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Future NASA Solar System Exploration Activities: A Framework for International Cooperation

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The Solar System Exploration Program today is in a critical transition between a glorious past and an uncertain, but potentially exciting, future. Planetary exploration has moved from the breathtaking pace of the 1960s and 1970s, when successful, groundbreaking missions were launched one after the other, and it is entering an era of fewer, but far more sophisticated, missions. The late 1980s and early 1990s are crucial times for solar system exploration, and the years between now and the end of the 20th century are filled with both challenges and opportunities.

Both the Challenger accident on January 28, 1986, and the subsequent cancellation of the Shuttle-Centaur upper stage drastically affected the planetary program. All the missions under development—Magellan, Galileo, Ulysses, and Mars Observer—have been delayed. These delays have forced the program to divert money and resources originally intended to support research and new program development into the continued planning and engineering of grounded missions. The unexpected absence of an energetic Shuttle-Centaur makes it necessary to carry out complex gravity-assist trajectories—which, in turn, produce much longer trip times—to reach the outer planets.

At the same time, other nations have begun major efforts in planetary exploration. The increasing presence of non-U.S. spacecraft beyond Earth orbit was especially noticeable in 1986, when a 5-spacecraft "Halley Armada" was launched to study the famous comet. The Armada consisted of the European Space Agency's highly successful Giotto Spacecraft, Japan's Planet-A and Sakigake, and the U.S.S.R.'s two VEGA Spacecraft. Although NASA provided critical ground support to the Armada with its Deep Space Network, no U.S. spacecraft was sent to join it. In addition, the Commonwealth of Independent States (C.I.S.), formerly the U.S.S.R., is now actively planning a decade of ambitious efforts to explore Mars. This effort has already begun with the launch of the Phobos Mission in July 1988, to study the moon of Mars of the same name, and it may lead to an unmanned sample return around the year 2000.

Clearly, things are different from the "Golden Age of Planetary Exploration" that took place during the last 25 years. For several reasons, future solar system exploration requires a new approach. First, we must recover from all the changes, good and bad, that have occurred since 1980. We must build our greatly increased understanding of the solar system into a series of more capable and more sophisticated exploration missions. We must develop the new potential for international cooperation that has become available. And we must begin to view planetary missions as something new—not just a way of obtaining valuable exploration for the sake of science, but also as the means to obtain essential data that we need to pursue a new national goal—expanding human presence beyond Earth orbit and into the solar system itself.

Plans and Outcomes: The Solar System Exploration Committee and What Happened

In 1980, upon recognizing that planetary exploration had changed radically, NASA formed the Solar System Exploration Committee (SSEC) of the NASA Advisory Council to begin a fundamental review of the entire planetary program. The charter of the SSEC was to formulate a long-term program for planetary exploration, within a constrained budget, that would ensure a vital, exciting, and scientifically valuable effort through the turn of the century. The most urgent priority was to provide stability to the program while ensuring its continued progress. The SSEC, therefore, first formulated a Core Program of planetary exploration that was stable, produced exciting and important scientific results, made the maximum use of existing facilities and technologies, and could be carried out within a reasonable level of continued funding.

The Core Program was developed around a number of elements. An initial sequence of Core Program Missions included the Venus Radar Mapper (now renamed Magellan), a Mars Geoscience/Climatology Orbiter (now Mars Observer), a Comet Rendezvous/Asteroid Flyby, and a Titan Probe/Radar Mapper. Within the Core Program, a Planetary Observer series was to be established, consisting of low-cost, modestly scaled missions within the inner solar system. For missions beyond the inner solar system, the Mariner Mark II series was to be developed—a straightforward, modular spacecraft that could easily be adapted to a variety of missions to the outer solar system and to primitive bodies—comets and asteroids. A common mission operations and information system was to be developed for all missions after Magellan. Finally, the Planetary Research and Analysis program was to be significantly strengthened, to expand our ability to analyze currently available data, to perform necessary ground-based research, and to develop instrumentation for the missions of the Core Program (table 16-1).

Initial progress toward establishing the Core Program was encouraging. Congressional approval of the Magellan Mission as a "new start" in 1983 was followed closely by approval for the Mars Observer (the first Planetary Observer) in 1984, but subsequent progress has been slow. Congress has endorsed the Planetary Observer concept, but the Mariner Mark II series still awaits adoption. The Comet Rendezvous/Asteroid Flyby (CRAF) Mission, the first of the Mariner Mark II missions, was submitted for, but did not receive, new start approval in fiscal years 1988 and 1989. However, the inclusion of this mission—together with the proposed Cassini Mission to Saturn—in the FY 1992 budget is a hopeful and encouraging sign for the future. However, to ensure that a robust Solar System Exploration Program still exists at the turn of the century, these missions must be approved soon. Finally, NASA has implemented the multi-mission operations concept, but the research and analysis activities still remain funded at an undesirably small fraction of the total program budget.

Since the SSEC made its recommendations, other events and new realities have drastically altered the environment in which solar system exploration must make its plans. Some of the events have produced major changes, both positive and negative, in our technical ability to explore the planets during the next few years. Other, less tangible, events have changed the political and social climate in which the national space program, and its planetary exploration component, will operate in the future.

In 1984, President Reagan endorsed a national commitment to human presence in the solar system through the initiation of the Space Station Program. Since then, Space Station Freedom has become an important factor in planning for future planetary exploration, and one that was not anticipated by the SSEC. Despite the fact that the Space Station will be physically located in Earth orbit, it can provide important capabilities for several important and exciting planetary exploration projects, two of which are being studied. The Cosmic Dust Collection Facility would trap particles of cosmic dust, measure their velocities, and determine their trajectories; the particles would then be returned to Earth for detailed laboratory analysis. The Astrometric Telescope Facility would begin a decades-long program of precise measurements of the motions of nearby stars to detect the possible presence of large planets around them.

Table 16-1: Planetary Missions Through Year 2000

Approved Missions

Missions	Target(s)	Launch	Mission Highlights
Magellan	Venus	April 1989	Radar mapping from near-polar, highly elliptical orbit for one Venusian year. Ninety percent of the surface mapped.
Voyager 2	Neptune	August 1989	Voyager 2 encountered Neptune and is now off to study the interstellar medium.
Galileo	Jupiter	October 1989	Asteroid flyby en route; using a corkscrew trajectory that will use gravity assists from Venus and Earth, Galileo will reach Jupiter in late 1995. An instrumented probe will enter the Jovian atmosphere; the orbiter will operate for 20 months, successively approaching most of Jupiter's large satellites.
Ulysses	Sun	October 1990	Ulysses will study the Sun out of the ecliptic plane.
Mars Observer	Mars	September 1992	Mapping of the Martian surface for one Martian year. Data collected on climatology, surface composition, topography, gravity field, and magnetic field.

Proposed Missions

Missions	Target(s)	Launch	Mission Highlights
Lunar Observer	Moon	mid-1990s	Extended orbital study of the lunar surface and gravitational and magnetic fields.
Comet Rendezvous Asteroid Flyby (CRAF)	Asteroid Hamburga Comet Kopff	August 1995	Asteroid flyby followed by comet rendezvous in 2000. Spacecraft will fly in formation with Kopff for 3 years as comet approaches and passes through perihelion. CRAF will deliver a penetrator to study the interior of a comet's nucleus.
Cassini	Saturn	April 1996	Fly past the asteroid Maja in 1997, gain gravity-assist from Jupiter, and arrive at Saturn in 2002 for 4 years of study of the Saturnian System. Probe will be ejected into Titan's atmosphere.
Mars Rover/ Sample Return	Mars	late 1990s	Advanced mission to land on Mars, traverse its surface, and return 5 kilograms of samples for study on Earth.

Future modifications of the Space Station might support more ambitious planetary exploration projects. Preliminary studies are being made to define Space Station-attached orbital telescopes for full-time planetary observations in both visible and infrared wavelengths. More complex Space Station developments could include the assembly, checkout, and launch of large planetary missions or the preliminary quarantine and analysis of returned extraterrestrial samples in a special laboratory module. These ideas will be developed in detail as plans for large planetary missions, and for the Space Station, evolve together in the future.

The loss of Challenger in 1986 had far-reaching effects on the Solar System Exploration Program. The restoration of the Space Shuttle to flight status was critical for near-term planetary exploration, and the successful launch of Discovery on September 29, 1988, was an important achievement for planetary exploration as it was for all of NASA.

By heroic efforts, the four missions under development at the time of the Challenger accident—Galileo, Ulysses, Magellan, and Mars Observer—have been preserved, but all of them have been delayed, and the increased costs and necessary mission redesigns have severely strained the planetary program. The Space Shuttle launches of Magellan in April 1989, and of Galileo in October 1989, were critical milestones along the path to a viable and stable planetary program for the future.

Launch plans for later missions are more flexible as a result of NASA's decision to proceed with a "mixed-fleet" policy, in which space missions would be launched either by the Space Shuttle or by expendable launch vehicles. When this plan is in effect, it will provide a substantially more robust launch capability for planetary missions.

The Solar System Exploration Program is following the establishment of this policy with extreme interest. As an initial step, the Mars Observer was designed to be compatible with either the Space Shuttle or an existing Titan-3 expendable; in late 1988, NASA decided to launch Mars Observer in 1992 on the Titan-3, rather than on the Shuttle, as was originally planned. A more powerful launch vehicle, the Titan-4, is expected to be available possibly for CRAF or other planetary missions in the 1990s.

Another factor in planning the future of solar system exploration is that attention is increasingly turning toward two relatively unexplored areas: the outer solar system and the primitive bodies. A huge amount of new information about the outer planets and comets was obtained from the Voyager 2 encounter with Uranus in January 1986, and from the International Halley Armada's flybys of Halley's comet in March of that year. In August 1989, Voyager 2 encountered Neptune and now continues on to study interstellar space. Also in 1989, Galileo was launched and is en route to study Jupiter and its moons. The next proposed major mission, CRAF, will visit an asteroid and a comet, and CRAF will be followed closely by the Cassini Mission to Saturn and its moon Titan. These less-explored areas of our solar system present intriguing possibilities for understanding the origin of the solar system, the formation of planets, and the origin of life.

Outside the Solar System Exploration Division, even outside of NASA, events have been occurring that will strongly influence the future of planetary exploration. These events have produced significant changes in the emphasis of our nation's space program, and these changes must be accommodated in the Solar System Exploration Program as well.

In 1986, the President's National Commission on Space released its report, "Pioneering the Space Frontier." This report planned for a very ambitious program for the future, emphasizing lunar bases and human exploration of Mars as long-term national goals. A year later, an internal NASA report to the Administrator by scientist and former astronaut Sally Ride, titled "Leadership and America's Future in Space," was released. This report recommended four major new initiatives for the long-term future of NASA: global Earth studies (or the "Mission to Planet Earth"), the Solar System Exploration Initiative (which includes expanded planetary exploration and a series of Mars Sample Return missions), a human outpost on the Moon, and the human exploration of Mars. At the same time, NASA established a separate office, the Office of Exploration (OEXP), to study human missions to the Moon and Mars and to determine the requirements for precursor missions to establish the data base needed for these explorations.

A new National Space Policy was signed in 1988, endorsing the maintenance of national leadership in space and explicitly including a new goal to "expand human presence and activity beyond Earth orbit into the solar system."

These events have combined to place the planetary exploration program in a far different situation from that envisioned by the SSEC 5 years ago. Major, and generally successful, efforts are being made to recover from the loss of the Space Shuttle and the Centaur stage and to launch our current missions. The return of the Space Shuttle to flight status was a heartening development, since both Magellan and Galileo used the Shuttle for their 1989 launches. The use of expendable launch vehicles for future planetary missions is being actively considered, and a decision has already been made to launch Mars Observer on a Titan-3 in 1992. Plans are also being made to use the unanticipated capabilities of Space Station Freedom (not considered by the SSEC) for new kinds of planetary exploration from Earth orbit. Especially important is the new interest in long-term human exploration of the Moon and Mars. This development has given a new and dual significance to certain planetary missions, not only as a means of scientific exploration, but also as precursors for future human landings.

Goals and Approaches for the Future*

The fundamental goals and approaches for planetary exploration as stated and embraced by the SSEC have not been changed by later events. These goals and approaches are the outcome of long-standing and continuing interactions between NASA and its advisory committees, and they are still accepted by NASA and the Solar System Exploration Division as the basis for the U.S. planetary program. Slightly revised from previous descriptions, these goals are

1. Origin and Evolution–To determine the present nature of the solar system, its planets, and its primitive bodies, to understand how the solar system and its objects formed, evolved, and (in at least one case) produced environments that could sustain life.

2. Comparative Planetology–To better understand the planet Earth by determining the general processes that govern all planetary development and by understanding why the "terrestrial" planets of the solar system are so different from each other.

*At the time this paper was first drafted, August 1988, the information contained herein was current. As four years have passed since that time, many changes to NASA's Solar System Exploration Program have taken and will continue to take place.

3. Pathfinders to Space–
To establish the scientific and technical data base required for undertaking major human endeavors in space, by carrying out essential precursor activities which include the survey of near-Earth resources, the characterization of planetary surfaces, and the search for life on other planets.

The manner in which programs and missions are carried out to reach these goals will also vary little from the guidelines established in the past. In particular, the planetary program of the 1990s will stress the five traditional themes described below.

1. Program Balance–
Planetary exploration will continue the balance of activity that has yielded such exciting results in the past. Two kinds of balance are involved: balanced activities between different planetary science disciplines, and balanced exploration of the three fundamental classes of solar system objects: terrestrial planets, primitive bodies (comets and asteroids), and outer planets, or gas giants.

2. Progressive Series of Missions–
The exploration of other worlds via spacecraft will continue the rational sequence of increasingly sophisticated and scientifically detailed missions that has been carried out in the past. This sequence progresses from space reconnaissance, which is accomplished by fast flybys, through exploration, which is achieved by orbiters and atmospheric probes, and into intensive study, which consists of landers, rovers, and sample returns.

3. Strong Ground-Based Support–
The mission activities, although more visible, depend on an essential foundation of ground-based research, mission operations, instrument development, and advanced studies. This component of the planetary program must be maintained, and in some cases, augmented.

4. International Cooperation–
Cooperating with other nations and groups of nations in space exploration has always been a part of NASA's activities. But such cooperation is especially important for the future, because the capabilities and plans of other nations have increased. A special emphasis on U.S.-U.S.S.R. activities was established by the agreements on space cooperation between the two countries. Cooperative studies and other activities, especially involving the future exploration of Mars, continue with the C.I.S.

5. Interdisciplinary Cooperation–
Because we have learned so much about the universe in the past 25 years, it is now possible to address larger and more specific scientific questions, many of which extend across the narrow boundaries of the scientific disciplines established in the early days of the space program. Such currently exciting problems as the relations between the Sun and interplanetary plasmas, the combined formation of stars and solar systems, the search for gravity waves, and the origin of life now involve more than one of the Divisions in NASA's Office of Space Science and Applications. As we enter a new period of space exploration, in which missions will be both less numerous and more sophisticated, the Solar System Exploration Division will work closely with other disciplines to ensure that new missions address this wide array of questions as completely as possible.

As we prepare to meet our long-standing goals in both traditional and new ways, we must assess the current status of planetary exploration. Before the launch of Magellan and Galileo in 1989, more than ten years had passed since the last U.S. planetary mission, Pioneer Venus, was launched in 1978. But even with this long hiatus, the achievements of the last 25 years constitute an awesome accomplishment and provide a solid base for new and exciting exploration.

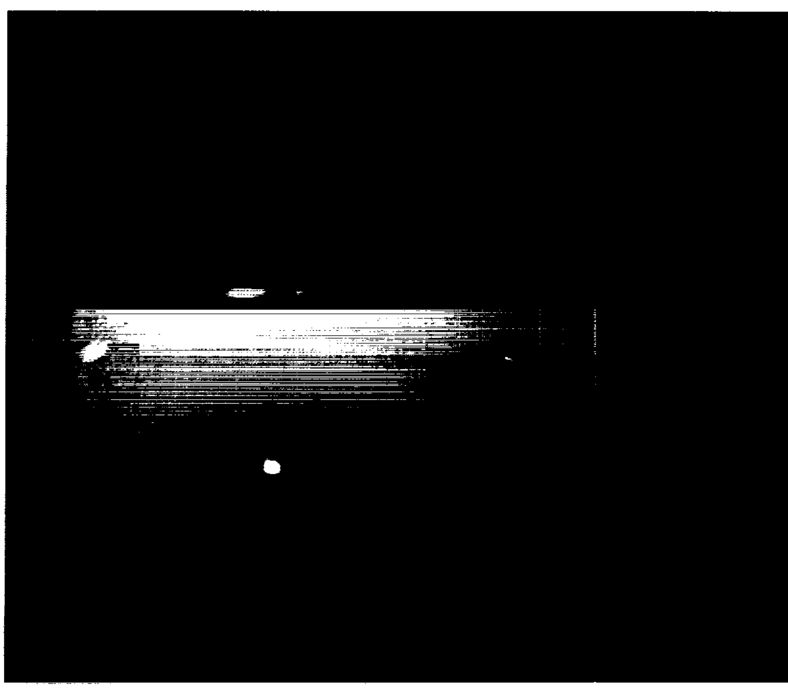
By the end of the 1980s, all the planets except Pluto had been studied by reconnaissance phase (flyby) missions which began with Mariner 2 in 1962, and ended with the Voyager 2 flyby of Neptune in August 1989 (fig. 16-1). More than two dozen planets and moons, some only dots of light even in the best telescopes, have been transformed into a fantastic variety of worlds, some familiar, some bizarre, and all surrounded by exciting problems and new scientific questions. The exploration phase of orbiters and probes has been established for all the inner planets, with the notable exception of Mercury, and the stage is now set to expand the intensive studies phase of the Moon and Mars that was briefly initiated by the Apollo and Viking programs.

Finally, new developments in technology and the establishment of Space Station Freedom (fig. 16-2) will make it possible to attack important planetary problems from Earth orbit—the nature and composition of cosmic dust, the detection of other planetary systems, and the long-term observation of other planets.

One of the most important long-term consequences of the Challenger loss has been the focusing of NASA on the issues of risk, reliability, and what to do to prevent failure. These heightened concerns were most visible during the long process of restoring the Shuttle to flight status, but they have major implications for how planetary exploration will be conducted in the future.

Planetary exploration has always been risky. In the early days, when missions were simple and inexpensive, the problem of risk was addressed in a straightforward way: by constructing and launching two duplicate spacecraft, each with the same payload. If one spacecraft or launch vehicle failed, its twin could carry out the planned mission. This method of risk reduction also provided an important bonus: if the first spacecraft worked perfectly, then the second could be used for a complementary mission.

Figure 16-1. False-color image of Neptune. Red areas are semitransparent haze covering planet.



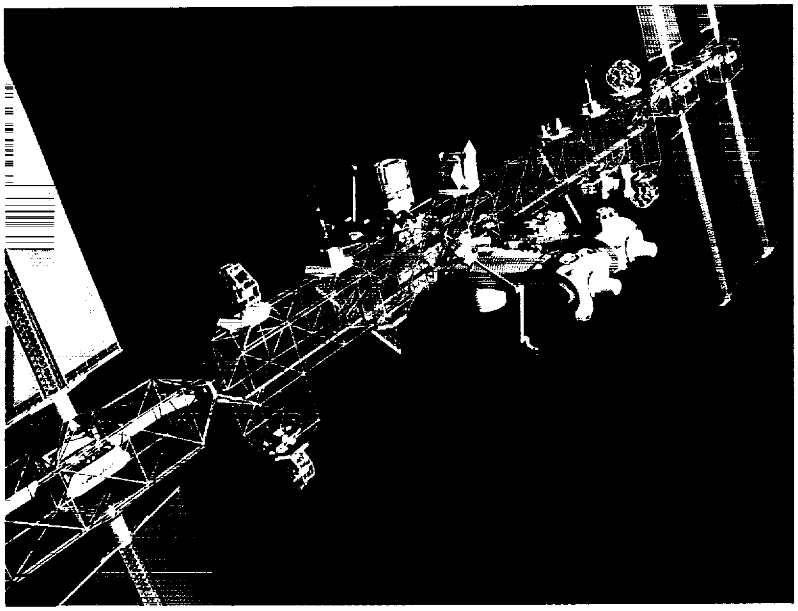


Figure 16-2. Space Station Freedom Concept.

This duplication, despite its obvious advantages, became increasingly difficult to implement as missions grew more complex and expensive, and Voyager was the last mission to which this method could be applied. With Galileo, risk reduction had to be built into the system—redundant systems, complementary instruments, contingency plans for operations, and a high degree of confidence in the launch systems. These precautions, although necessary for a single mission, further increased the cost. In addition, this protection is not complete; because only one mission is involved, a single failure in the spacecraft, the launch vehicle, or even in one or more payload instruments can result in a major loss of data or even the loss of the mission itself.

The planetary program is presently responding to two factors: the heightened NASA-wide concern about risk, and the absence of any series of common missions to provide the originally planned backup. The program has, therefore, developed a risk-reduction approach that is based, not on fully developed backup missions, but on the purchase of essential spare components for both the spacecraft and its payload for any given mission.

These spares will reduce risk in two ways. First, they will be available to support the schedule for assembly and testing of the original mission. If one component has problems during this period, it can be quickly replaced by the spare so that the schedule and the launch opportunity can be met. Second, in the event of a major failure in the original mission, the available spares will provide an essential nucleus for rebuilding the spacecraft and its payload for the next launch opportunity.

This policy is already being put into effect. In FY 1988, Congress appropriated funds to purchase spares of certain critical spacecraft and instrument components for the Mars Observer Mission. These spares will provide increased assurance that the current schedule for Mars Observer, based on a 1992 launch, can be met. In the event that the Mars Observer has a major failure, the spares will be used as the nucleus for reconstructing another mission to meet the next launch opportunity to Mars.

If the Mars Observer Mission is successful, the spares can then be used as the basis for the next Planetary Observer mission, the Lunar Observer, which is under study for a new start in the early 1990s. Once this mission is approved and under way, it will obtain its own set of spares, which can then be used in the next Planetary Observer mission, and so forth. Similarly, the planned development of the CRAF Mission will include similar essential spares, which can then be used in the next Mariner Mark II mission, the Cassini Mission to Saturn and Titan.

No amount of spares will ever substitute for the main goal: making the greatest possible effort to ensure that each mission is fully successful in and of itself. The new spares will support that goal by reducing the risk that minor problems during mission development could produce major delays. And the "rolling spares" philosophy, in which the spares for each mission provide the nucleus for the next one in the series, will provide both support and continuity for planetary exploration in the 1990s.

Origin and Evolution: The Outer Solar System

Clues to the origin and evolution of the planets can be found throughout the solar system. But the most fundamental of these clues, and the best-preserved information, can be found in the bodies that lie in the chill darkness beyond the orbit of Mars.

During most of the 4.6 billion years since its origin, the solar system has been recovering from the violent, dynamic processes that created it. On Earth and the other terrestrial planets virtually all evidence of the earliest epochs has been erased by continuing internal processes—volcanism, mountain-building, and the development of oceans, atmospheres, and life. By contrast, the comets, the asteroids, and the bodies of the outer solar system have largely escaped these processes, and these objects have thus retained some record of early planetary formation.

Because they are small, comets and asteroids have never been able to generate the internal heat that powers large planets and produced wholesale alterations of the materials that formed them.

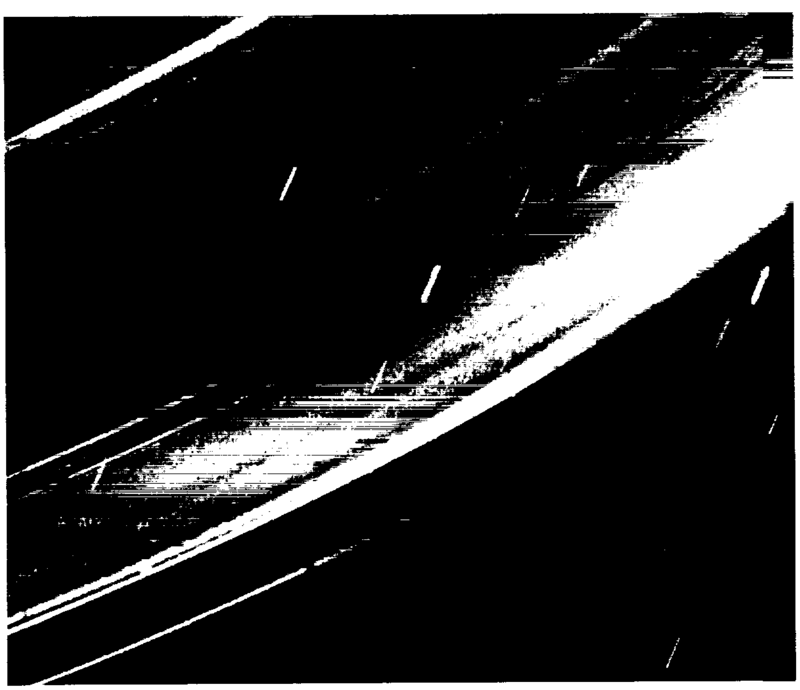
In currently held theories for planetary formation, both the terrestrial planets and the cores of the outer planets grew through the accretion of countless small solid bodies called planetesimals, which were similar to present-day asteroids and comets. One group of these original small bodies has been preserved as asteroids in the asteroid belt, a relatively stable region between the orbits of Mars and Jupiter. Disturbances by Jupiter's gravity probably prevented the asteroids from accreting in a single planet-sized body, and thus they retain many of their primitive chemical and physical characteristics.

Just as asteroids (and the meteorites derived from them) may be samples of the inner parts of the original solar system, so comets may be icy remnants from the accretion of the more distant outer planets. According to this view, the newly formed outer planets then gravitationally scattered the comets to the most remote part of the solar system—the distant Oort cloud, halfway to the nearest star. There the comets remain, in the deep freeze of space, until a passing star, a giant molecular cloud, or the tidal forces of the galaxy perturb them into new orbits that bring them back into the planetary region. An alternative theory is that comets are icy planetesimals that formed in the solar nebula beyond the orbit of Neptune. In either case, comets have most likely been preserved in a condition approaching their original state.

The giant planets of the outer solar system, Jupiter and Saturn in particular, are so massive, and so cold, that they have retained essentially all the material from which they were originally made. Thus, these planets are expected to contain a representative sample of the original solar nebula material, possibly altered to new chemical forms, but retaining the elemental and isotopic signatures of the primordial solar nebula.

The ring systems around the outer planets permit us to study the dynamic interactions of small co-orbiting bodies, which are similar to the interactions among planetesimals that led to the accretion of planets (fig. 16-3). The moons of the outer planets, stunningly revealed by the Voyager pictures, are mostly a variety of cold, frozen worlds that nevertheless record histories that in some ways parallel the evolution of the terrestrial planets. Ranging from highly modified to the nearly pristine worlds, these satellites, like the comets, may contain records of the early solar system, frozen and preserved for our inspection.

Figure 16-3. Backlit view shows continuous distribution of fine particles throughout ring system of Uranus.



The exploration of the outer solar system is an area where American leadership remains unchallenged. Only U.S. spacecraft have ever passed the asteroid belt. Pioneers 10 and 11 and Voyager 1 made historic encounters with Jupiter and Saturn. Voyager 2, after passing Jupiter and Saturn, made the first encounter with Uranus in January 1986, and then met with distant Neptune in August 1989.

Despite these achievements, we have obtained only quick glimpses; we have visited, but we have not yet begun to explore. And although we learned much about comets through data gathered by the Halley flybys, what we learned is only an intriguing glimpse into the mysteries of comets. We have yet to encounter an asteroid, we have yet to rendezvous with a comet and study it for any

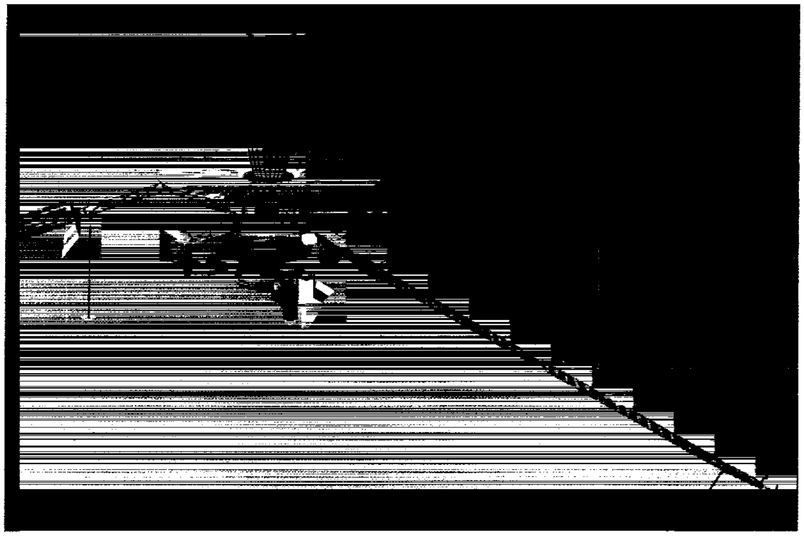


Figure 16-4. The Galileo spacecraft, with its large radio antenna furled like an umbrella, is shown in this artist's design. The long boom extending to the right contains sensitive instruments for magnetic measurements.

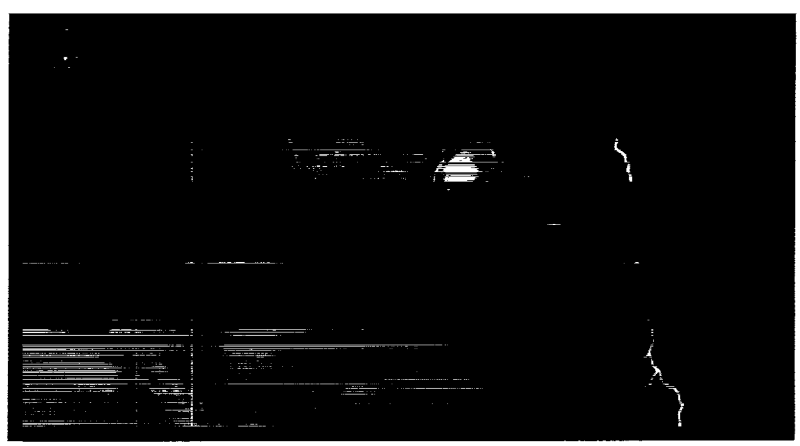
length of time, and we have yet to place an orbiter around any of the outer planets. To understand these worlds, and to learn what they can tell us about the solar system, we need to explore them at length, and to learn much more about them: what they are like, how they formed, how they change with time, and why they are so different.

We are now ready to begin this exploration. We can now build on what we have learned to design new missions that provide the longer observation times and the more sophisticated studies that we need. We can respond to the challenges of the outer solar system, the excitement of new scientific explorations, and the opportunities to gather new knowledge about the solar system and about ourselves.

The exploration phase for the outer solar system began with the October 1989 launch of the Galileo Mission to Jupiter and its moons (fig. 16-4). When it arrives at Jupiter in 1995, Galileo will begin our first long-term examination of this huge world, its strange moons, and its giant magnetic field.

Galileo is actually two spacecraft which will be launched as a single unit and will then separate shortly before arrival at the planet (fig. 16-5). One spacecraft, a probe, will plunge into Jupiter's atmosphere and will descend on a parachute until it is crushed by the increasing pressure. During its brief lifetime, it

Figure 16-5. In this artist's concept, the Galileo probe plunges into the thick, swirling atmosphere of Jupiter and releases its reddened heat shield to begin its measurements. The Orbiter (upper left) will serve as a data relay for the short-lived probe.



will make the first direct analyses of the upper layers of Jupiter's atmosphere. The second spacecraft is a long-lived orbiter that, for nearly 2 years, will map the behavior of Jupiter's atmosphere, record its magnetic field and radiation belts, and make orbital excursions for closer looks and more detailed studies of the four large moons revealed to the Voyager spacecraft in 1979.

Galileo will also explore on its way to Jupiter. As it passes through the asteroid belt in the early 1990s, it will be directed to pass close to two asteroids, Gaspra and Ida, and it will give us our first close-up view of these tiny bodies. After Galileo, all missions to the outer solar system will make similar flybys of other asteroids.

After the loss of Challenger and the cancellation of the Centaur upper stage, the path to Jupiter required major revisions. Because of the change in launch opportunity and the lower available launch energies, the trip time to Jupiter is now longer than originally planned, and a complicated trajectory, involving multiple gravity-assist flybys at Venus and Earth, is required. Nevertheless, Galileo will reach Jupiter and its moons in 1995. Galileo involved substantial cooperation with Germany in the design of the retro-propulsion module, the rocket motor that will place the spacecraft in orbit around Jupiter.

After Galileo, all missions to the outer solar system will use the Mariner Mark II series of spacecraft envisioned by the SSEC. The Mariner Mark II is a modular spacecraft design, with 3-axis stabilization like Voyager, that can be easily modified to accommodate a variety of missions to the outer solar system, including the primitive bodies. The spacecraft is specially designed to meet the wide range of demands imposed by the nature of these missions to the outer solar system: generating power at great distances from the Sun; transmitting large amounts of data to Earth over vast distances; and providing highly accurate pointing for the precise aiming of penetrators, probes, and remote sensing instruments, as well as for the proper orientation of antennas. Of equal significance is the need for a high degree of autonomous operation and reliability.

The Mariner Mark II missions will focus on exploring the origin and evolution of the solar system by studying the primordial material and the early organic chemistry to be found in the outer planets and small bodies. The Mariner Mark II program begins with a dual initiative: the Comet Rendezvous/Asteroid Flyby (CRAF) Mission and the Cassini Mission to Saturn.

The CRAF Mission is a critical element of the Solar System Exploration Program for two reasons: it initiates the Mariner Mark II program, and it begins the major search for our origins in some of the most primitive solar system objects, the comets and asteroids (fig. 16-6). The molecular and mineralogical compositions of cometary material will yield information about the physical and chemical conditions that existed in the early solar nebula. Studies of the dark material on comets and on carbonaceous asteroids will tell us what these organic compounds are, how they formed, and what role they might have played in the origin of life. Studies of the interactions of the solar wind with the gas and dust emitted from an active comet will reveal the chemical and physical processes that controlled the origin and evolution of dust, gas, and

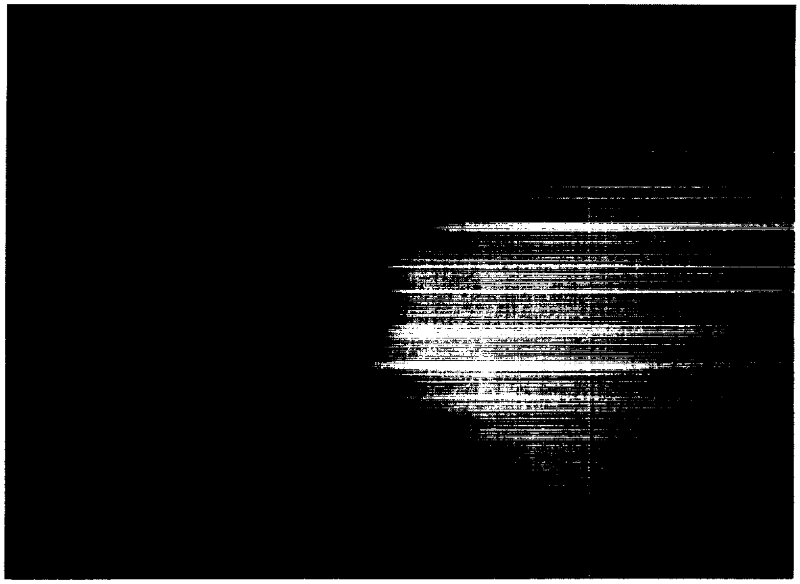


Figure 16-6. Halleys comet, 1986.

small solid planetesimals in the solar nebula.

During its 10-year journey, CRAF will fly past at least one asteroid and will explore a comet in detail. To discover how a comet was formed, and to see how it evaporates under the influence of the Sun's warmth and light, CRAF will rendezvous with a typical short-period comet and will fly in formation with it as it moves around the Sun from its most distant to its closest point of approach. During this multi-year observation, instruments on CRAF will determine the elemental, isotopic, molecular, and mineralogical composition of cometary material and will also investigate the comet's microscopic and large-scale physical structure. As the comet becomes more active near the Sun, CRAF will study the physics and chemistry of the comet's atmosphere and its interaction with the sunlight and the solar wind.

During the asteroid flybys before the comet rendezvous, CRAF will determine the physical properties of one or two asteroids, measuring such unknown qualities as their sizes, shapes, bulk densities, and rotation periods. Instruments trained on the asteroids as the spacecraft flies by them will photograph their surface features and will collect data about their mineral and chemical composition.

Once through the asteroid belt, CRAF will fly on to rendezvous with a comet and to begin long-term observations that will produce a major increase in our knowledge of comets. The Halley Armada flybys of 1986 provided brief *in situ* measurements of cometary gas and dust, and gave us our first glimpse of the dark nucleus of a comet. In many respects, however, the Halley flybys raised more questions than they answered, and the long rendezvous mission designed for CRAF represents a substantial advance.

In a rendezvous mission, a spacecraft follows an orbit around the Sun that precisely matches the comet's orbit. When the spacecraft catches up with the comet, it makes a small rendezvous maneuver, and then the spacecraft and the comet travel together indefinitely. Among the many significant advantages of a rendezvous mission over a flyby are its ability to produce longer and more detailed mapping, the ability to adapt to changing conditions as the mission progresses, and—especially important—the ability to observe the comet's entire lifestyle, from cold inertness in the outer solar system to violent activity near the Sun.

While the comet is quiescent, CRAF will use a wide variety of remote sensing instruments to study it from close range. About a year after CRAF arrives at the comet, the spacecraft will fire a large, needle-like penetrator directly into the surface of the comet's solid nucleus (fig. 16-7). Instruments in the penetrator will measure the chemical composition of the nucleus and will determine the temperature profile within the nucleus, its surface strength, and the exact nature and composition of the mixture of ices, dust, and organic materials that are thought to make up the nucleus. The penetrator, powered by batteries, will transmit its data back to the CRAF spacecraft for about 1 week.

When the comet becomes active near the Sun, the spacecraft will move in and out through its atmosphere, collecting dust for on-board analysis. Several plasma detectors on the spacecraft will study in detail the interactions between the comet's gas and dust and the radiation and solar wind coming from the Sun. After the comet makes its closest approach to the Sun, the CRAF spacecraft will make a 50,000-km excursion down the comet's tail to explore the comet-solar wind interaction in more detail.

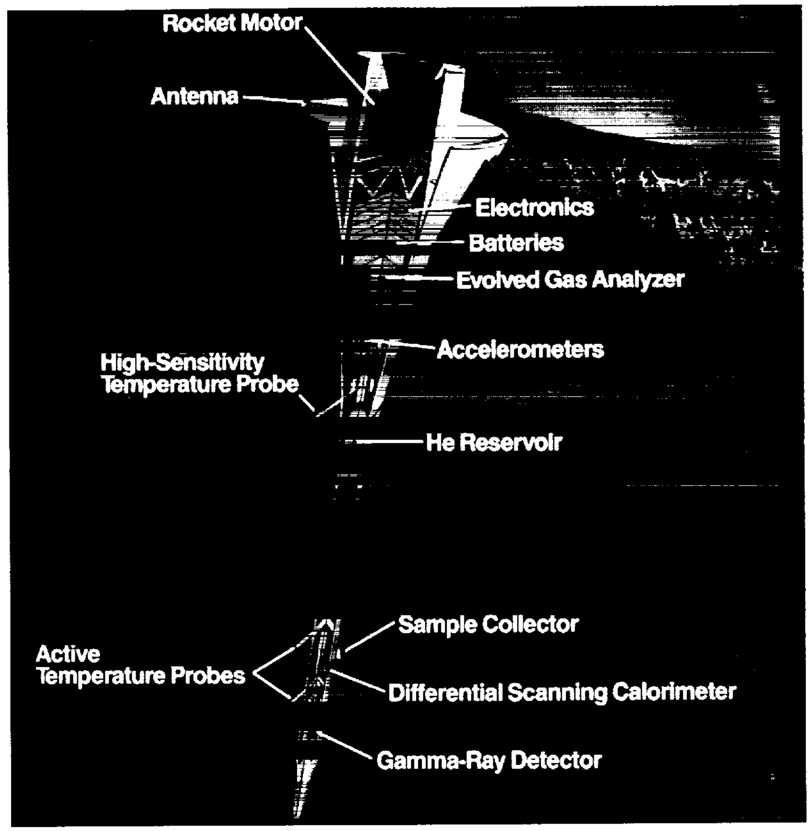


Figure 16-7. This cutaway diagram shows the various components of the CRAF penetrator, a harpoon-like probe that will bury itself in the comet's nucleus and transmit data to the spacecraft. Instruments that will measure the physical and chemical properties of the nucleus include accelerometers, gas analyzers, temperature probes, a gamma-ray detector, and a calorimeter to analyze samples collected from the surrounding nucleus.

The next Mariner Mark II mission after the CRAF Mission is called Cassini, and it combines two of the original Core Program missions recommended by the SSEC: the Saturn Orbiter and the Titan Probe. Cassini will explore the whole Saturnian system, which contains a host of volatile-rich objects—Saturn, Titan, many small moons, and the rings themselves (fig. 16-8). In addition to providing possibly pristine samples of the outer solar system, these objects may also contain records of the processes that have modified them. Like Galileo, the Cassini Mission will consist of two connected spacecraft, a Saturn Orbiter spacecraft built by

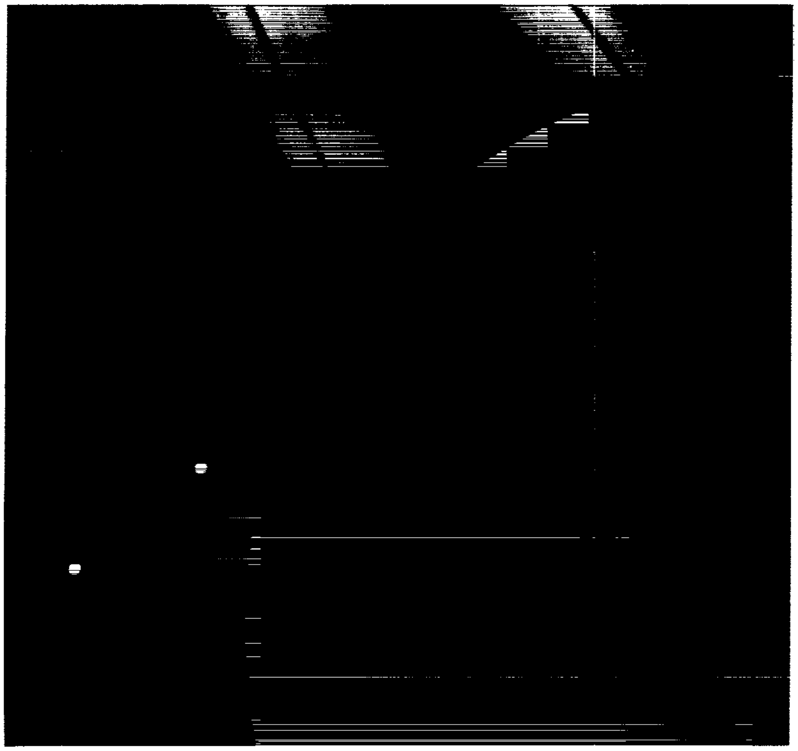


Figure 16-8. Saturn and two of its moons, Tethys and Dione.

NASA and a detachable Titan Probe, which might be supplied by the European Space Agency. This mission will enable us to begin to make comparisons between Saturn and the data we receive about Jupiter from the Galileo Mission.

Before going into orbit around Saturn, the Orbiter will deliver the probe to Titan. The short-lived probe, powered by batteries, will plunge into Titan's thick, organic-rich atmosphere, make chemical measurements as it descends, and broadcast the data back to the Orbiter until it reaches the hidden surface of Titan. Subsequently, the Orbiter will make close flybys of Titan on every orbit to carry out intensive studies of this most unusual moon, and a radar instrument will penetrate the opaque orange atmosphere of Titan to map the surface beneath it.

One of the most intriguing aspects of Titan is the possibility that its surface may be covered with oceans or lakes of liquid hydrocarbons produced by photochemical processes in Titan's atmosphere. These processes may be similar to those that occurred on Earth in primordial times, also producing organic chemicals that, in the more benign environment of Earth, led to the origin of life.

One of the benefits of the Cassini trajectory from Earth to Saturn is that it takes the spacecraft through the asteroid belt. By that time, Galileo and CRAF will have made close flybys of asteroids, and a different compositional type will be chosen for a Cassini flyby. Thus, in the course of these three great explorations, several asteroids, each with different surface compositions, will be studied independently.

The continued exploration of the outer solar system, where the United States has established preeminence, depends on the Mariner Mark II program and on the early approval of CRAF and Cassini to get it started. This major step had already been postponed for several years beyond the date recommended by the SSEC, and the CRAF Mission has become increasingly well-studied and well-defined. The inclusion of the CRAF and Cassini Missions in the FY 1992 budget is a welcome sign; this project is long overdue, and our continued exploration of the solar system depends critically on it.

Further delays in making such commitments will cause significant losses to our plans and our prospects for the future. We will lose the benefits, in cost, in planning, in science, and in morale, that come from being able to follow the Galileo launch with a strong and well-planned program of further exploration. We will lose the opportunity for significant cooperation with potential international partners, such as the European Space Agency, who have their own schedules and plans.

Finally, if we delay further, the movements of the planets themselves will work against us. In just a few years, Jupiter will move out of the alignment that now makes it possible to use it as a "slingshot" to reach Saturn in greatly shortened times. Without the ability to use Jupiter in this way, travel times to the outer solar system will be substantially longer. Further delay will, for all these reasons, create a major gap in the U.S. planetary program, a gap similar to the interval between 1978 and 1989, when no planetary missions had been launched.

The leadership that the United States has established in exploring the worlds beyond Mars deserves to continue, and it can. The outer solar system is waiting with its unknown worlds, its unsuspected discoveries, and its new knowledge. We are ready to explore it, and we know how to go about it. We can maintain visible national leadership here, and at the same time, we can push the frontiers of scientific discovery even farther out into the universe.

Comparing Planets: The Inner Solar System

Unlike the outer solar system, the worlds of the inner solar system, Mercury, Venus, Earth, the Moon, and Mars, have had much of the record of early solar system history erased from them. The inner planets have been dramatically changed from what they were originally, largely by their own internal forces. Radioactive elements trapped within them generated heat, and this heat produced geological activity, volcanism, earthquakes, mountain-building, and the development and migration of huge crustal plates. Original atmospheres were lost, perhaps stripped by the force of huge solar flares, sometimes replaced by volatiles released from inside, and then, on worlds of low gravity, slowly lost again to space. The atmospheres that did remain were continually modified by the Sun's energy, by internal volcanism, and, on Earth, by the development of life.

We study the inner solar system for many reasons, but for one reason in particular: to better understand our own planet by determining the present nature of similar worlds and by determining the general processes that govern all planetary development (fig. 16-9). The worlds of the inner solar system share many similar characteristics, but they also display a wide variety of individual features. The terrestrial, or Earth-like, bodies share common origins and compositions, and they have been modified by the same processes—meteorite bombardment, core formation, volcanism, mountain-building, and the formation of atmospheres. But these forces have acted differently on different bodies, and our search through the inner solar system is an attempt to relate what we see to the different processes that have produced it.

To understand these similarities and differences, we need to obtain a wide range of data. To fully understand the worlds of the inner solar system requires many extensive and difficult studies: global characterization of surfaces and atmospheres, use of geophysical stations for studying internal structure, and ultimately, the return of samples to Earth to determine their detailed character and to unravel the complex historical records that are preserved in them.

Figure 16-9. A view of Earth taken from an Apollo spacecraft.

A new impetus for studying the inner solar system comes from the recent announcement of a national goal to expand human presence beyond Earth orbit and into the solar system. The first and most likely locales for human exploration are the Moon and Mars. From now on, data gathered from these two worlds will serve a two-fold related purpose: to understand the Earth through comparative planetary studies, and to develop the technical and scientific foundation for future human exploration.

During the past two decades, significant strides have been made in the exploration of the inner solar system. The currently scheduled missions, Magellan and Mars Observer, will complete the global characterization of Venus and Mars. The next logical step is the intensive study of Mars by a sample return mission, a mission that will also significantly support the planning of future human initiatives to the Red Planet.

The Planetary Observer program is the backbone of our strategy for the global characterization of the inner planets. The Mars Observer, planned for launch in 1992, will study the surface and atmosphere of Mars (fig. 16-10). The Lunar Observer, the next in the series, is under development to study the geoscience of the Moon.

Beyond the Observers, a Mars Rover/Sample Return Mission is being studied—a mission that would land on the surface of Mars, traverse significant distances over that surface, and return a handful of Mars to Earth laboratories for analysis. Such samples would be chosen with the interests of both planetary scientists and exobiologists in mind, and they would provide a new level of understanding about Mars including its chemistry, mineral composition, physical properties, history, organic compounds, and the existence of present or past life.

The Mars Rover/Sample Return is a complicated mission. Much of the technology that would enable or enhance this mission does not yet exist; however, the recent funding for Project Pathfinder, both in FY 1988 and FY 1989, is encouraging.

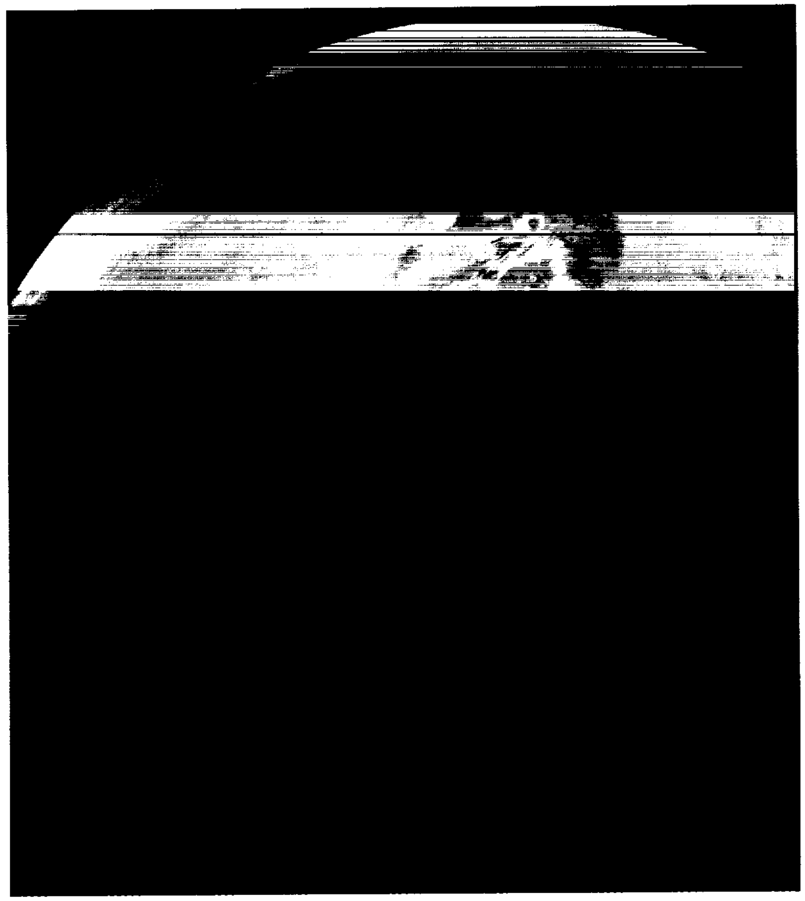


Figure 16-10. The panoramic view and complex geology of Mars is presented in a mosaic of computer-enhanced Viking pictures. The huge canyon of the Vallis Marineris stretches horizontally across the center of the picture, and three of Mars' huge volcanoes appear as brown spots at the left.

Many of Pathfinder's technology studies would support this mission. Because of the complex requirements, and also because the C.I.S. has stated its interest in such a mission, a Mars Rover/Sample Return is a potential candidate for a cooperative venture with the C.I.S. A NASA delegation traveled to Moscow in 1988 to discuss the process whereby cooperative exploration missions with the U.S.S.R. might occur. Cooperative discussions continue today with the C.I.S. We are also working in close cooperation with NASA's Office of Exploration to determine the requirements and plans for this mission relative to their plans for human exploration.

Next Steps for the Future

The first priority for planetary exploration is to preserve the current missions and other elements of the ongoing program, and to ensure that scheduled missions are launched as soon as possible. In the meantime, we will begin to develop the payloads that will allow us to make maximum use of the Space Station: the Cosmic Dust Collection Facility, and the Astrometric Telescope Facility to search for other solar systems. Furthermore, we plan to augment the research and analysis programs that are so fundamental to the success and value of our flight projects.

Planetary exploration, in the 1990s, is facing a contradictory "best of times and worst of times." Many challenges and stresses in our program need to be overcome. But tremendous potential can be seen in future missions. We are on the threshold of major steps to begin exploring the outer solar system, and thus to discover our origins. We are poised to make major contributions to the national goal of major activities in space. We are planning and considering cooperative ventures with many other spacefaring nations. The possibilities are endless—the other worlds are waiting for us—we have only to choose to explore them.

Additional Reading

NASA Life Sciences Strategic Planning Study Committee: Exploring the Living Universe: A Strategy for Life Sciences. National Aeronautics and Space Administration, Washington, D.C., 1988.

Solar System Exploration Committee: Planetary Exploration Through the Year 2000: A Core Program. National Aeronautics and Space Administration, Washington, D.C., 1983.

Solar System Exploration Committee: Planetary Exploration Through the Year 2000: An Augmented Program. National Aeronautics and Space Administration, Washington, D.C., 1986.