB, 1990a). General programmatic issues are discussed in Chapter 9, including aspects of a newly proposed program of small missions for planetary exploration, concerns about the impacts of inadequate reserves fro flight programs, and several issues related to research and analysis programs.

The committee has provide ancillary information in the form of letter reports to address the scientific content of the Comet Rendezvous/Asteroid Flyby (CRAF) and Cassini (Saturn Orbiter/Titan Probe) missions, the science impact of descoping the Mars Observer mission, and a scientific evaluation of three proposed Planetary Observer missions—the Mars Aeronomy Orbiter, the Lunar Geoscience Orbiter, and the Near-Earth Asteroid Rendezvous. However, the content of these letter reports is not discussed in this report.

2
Exploration of the Inner Planets

The committee's Strategy far the Exploration of the Inner Planets: 1977-1987 (SSB, 1978) established a comprehensive set of scientific goals and objectives for the exploration of Mercury, Venus, Earth, the Moon, and Mars, together with a number of related policy and program recommendations. In that report, COMPLEX concluded that observation and measurement of the morphologic, physical, and chemical character of Mars, Venus, Mercury, and the Moon on a global scale have high general scientific importance and are basic to all planetological studies. The committee recommended that the triad of terrestrial planets—Venus, Earth, and Mars—should be the major focus in exploration of the inner solar system for the succeeding decade.

SCIENCE OBJECTIVES

Specifically, the committee established the following scientific objectives in the 1978 report for the inner planets:

Mercury

- Determine the chemical composition of the planet's surface on both a global and regional scale.
- Determine the structure and state of the planet's interior.
- Extend the coverage [to the entire planet] and improve the resolution of orbital imaging.

Venus

- Obtain a global map of the topography and morphology of [the planet's] surface at sufficient resolution to allow identification of the gross processes that have shaped it. [Obtain some images] of a limited number of selected regions at a substantially higher resolution.

- Determine the major chemical and mineralogical composition of the surface material.

- Determine the concentrations of photochemically active gases in the 65-135 km altitude region.

- Investigate the physical and chemical interactions of the surface with the atmosphere and study the composition and formation of atmospheric aerosols.

Earth

Resolve the following fundamental questions:

1. Why the Earth alone possesses vast water oceans, and why the Earth's atmosphere has a markedly different mass composition and evolutionary sequence than either Venus or Mars;

2. Why the Earth and Venus, with nearly identical mass and diameter, and why Mars with smaller diameter and bulk density, each had markedly different thermal and tectonic histories;

3. What are the rates and mechanism of transport of materials from the deep interior of the planets to their exteriors, and what are the chemical and physical processes of exchange of matter between the interior and the crusts of the planets and their atmospheres;

4. Why the Earth, Venus, and Mars possess very different internal magnetic fields;

5. Why particular conditions on Earth have led to the evolution of living organisms but apparently not on Venus or Mars;

6. How and why the atmospheric circulation and the long-term climatic variations on Earth differ from those of her nearest neighbors;

7. How man and his culture will influence and modify the biosphere and the physical and chemical composition of the Earth on a global scale.

Moon

- Determine the chemistry of the lunar surface on both a global and regional scale.

- Determine the surface heat flow on both a global and a regional scale.

- Determine the nature of any central metallic core in the Moon.

Mars

- [Study local areas intensively] (a) to establish the chemical, mineralogical, and petrological character of different components of the surface material, representative of the known diversity of the planet; (b) to establish the nature and chronology of the major surface forming processes; (c) to determine the distribution, abundance, and sources and sinks of volatile materials, including an assessment of the biological potential of the Martian environment, now and during past epochs; (d) to establish the interaction of the surface material with the atmosphere and its radiation environment.

- Explore the structure and general circulation of the Martian atmosphere.

- Explore the structure and dynamics of Mars's interior.

- Establish the nature of the Martian magnetic field and the character of the upper atmosphere and its interaction with the solar wind.

- Establish the global chemical and physical characteristics of the Martian surface.

Fields and Particles

- [Determine] the strength and character of the internal magnetic fields (both global fields and, where possible, small-scale remanent fields).

- Both cruise and orbiting phases of planetary missions should be utilized to conduct appropriate interplanetary and solar measurements.

- [Characterize] each planet's interaction with the solar wind.

CURRENT STATUS OF NASA'S EXPLORATION OF THE INNER PLANETS

The committee recently completed a review of the 1978 document, which was published as the *1990 Update to the Strategy for Exploration of the Inner Planets* (SSB, 1990b). Most of the scientific goals and objectives established in the original strategy were found to be still relevant and unfulfilled. Rather than establishing an entirely new science strategy, therefore, the committee left the 1978 strategy intact with the following modifications:

Mercury

The report (SSB, 1978) concluded that insertion of an appropriately instrumented planetological payload into a relatively low-altitude, circular orbit around Mercury required development of a low-thrust propulsion system. Such a mission is now deemed feasible with conventional rocket launches and gravity assists at Venus and Mercury. Therefore, a Mercury mission is a possible near-term activity, and justification of such a mission should rest on the important role of Mercury in understanding the origin and evolution of all the terrestrial planets.

In the 1978 report, exploration of Mercury's magnetosphere was relegated to a secondary objective. One of the major unsolved problems in geophysics is understanding how the Earth's geodynamo works; characterization of Mercury's magnetic field should provide crucial insights and constraints on dynamo theories. Because of the direct connections between Mercury's magnetic field and the size and physical state of its core, determination of the multipole structure of the planet's magnetic field should be a primary science objective along with surface chemistry, internal structure, and imaging.

Venus

Essentially all of the strategy developed for Venus in the 1978 report remains valid. The highest priority objective to provide a global map of the surface of Venus at high spatial resolution is now being accomplished by the Magellan mission. Results from missions by NASA's Pioneer Venus and the Soviet Union's Venera spacecraft series raised some significant questions pertaining to middle and lower atmospheric composition, including time variability and the combined effects of dynamics and chemistry. Therefore, COMPLEX in its 1990 update recommended that "characterization of the basic structure, composition, and dynamics of the Venus atmosphere be a primary objective."

The committee also elevated studies of the Venus interior to primary status, together with studies of the surface and the atmosphere, so that acquisition of seismic data is now a primary objective. The committee therefore restated the recommendation of the 1978 report to emphasize that "acquisition of seismic data from Venus should be maintained as a highly desirable goal," and that "serious study of instruments operating at Venusian surface temperatures should be undertaken and preliminary studies should be conducted to determine the technical feasibility of sample return from Venus."

In addition, the committee noted that a more sensitive search for any intrinsic magnetic field of Venus is of primary significance for determining the nature of the planet's interior.

The Moon

In its 1990 update, the committee again endorsed the recommendations in the 1978 report, and stated: "Measurement of the Moon's global chemical composition remains a high priority, but the committee recommends that global mineralogical measurements at high spatial and spectral resolution also be given a high priority."

Mars

As described in the 1978 report, the detailed analysis of surface materials involved samples to be collected from a region within easy reach of a landed vehicle. The current scientific consensus is that such samples are no longer considered adequate to address this objective. Rather, samples need to be obtained from a variety of locations spread out over perhaps hundreds to thousands of kilometers, and they need to be identified with sufficient information to provide the geologic context for each sample.

Only determination of the whole-planet and major-unit chemical composition at low spatial resolution from orbit is called out specifically in the 1978 statement of measurement requirements. Remote sensing instruments available now or under development, however, permitted the committee to extend this objective to include regional- and intermediate-scale surveys of surface mineralogy and physical properties (e.g., density and grain size)-a particularly important consideration for Mars, with its chemical and physical diversity at various scales.

In 1989 the Soviet Phobos probe provided data on the Martian atmosphere and surface, primarily in the equatorial regions, and on the Martian charged-particle environment and its interaction with the solar wind. Because of the short mission lifetime and the limited geographic extent of observations, however, none of the major goals outlined in the 1978 report was addressed completely.

The U.S. Mars Observer mission is a near-polar orbiting spacecraft scheduled for launch in 1992, with global mapping in late 1993. Its goal is to map the surface and atmosphere for an entire Martian year. If Mars Observer is successful, the original COMPLEX objectives of establishing the nature of the magnetic field and characterizing the global distribution of chemical and physical characteristics. of the surface should be partly accomplished. In addition, contributions will be made to the objectives of exploring atmospheric structure and circulation, establishing the distribution of volatiles, and constraining the planet's interior structure by means of topography and gravity data. Mars Observer will also provide a base of data to guide the selection of sampling sites for a Mars sample return mission and to identify resources to be used in potential future human exploration of the planet.

The principal components of the 1978 report's objectives that will remain largely unaddressed after a successful Mars Observer mission are the prime objective of in situ (or remotely sampled) elemental, mineralogical, and petrological studies of selected areas; seismological and precessional studies of the interior structure of the planet; direct measurements of winds; and the dynamical and chemical properties of the upper atmosphere and its interactions with the solar wind. Also, the question of past life on Mars will remain open. If life developed in the more clement ages on Mars, it may have left chemical and fossil evidence. COMPLEX therefore recommended in its 1990 update report "that the geochemical, isotopic, and paleontological study of Martian surface material for evidence of previous living material be a prime objective of future in situ and sample return missions."

Space Exploration Initiative

The administration and NASA are planning a major program called the Space Exploration Initiative (SEI), which involves human exploration and permanent habitation of the Moon and then Mars. COMPLEX is currently contributing to a Space Studies Board report on the interaction of science programs with the human exploration of space. That study addresses the scientific information required to enable safe and effective human activities on the Moon and Mars, and the opportunities that arise for planetary science as a part of any program that prepares for, and carries out, prolonged human space missions. These opportunities include, of course, those enhanced by the presence of humans. Many of the same objectives for understanding the environment of Mars and the Moon are shared by the scientific strategy for planetary exploration and the concern for astronaut safety. The design and implementation of future spacecraft missions to meet these combined objectives should be a major goal as NASA carries out the Space Exploration Initiative.

In its 1990 update, however, the committee also made a recommendation with regard to program balance. It urged that "exploration of the inner planets in the next two decades should include further exploration of Mercury and Venus because a program of planetary exploration that includes only Mars and the Moon is scientifically inadequate."

3
Exploration of the Outer Planets

The committee's first science strategy for outer planet exploration was published in *Report on Space Science 1975* (SSB, 1976). That strategy was reviewed and revised in *A Strategy for the Exploration of the Outer Planets: 1986-1996* (SSB, 1986b). The principal science goals and objectives and related recommendations follow.

SCIENCE OBJECTIVES

The Saturn System

The highest priority for outer planet exploration in the next decade is intensive study of Saturn—the planet, satellites, rings, and magnetosphere—as a system.

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

- Titan's atmosphere—measure the composition, structure, and circulation of Titan's atmosphere, and characterize the atmosphere-surface interaction.

- Titan's surface—carry out a reconnaissance of the physical properties and geographical variability of Titan's surface: solid or liquid, rough or smooth. Emphasis should be given to any information needed to guide the design of a lander vehicle.

- Saturn's atmosphere—determine the elemental composition, dynamics, and cloud composition and structure, to a level well below the H_2O

cloud base.

- Saturn's rings—measure particle composition and its variety, spatial distribution of particles, and determine the evolution of dynamic structures.

- Saturn's small satellites—make comparative determinations of surface composition, density, geologic history, and geomorphological processes.

- Saturn's magnetosphere—specify the structure, dynamics, and processes, and the material interactions of the magnetosphere with Saturn's atmosphere, rings, icy satellites, Titan, and the solar wind.

The Outer Solar System

The next priority for outer planet exploration is assigned to post-1996 objectives that depend on the results of current missions (analysis of the Voyager data and exploration by the Galileo mission), developments in instrumentation, and demonstrations of technical feasibility. Specifically, these longer term objectives include exploration and intensive study of the following:

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

- Planetology of the Galilean satellites and Titan—surface composition and physical properties, seismic activity, heat flow, and where applicable, atmospheric composition and meteorology.

- Inner Jovian system—density, composition, and energy of magnetospheric particles; large-scale structure, rotation, and time-dependent phenomena in the Io torus, and relation to Io and other satellites, orbiting gas and plasma, auroral activity on Jupiter, and electromagnetic emissions.

Pluto, the only known planet in the solar system as yet unvisited by spacecraft, will continue to be an important target for Earth-orbital and Earth-based studies. As a goal for the long term, a Pluto flyby or orbiter is clearly of great interest.

CURRENT STATUS OF NASA'S EXPLORATION OF THE OUTER PLANETS

The 1986 COMPLEX report contains two major recommendations. The first is: "The highest priority for outer planet exploration in the next decade is intensive study of Saturn—the planet, satellites, rings, and magnetosphere as a system." The proposed joint NASA/ESA Cassini mission, planned to arrive at Saturn in 2002, constitutes a major step toward achieving this goal. This mission would enable intensive study of Titan's atmosphere and surface, and Saturn's rings, small satellites, and magnetosphere. The Cassini orbiter and probe investigations from the U.S. and European scientific communities were recently selected, and instrument development continues.

The report's second major recommendation involved post-1995 objectives for the exploration and intensive study of the Uranus and Neptune systems, the planetology of the Galilean satellites and Titan, and the inner Jovian system, whose implementation depends on the results of the Voyager and Galileo missions. The committee is pleased to note that both missions have proceeded as planned. Voyager 2 completed its reconnaissance of the outer planets upon its encounter with Neptune in August 1989. Analysis of the Neptune data has yet to be completed. Galileo flew by Venus and Earth in 1990, and the spacecraft appears to have adequate fuel reserves for two asteroid encounters and a full-term petal orbit for studying the Jupiter system.

During the five-year period ending in 1990, several events have increased both knowledge of and interest in the Pluto-Charon system: (a) a series of Pluto-Charon mutual eclipses, (b) discovery of Pluto's atmosphere by Earth-based observations of a stellar occulation, and (c) analysis of IRAS serendipitous observations of Pluto. The Hubble Space Telescope also has produced a spectacular image of the Pluto-Charon system. Given our enhanced understanding of the system, the committee recognizes that a well-conceived spacecraft mission to Pluto would be a significant contribution to the scientific goals of planetary exploration.

No progress has been made on one major part of the committee's highest priority for outer planets exploration, namely, exploration and intensive study of Saturn's atmosphere. The committee's 1986 report specified determination of the elemental composition, dynamics, and cloud composition and structure to a level well below the H_2O cloud base. To meet these objectives will require an atmospheric probe that can go deeper than the Galileo probe. The report called for studies of such deep atmospheric probes, and these studies should be pursued as soon as possible.

Study of deep atmospheric probes is just one of a variety of support activities that the committee's 1986 report recommended as being necessary for meeting the near-term and long-term objectives for exploration of the outer solar system. These support activities remain a necessary and integral part of a scientifically balanced exploration strategy. In addition to the studies of deep atmospheric probes, other areas where little progress has been made are as follows:

- *Support of laboratory and theoretical studies.* The committee supports the initiation of the Planetary Instrument Upgrade Program (PIUP) at the earliest possible date.

- *Development of radiation-hardened spacecraft.* This has not been pursued at a level sufficient to make significant progress.

- *Development of low-thrust propulsion systems.* This area of technology development has likewise not received significant support.

4
Exploration of Primitive Solar-System Bodies

In its report *Strategy for the Exploration of Primitive Solar-System Bodies—Asteroids, Comets, and Meteoroids: 1980-1990* (SSB, 1980), COMPLEX established the scientific goals and objectives and related program requirements.

SCIENCE OBJECTIVES

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.

The 1980 report defined three additional goals:

- A goal in the study of primitive bodies is to determine their diversity of composition and structure.

- 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.

- 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.

CURRENT STATUS OF NASA'S EXPLORATION OF PRIMITIVE BODIES

This section addresses the progress made in achieving the scientific goals and objectives of exploring comets; asteroids, meteorites, and interplanetary dust, and notes areas that have significant deficiencies.

Comets

The primary objectives for the exploration of comets, in order of priority, are as follows:

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. Progress in the study of comets has been substantial owing to (1) the retargeting of the International Sun-Earth Explorer (ISEE-3), to study the Giacobini-Zinner and Halley's comets; (2) augmented ground-based and Earth-orbit telescopic observations carried out during the apparition of Halley's comet; (3) European, Soviet, and Japanese spacecraft missions to Halley's comet; and (4) a new start given to the NASA Comet Rendezvous/Asteroid Flyby (CRAF) mission in FY 1990 to rendezvous with a short-period comet.

According to current mission plans for CRAF, the specific measurement requirements are to study the composition and structure of a comet nucleus and to map the nucleus in terms of composition, structure, and temperature. These are expected to be met with data returned from the mission starting at the turn of the century. Similarly, data already received from Giotto and those to be obtained by CRAF will address the measurement requirements of cometary dust and molecular species in the coma. Solar wind interactions were studied in the 1980s by ISEE-3, Giotto, and Vega. The diversity of comets is being studied primarily from ground-based observations. In short, the committee finds that significant progress has been made toward achieving the goals established in the 1980 strategy and will continue to be made if the current plans for CRAF are realized and support of ground-based research is continued. The 1990 deselection of the CRAF penetrator experiment requires continuing attention to alternative means of directly sampling a comet nucleus. The completion of this goal may still require acquiring and returning a sample of a cometary nucleus in some future mission.

Asteroids

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

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.

Progress in achieving the above goals has been minimal in the past decade. There are no plans to measure the abundance of the major elements of an asteroid. The current capabilities of studying asteroid mineralogy-reflectance spectroscopy and radar-are not capable of unambiguously making associations with all meteorite types. NASA currently has plans only for flybys of asteroids. The agency should consider more capable missions to meet the established scientific objectives.

The committee anticipates that the planned flybys of asteroids Gaspra and Ida by the Galileo spacecraft will provide some information on the size, shape, and bulk density of these objects, and imaging by the Galileo cameras should provide information on the nature of endogenic and exogenic processes. Flybys of asteroids are also expected to be made by CRAF and Cassini.

In the past decade, ground-based studies have produced information that expands our understanding of the processes and composition of the asteroids as a whole population. Among the significant ground-based achievements are (1) demonstration of the compositional gradient across the main asteroid belt; (2) discovery of rare, Q-type asteroids, which are probably ordinary chondrite analogues; (3) collisional modeling studies explaining the size-frequency distribution of different taxonomic types; and (4) two-dimensional imaging of asteroids with radar. Continued support for ground-based studies of asteroids will enable additional advances in our understanding of asteroids in preparation for future flight missions.

Meteorites, Interplanetary Dust, and Meteors

Because meteorite studies are intimately related to studies of asteroids and comets, COMPLEX recommended in its 1980 report "that a vigorous program of laboratory and theoretical investigations of meteorites be maintained." Meteorite research is essential to understanding primitive solar system bodies and their origins, and progress over the past decade has been substantial. However, the committee is concerned that continued cuts in the research and analysis (R&A) budget, which is the source of funding for almost all meteorite research, will erode the scientific community's ability to do this valuable research. In this regard, the Origins of Solar Systems Program could be instrumental in deciphering the origins of primitive bodies.

COMPLEX also recommended that, "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." Although several new techniques have been applied to meteorite research during the past several years, the lack of growth in the R&A budget has inhibited instrument development and has prevented significant upgrading of existing instruments.

Considerable progress has been made in the study of interplanetary dust. In 1980, COMPLEX recommended "that the development of techniques to isolate, manipulate, and analyze small samples of extraterrestrial matter be vigorously supported." Advances have been made in the collection of stratospheric dust, in the curation and manipulation of the samples, and in techniques used to analyze them. The Infrared Astronomical Satellite (IRAS) provided information about the distribution of interplanetary dust through its discovery of dust bands in the asteroid belt.

In discussing future research directions, COMPLEX has recommended that interplanetary dust experiments including collection, analysis, and orbit determination have high priority in the overall program of science conducted in Earth orbit. The committee now urges the implementation of such experiments for the space station.

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5
Detection and Study of Other Solar Systems

The committee recently published its first report in this area, *Strategy for the Detection and Study of Other Planetary Systems and Extrasolar Planetary Materials: 1990-2000* (SSB, 1990d). NASA has not yet had an opportunity to implement the scientific goals and objectives and related recommendation established in that strategy. This chapter therefore only summarizes the principal recommendation from the report's *Executive Summary* and discusses several parallel activities at the agency.

- Initiate, and maintain for at least a decade, systematic observational planet searches that encompass the widest feasible domain of the planetary mass versus semimajor axis exploration space. Specifically,

  1. Initiate an astrometric observational survey program designed to track the reflex motion of 100 or more stars in the solar neighborhood ($r \lesssim 10$ parsecs) with a design goal for relative astrometric accuracy of σ = 10 microarcsec, sufficient in a search of adequate duration to detect and track Uranus-mass planets in a solarlike system.

  2. Obtain and interpret a record of Doppler shifts in stellar spectral features due to reflex motion, at or above the current measurement accuracy of $\sigma \cong 10$ m/s^{-1} for the velocity of the orbital reflex, in a survey of the duration and extent specified for the astrometric survey.

  3. Until such systematic searches are mounted, maintain ongoing ground-based searches at their present best accuracies, and investigate and implement improvement of these accuracies if technically and financially feasible.

- Augment current observational studies of young stellar systems, and of the physical properties of circumstellar-interstellar dust systems as precursors to and products of planetary systems, on a variety of spatial and spectral resolution scales. Survey a statistically meaningful number of stars of varied masses and types to detect such systems.

- Continue investigations of links between interstellar-circumstellar dust and isotopically "exotic" grains in solar system materials such as primitive meteorites, interplanetary dust, and comets. Important elements and objectives of this effort include collection and curation of rare interplanetary asteroidal-cometary dust particles (IDPs); laboratory identification and analysis of micron to submicron presolar dust grains preserved in these meteoritic and IDP materials; and laboratory simulation and theoretical studies of the astronomical dust cycle, including the formation and physical and chemical processing of interstellar grains in preplanetary and planet-forming environments.

- Improve the capability of theoretical models and computer experiments to make specific predictions regarding the observational properties of planetary systems at all stages of their evolution, and further develop models to aid in the interpretation of existing data.

- Encourage the following multidisciplinary activities between the responsible divisions at OSSA: participation of planetary scientists in the design and building of future observatories and facility instruments, and in the allocation of observing time at existing observational facilities; joint support for multidisciplinary scientific initiatives; and joint development of instrumentation for extrasolar observation.

- Pursue long-range instrumental and strategic initiatives that are conceptually applicable and potentially valuable to the investigation of extrasolar planetary materials in later stages of reconnaissance or in subsequent phases of exploration and intensive study, but that at present are technologically or theoretically too undeveloped to be of immediate utility in implementing the short-term strategy proposed in this report.

Prospects for the detection of extrasolar planetary systems have also been under investigation by the Planetary Systems Science Working Group (PSSWG), chartered by the Solar System Exploration Division to explore the science strategy for detecting other planetary systems. Similar to the recommendations of COMPLEX listed above, the PSSWG has concluded that NASA should begin a concentrated, long-term effort to detect extrasolar planetary systems. The PSSWG envisions an evolutionary approach, starting with current ground-based astrometric and radial-velocity searches, which are capable of detecting Jupiter-mass planets around stars in the solar neighborhood. The next step would be major ground- or space-based instruments, using astrometry, direct imaging, interferometry, or some combination of these techniques. This effort could potentially allow detection of Uranus-mass planets around the same nearby stars, or (for imaging techniques) of relatively fine details (with a resolution of 1 to 10 AU) in the structure of preplanetary disks in the Taurus or

Ophiuchus molecular clouds. Finally, the ultimate instrument might be a lunar-based interferometer capable of detecting Earth-mass planets or extremely fine details (at scales 0.1 to 1.0 AU) in preplanetary disks. The Astrophysics Division has initiated parallel studies of the capabilities of the Large Deployable Reflector and the Space Infrared Telescope Facility to detect planetary bodies around nearby stars. Other activities in astrophysics include theoretical studies of star formation at a center established for that purpose.

6
Exobiology Programs

SCIENCE OBJECTIVES

As noted in the Introduction, COMPLEX received formal advisory oversight for exobiology issues only in 1989, following the reorganization of the Space Science Board into the Space Studies Board and the dissolution of the Committee on Planetary Biology and Chemical Evolution (CPBCE). As a result, COMPLEX now has the responsibility for monitoring NASA's progress in the implementation of its exobiology program in relation to the existing CPBCE science strategy, and to revise that strategy as it becomes implemented or superseded by advances in scientific understanding.

The recent CPBCE report *The Search for Life's Origins: Progress and Future Directions in Planetary Biology and Chemical Evolution* (SSB, 1990c), lists the following scientific goals and objectives for exobiology research:

The Cosmic History of the Biogenic Elements and Compounds

- Understand the history of physical and chemical transformations undergone by the biogenic elements and compounds from nucleosynthesis to their incorporation and subsequent modification in preplanetary bodies.

Early Planetary Environments: Implications for Chemical Evolution and the Origin of Life

- Understand the processes responsible for the chemical evolution of organic matter in the outer solar system.

- Understand how the conditions for chemical evolution and the origin of life were influenced by the physical and chemical development of the terrestrial planets.

Origin of Life

- Understand the origin and evolution of metabolism in primitive life forms.

- Understand the origin and evolution of replication.

- Understand the origin and evolution of gene expression.

- Determine evolutionary events leading to the accretion of complex genomes.

The Evolution of Cellular and Multicellular Life

- Develop a universal understanding of the temporal sequence and evolutionary relationships of life on Earth.

- Determine the properties of the universal ancestor of extant organisms.

- Understand what factors drive the biosphere.

- Generalize our understanding of environmental and early cellular evolution on Earth by comparative studies of Mars.

Search for Life Outside the Solar System

- Understand the nature and distribution of life in the universe.

CURRENT STATUS OF NASA'S EXOBIOLOGY PROGRAMS

Although NASA has not yet had an opportunity to implement the new recommendations of the 1990 CPBCE report, many of the recommendations are carried over from an earlier report by that committee, *Origin and Evolution of Life—Implications for the Planets: A Scientific Strategy for the 1980's* (SSB, 1981). COMPLEX has received the agency's existing program and plans, and can provide the following brief assessment of its status on the basis of earlier recommendations.

The 1990 CPBCE report listed major research recommendations, which were divided into two categories: flight opportunities and ground-based research. Studies of materials associated with hydrological activity on Mars were identified as the highest priority in the flight category. Currently planned robotic missions and proposed human exploration missions for investigation of Mars, if properly executed, promise to make significant contributions to the goals listed in the CPBCE report.

Also discussed in the 1990 report were flight opportunities to comets and asteroids, and missions to Titan and the giant outer planets. The CRAF and Cassini missions are respectively expected to rendezvous with a comet and send a probe to Titan with an orbiter around Saturn. These missions and the Galileo mission to Jupiter will address many existing exobiology goals dealing with chemical evolution. Besides flybys on the Galileo, CRAF, and Cassini missions, there are no firm plans to investigate asteroids as discussed in the previous chapter.

Recommendations for flight opportunities include use of Earth-orbital facilities for astronomical observations related to exobiology (e.g., extrasolar planetary detection), and Earth-orbital collection of interplanetary dust particles. Studies of these opportunities are now underway. In the main, however, exobiological considerations are largely incidental to currently planned missions. Intensive study of the Martian surface should include exobiological investigations as an important part of the scientific goals. COMPLEX notes that any excursion to the surface of Mars and the return of samples to Earth pose significant planetary quarantine issues.

The 1990 report also recommends a program of ground-based research to support these flight opportunities. Important among these are studies of the origin and evolution of life. Currently, these programs are supported in the NASA (Code SB) Exobiology Research and Analysis program, Some progress has been made in these areas in recent years, partly as a result of NASA support. The NASA Exobiology Branch has played a leading role in organizing the loosely-knit community of biologists and chemists with interests in exobiology, through sponsorship of conferences and workshops. Unfortunately, many of the recommendations of the 1981 and 1990 CPBCE reports, although embraced by the NASA Exobiology Branch, await implementation because of severe funding limitations.

7
Data Management and Computation Issues in Planetary Science

A former committee of the Space Science Board, the Committee on Data Management and Computation (CODMAC), published a series of reports between 1982 and 1988 (SSB, 1982, 1986c, 1988a). Their recommendations were designed to facilitate scientific progress using data returned from NASA missions. The committee also made recommendations about the types of and access to computational resources needed to carry out NASA missions.

COMPLEX restates here the following subset of CODMAC recommendations to ensure that past efforts partly initiated by CODMAC be continued:

1. Active involvement of scientists must exist in all phases of data management planning.

2. Data must be made available to the scientists—
   a. in a usable format,
   b. in a format in which multiple data sets can be compared, and
   c. in a timely manner.

3. Scientific data should be annotated and stored in a permanent and retrievable form.

4. Adequate financial resources to analyze mission data should be set aside and protected from loss due to cost overruns in NASA's flight programs.

A significant product of the first three of these recommendations is the Planetary Data System (PDS), which archives and distributes digital data from past and ongoing planetary missions. The purpose of the PDS is to facilitate access to multiple data sets by planetary scientists, who have had an active role in the design of the data system to ensure its utility. COMPLEX will continue to monitor the progress of the PDS to measure its contribution to meeting the scientific objectives of solar system exploration.

During the lifetime of CODMAC, a revolution in computer networking occurred. The ability to communicate with colleagues via electronic mail and to transport data among computers has speeded scientific progress. At this time the networks are a great facilitator of science.

The Data analysis programs supported by the Solar System Exploration Division are designed to provide adequate resources to analyze data from spacecraft missions. As part of the Research and Analysis program, the Data Analysis programs continue to be subject to cuts due to programmatic taxes and cost overruns in flight programs.

Another issue that CODMAC addressed was access to supercomputers. We note that the National Science Foundation has provided access to supercomputers that has enabled computational studies in planetary sciences, but that there is a need for scientists to have local workstations to carry out those aspects of their work not requiring supercomputers, such as data storage and display.

8
International Cooperation in Planetary Exploration Programs

COMPLEX strongly endorses the principle of international cooperation on specific planetary missions as a means of enhancing the scientific output and of reducing the cost to each party. Presidential endorsement of this view came in February 1988 with the "Directive on National Space Policy," which stated that "the United States will seek mutually beneficial international participation in its space and space-related programs." In its *1990 Update to the Strategy for Exploration of the Inner Planets* (SSB, 1990b), the committee made the following recommendations on international cooperation:

- Selection of foreign scientists and experiments for U.S. missions should be based strongly on scientific merit, and the free flow of scientific data and results should be a necessary precondition for any cooperative arrangements.

- NASA should consider all appropriate foreign capabilities available for planning and carrying out its missions and should cultivate those that enhance the scientific return.

- NASA should fully involve the scientific community in planning for international cooperation and in assessment of proposed cooperative missions.

Two other Space Studies Board publications have dealt with collaborations with Western Europe and the USSR, respectively, and some steps have been taken to implement their recommendations. These are discussed below.

U.S.-EUROPEAN COOPERATION IN PLANETARY EXPLORATION

In 1986 the National Academy Press published *United States and Western Europe Cooperation in Planetary Exploration* (SSB, 1986d), a report written by the Joint Working Group (JWG) on Cooperation in Planetary Exploration. The group was composed of scientists associated with the SSB and with the Space Science Committee of the European Science Foundation. The JWG concluded that planetary investigations continue to be among the most intellectually challenging and important areas of basic scientific research. They made specific recommendations for missions to be undertaken as cooperative projects and their current status is summarized below.

Titan Probe and Saturn Orbiter

This project is now an approved joint NASA/European Space Agency (ESA) mission known as Cassini. NASA is to provide a Mariner Mark II spacecraft as the orbiter, while ESA will provide the probe. A joint Announcement of Opportunity attracted over 200 proposals, and a set of investigations were selected in the fall of 1990. The mission is planned for a 1995 launch.

Mars Surface Rover

This mission may be superseded by tentative plans to proceed directly to a sample return mission, as part of which a rover would be used to survey the surface and gather samples for return to Earth. Meanwhile, ESA has begun an assessment study under the title "Isabella," which seeks to identify detailed European contributions to a U.S. Mars rover/sample return and any corresponding Soviet Mars missions. Areas being targeted by the Europeans include orbiter instrumentation, Mars surface instruments, and an intelligent robot arm for the rover.

Multiple Asteroid Orbiter

The proposed joint mission is not under study by either prospective partner. Instead, interest has been focused on a Comet Nucleus-Sample Return mission known as "Rosetta." This is now a core element of ESA's Space Science Plan, "Horizon 2000," as a joint mission with NASA. Advance studies of technology and experiments for this mission are being carried out at a low level, but no launch date has yet been set.

INTERNATIONAL COOPERATION FOR MARS EXPLORATION

The SSB ad hoc Committee on Cooperative Mars Exploration and Sample Return recently published *International Cooperation for Mars Exploration and Sample Return* (SSB, 1990a). Its recommendations included the robotic study of the Martian surface and sample return from several sites, to be undertaken in an international program coordinated with the Soviet Union and involving close cooperation with "traditional" partners in Western Europe.

Early progress on a small scale has included the provision on Mars Observer of an antenna for tracking balloons to be delivered by the Soviet Mars-94 mission, and participation by U.S. and European scientists in Phobos and Mars-94. COMPLEX endorses further examination of Soviet involvement in the Space Exploration Initiative.

Additional cooperation with other nations, especially Japan, also deserves serious consideration. As a beginning, coordination between the proposed NASA Lunar Observer and the Japanese Lunar Orbiter missions is under discussion.

CONCLUDING REMARKS

While strongly advocating international collaboration on large projects, COMPLEX believes that such cooperation should not be entered into lightly. Termination of collaborations before completion not only forfeits all the related benefits, but can also have a chilling effect on future cooperation. The withdrawal by the U.S. from the joint NASA/ESA International Solar Polar Mission and the recent cancellation of the Omega-VIMS instrument for the Soviet Mars-94 mission are examples where substantial damage has been done. It is important, therefore, that future efforts at collaboration be based on stronger commitments.

9
General Programmatic Issues

In this section we address several general issues that have a substantial impact on NASA's planetary science programs.

PLANETARY FLIGHT PROGRAMS

Small Missions Program for Planetary Exploration

NASA's Solar System Exploration Division is developing a new initiative, named the Discovery Program, for carrying out small, low-cost spacecraft missions. Potential aspects of this program would cover a triad of "small missions," "mission partnerships," and "mission participations." The small missions portion of the program would consist of simple, small spacecraft costing under $100 million. Mission partnerships could include joint missions or collaboration on building instruments, whether between government agencies in the U.S. or with other countries. Mission participations might involve the provision of instruments, of spacecraft subassemblies, and of self-contained mission components such as surface probes.

This program has similarities to the Explorer Program in the Astrophysics and Solar and Space Physics divisions, and to the new Earth Probes line in the Earth Science and Applications Division. We note here some of the reasons for the past successes of the Explorer Programs as stated in three Space Science Board reports: *Strategy for Earth Explorers in Global Earth Sciences* (SSB, 1988c), *The Explorer Program for Astronomy and Astrophysics* (SSB, 1986a), and *A Strategy for the Explorer Program for Solar and Space Physics* (SSB, 1984). These reports found that such small mission programs promote frequent access to space; support specific, well-defined scientific objectives; enhance programmatic flexibility because of their small size and shorter lead-time requirements than larger missions; provide data not obtainable from the ground, yet not acquired in larger missions; provide opportunities for international cooperation; and augment training for science and engineering students at universities.

A Discovery Program could bring many of these advantages to the planetary exploration program. The mission and program structure should be such that no single element absorbs the program resources for more than two years. The selection process ought to be structured so that a large investment in engineering design is not required. The data from the missions should be delivered to scientific archives in a timely manner, and adequate funding for data analysis and related theoretical modeling must be available.

While the desire to provide additional diversity and breadth to the planetary program is worthy in itself, particularly with regard to program balance, the Discovery Program needs to carefully choose objectives and goals that are worthwhile, largely unattainable by other means, and within its resources. A major requirement of proper implementation is an adequate and steady source of funding directed at carefully chosen scientific objectives. Discovery missions to near-Earth asteroids and to Pluto have been considered. The committee supports further investigation of these and other missions for the Discovery Program.

Reserves for Flight Missions

The provision of adequate reserves for flight missions is vital to the delivery of instruments and spacecraft systems on schedule and within cost. The lack of adequate reserves on a year-by-year basis can lead to more—not less—cost growth, as there is a tendency to push problems into later years when remedies may be more costly and more drastic. The scientific integrity of a mission may be threatened by cost-saving measures, or funding may be transferred from other activities such as R&A programs, producing unanticipated and detrimental effects on program science. In extreme cases, instruments may be sacrificed, not because they have low priority, but simply because their funding for a single year matches a mission deficit for that year.

To avoid these problems, missions need to be planned carefully and carry adequate reserves for each year. When year-by-year caps are imposed, whether by NASA or by Congress, the mission budgets must reflect accurately the schedule of work to be done at the instrument and spacecraft assembly level, and must include adequate reserves.

RESEARCH AND ANALYSIS PROGRAMS

The scientific achievements of planetary exploration are not limited to the time of the nominal mission. Significant advances in understanding occur during extended mission phases, post-mission data and analysis programs, thematic study programs, and basic R&A. Such programs are essential for fully realizing the scientific potential of each mission and for establishing critical objectives for future exploration.

Results from the Mariner 10, Viking, and Voyager missions have all underscored the importance of extended mission phases. Follow-on encounters of Mercury by Mariner 10 acquired multiple data sets of the near-Mercury environment. The extended Viking mission allowed high-resolution imaging of the surface that profoundly affected our understanding of surface processes. Without the extended Voyager mission, Uranus and Neptune would remain unexplored. Magellan's nominal mission will not provide gravity data for Venus, fill in gaps left by solar conjunction, or allow for a search of short-term changes on the planet's surface. Therefore, *the committee strongly recommends approval for the extended mission for Magellan*.

Post-mission data analysis programs not only capitalize on unique and ephemeral expertise gathered during the mission, but also maximize the overall scientific return by involving new perspectives, techniques, and approaches from the science community at large. In general, COMPLEX expresses its support for the development within the Solar System Exploration Division of an ongoing sequence of data analysis programs, each of approximately three years' duration and focused on the analysis of data from specific missions. These programs serve to broaden the involvement of the planetary science community at an early date and also provide opportunities for new researchers to enter into the NASA R&A program. Interdisciplinary thematic studies also have proven effective for broadening our understanding of the planets. Just as post-mission data analysis programs capitalize on expertise and excitement associated with a mission, finite (e.g., three-year) thematic programs build on timely scientific issues related to planetary research. In view of the importance of this facet of NASA's R&A program, COMPLEX expresses concern for the delays in implementation of such programs in recent years.

In the *1990 Update to the Strategy for Exploration of the Inner Planets*, COMPLEX recommended "that NASA should support a vigorous program of data analysis, basic research, and scientific instrument development." Basic R&A provides essential continuity and backbone for achieving NASA's goals. As emphasized in the 1990 report, significant advances have come not only from new mission data, but also from new ideas and unexpected discoveries made possible by a vigorous program of basic R&A. Examples include the discovery of meteorites from the Moon and Mars in Antarctica; geochemical cosmic signatures on Earth at times of dramatic biologic and climatic change; advanced computational models allowing tests and constraints for the origin of the Moon by a catastrophic collision on the Earth; the first imaging of an asteroid by Earth-based radar; and new insights for Pluto that have dramatically challenged our view of the last planet in our solar system yet to be explored by a spacecraft.

The Committee on Planetary and Lunar Exploration acknowledges the sincere efforts by NASA to preserve a balanced research program, but it is deeply concerned by NASA's view of the R&A program as a financial reserve for fixing fiscal crises in its flight programs. This practice is harmful to the continuity and long-term stability of the R&A activities. Moreover, it significantly reduces the number of young scientists in a field with a median age approaching 50. *Research and analysis programs should not be viewed as another source for mission reserve funds and need to be insulated from mission cost overruns.*

GROUND-BASED AND EARTH-ORBITAL ASTRONOMY

The committee notes that currently there are several projects in various stages of planning that have a favorable impact on the goals outlined in this report. They are as follows:

SIRTF (Space Infrared Telescope Facility)—a cryogenically cooled infrared telescope planned for a high Earth orbit. It will be capable of studying planetary atmospheres, primitive bodies, interplanetary dust, and potential extrasolar planetary systems. The inclusion of planetary scientists on the planning team has helped assure that the telescope will be capable of observing planetary objects. COMPLEX strongly recommends the completion of this project.

SOFIA (Stratospheric Observatory for Infrared Astronomy)—an aircraft-based telescope facility proposed to replace the Kuiper Airborne Observatory (KAO). A significant portion of the KAO time has gone to planetary projects, and the committee urges NASA to provide similar opportunities with the SOFIA.

OPT (Orbiting Planetary Telescope)—a 1-meter orbiting telescope proposed as a joint ESA-NASA project. It will be dedicated to planetary projects at multiple wavelengths. Excellent planetary research has been done with the International Ultraviolet Explorer in the past and the OPT would continue this trend.

Second Keck 10-Meter Telescope—primarily for the detection of extrasolar planetary systems and proposed as a joint NASA-Keck observatory facility. It will be operated in an interferometric mode with the first Keck 10-meter telescope. This would be a potent instrument for search for extrasolar planets.

COMPLEX recommends the development of these and other interdisciplinary projects. The inclusion of planetary scientists in the planning of telescope facilities helps in the establishment of critical planetary observational capabilities. NASA should be commended for including planetary scientists with relevant expertise on astronomy projects in the past, and the committee strongly supports the continuation of this practice.

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