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A Program for Planetary Exploration

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Summary. On the basis of a two-year study, the NASA Solar System Exploration Committee recommends a core program of planetary missions through the year 2000. By incorporating a number of cost-saving measures, an exciting program of planetary exploration can be achieved within a highly constrained NASA budget.

During the 20 years from the first Mariner flyby of Venus to the Voyager 2 encounter with Saturn, planetary exploration experienced its golden age. More than 40 robot spacecraft probed first toward the moon, Venus, and Mars, then ultimately to every planet known to ancient peoples, from Mercury to Saturn. Most of these spacecraft were launched by the United States, bearing names symbolic of their exploratory missions: Ranger, Surveyor, Pioneer, Mariner, Viking, and Voyager. The Soviet Union, the other nation to contribute to this era of discovery, focused its efforts more narrowly on the moon and Venus, but it too achieved remarkable successes. Within less than a generation, there was a revolution in our understanding of the solar system.

After such a brilliant beginning, it is natural to ask, What next? What new worlds remain to be explored? How do we best capitalize on our past successes? And perhaps most important in a time of constrained budgets, how do we justify continuing planetary exploration in the face of so many other worthy programs competing for federal research dollars?

As the 1970's drew to a close, planetary scientists asked these questions with increasing urgency. Following the 1977 approval for development of a Galileo orbiter and probe to Jupiter, there was increasing resistance to proposals for further initiatives in planetary exploration. Galileo was postponed repeatedly by launch vehicle delays, and its status remained precarious until the decision last August to adapt the powerful Centaur upper stage for the Shuttle (*1*). Meanwhile, the funds available to NASA for planetary exploration have dropped to 20 percent of their mid-1970's peak (*2*), and even the excitement of the Voyager encounters with Jupiter and Saturn and the once-in-a-lifetime opportunity to send a spacecraft to Comet Halley in 1986 (*3*) failed to reverse the declining support for planetary science.

The need for a fresh look at planetary priorities prompted the NASA administrator in late 1980 to appoint a special committee of the NASA Advisory Council to recommend an implementation strategy for planetary missions through the year 2000. This Solar System Exploration Committee (SSEC) (*4*) has now completed the first part of its task with the publication of a recommended core program of low- and moderate-priced missions. The program is intended to establish a stable basis for planetary science, so that scientifically exciting missions can be carried out within a framework of cost-saving engineering and management approaches. We report here the most important elements of this core program (*5*).

The Basis for Planetary Exploration

Planetary science is a relatively young discipline which has flourished in the United States primarily in response to the development of a deep space launch capability. Before the space age, planetary research was largely the province of a handful of astronomers, such as those working with Gerard P. Kuiper at the University of Chicago, while in the geosciences a few workers, notably Harold C. Urey, had begun to look at the meteorites as an important potential source of information on the formation of the solar system. Today, planetary science has more than a thousand full-time participants (*6*), drawn from backgrounds in physics, astronomy, meteorology, meteoritics, geology, geophysics, and geochemistry, and is supported by tens of millions of dollars in federal funds. Drawing on this multidisciplinary background and spacecraft data of unprecedented quantity and quality, planetary science has achieved a new perspective in the way we view our own planet. From the complex atmospheric chemistry of Venus to the evidence for climatic change on Mars, from the sulfur volcanoes of Io to the spiral density waves propagating through the rings of Saturn, from the superheated plasma of the Jovian magnetosphere to the isotopic imprint of supernova nucleosynthesis in the Allende meteorite, planetary perspectives now pervade our approach to a wide variety of problems in physics, astronomy, and the geosciences.

The fundamental goals of scientific exploration of the solar system have been (i) to determine the present state, origin, and evolution of the solar system, (ii) to better understand the Earth by comparative studies, and (iii) to improve our understanding of the relation between the appearance of life and the chemical history of the solar system. In the case of the moon, the Ranger, Sur-

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veyor, and Lunar Orbiter missions also provided critical support to the manned Apollo Program, and in the future the need to assess resources for utilization by an increasing human presence in space may become an important supporting objective of planetary exploration (*7*).

To translate these general goals into a plan of action, we may consider a matrix. Along one dimension lie the diverse objects within the solar system: (i) the inner or terrestrial planets; (ii) the outer or Jovian planets, with their rings and satellite systems; and (iii) the comets and asteroids, chemically primitive debris surviving from the origin of the solar system. The second coordinate of the matrix is a measure of our level of knowledge. This knowledge has progressed, through a series of missions of increasing technological sophistication, from flyby reconnaissance spacecraft to orbiters, entry probes or landers, and ultimately return of samples for terrestrial analysis. Our progress in filling in this matrix has been uneven. We have been most successful in the inner solar system, reaching the level of landers on Venus and Mars and of sample return from the moon. In the outer solar system, we have accomplished flybys of Jupiter and Saturn, and in 1988 Galileo will provide an orbiter and entry probe for Jupiter. No missions have yet been launched to the small, primitive bodies, although several non-U.S. flyby missions are planned for Comet Halley when it approaches the sun three years from now (*3*).

Excluding the special case of the moon, the United States has launched 17 successful planetary spacecraft, including two Viking Mars landers and a group of Pioneer Venus atmospheric entry probes (Table 1). The U.S.S.R. has achieved success with 11 Venera missions to Venus, including seven landers. These missions have demonstrated our ability to apply the most advanced technology to important and challenging tasks outside the national security arena. But the pictures returned by a Viking or Voyager can also distort our perspective, because our approach to planetary exploration is the reverse of that used over centuries in the exploration of Earth. From space, we begin with a global view of another planet and only later move to detailed observations and measurements in selected regions. This has proved to be a powerful approach, but only because scientists have been able to extrapolate from their knowledge of basic processes learned on Earth. It generates an immediate global perspective, even from a first mission, but also tends to create an overly optimistic impression of the state of our knowledge. Experience has shown that many interpretations based on data from first-generation reconnaissance missions require substantial revision when more capable spacecraft arrive later (*8*). The importance of following up on our early discoveries cannot be overemphasized if we desire a true understanding of other planets and the processes that mold them.

A critical appraisal of where we stand today in planetary science also reveals large parts of the solar system where we have not even begun to explore. The entire surface of Venus and half that of Mercury remain terra incognita (*9*). No spacecraft has yet visited Uranus, Neptune, or Pluto (*10*), and we have only flyby data on Jupiter, Saturn, and their ring and satellite systems. We have yet to send a spacecraft to a comet or asteroid. These small, volatile-rich messengers from the distant past have not experienced the large-scale chemical and physical modification that has affected the larger planets and satellites, and they promise especially rewarding insights into the earliest history of the solar system.

Table 1. NASA planetary missions (not including lunar flights).

Spacecraft	Launch date	Destination	Encounter date	Type of encounter
Mariner 2	26 August 1962	Venus	14 December 1962	Flyby
Mariner 4	28 November 1964	Mars	14 July 1965	Flyby
Mariner 5	14 June 1967	Venus	19 October 1967	Flyby
Mariner 6	25 February 1969	Mars	31 July 1969	Flyby
Mariner 7	27 March 1969	Mars	5 August 1969	Flyby
Mariner 9	30 May 1971	Mars	13 November 1971	Orbiter
Pioneer 10	3 March 1972	Jupiter	4 December 1973	Flyby
Pioneer 11	6 April 1973	Jupiter	3 December 1974	Flyby
		Saturn	1 September 1979	Flyby
Mariner 10	3 November 1973	Venus	5 February 1974	Flyby
		Mercury	29 March 1974	Flyby
Viking 1	20 August 1975	Mars	19 June 1976	Orbiter
			20 July 1976	Lander
Viking 2	9 September 1975	Mars	7 July 1976	Orbiter
			3 September 1976	Lander
Voyager 1	5 September 1977	Jupiter	5 March 1979	Flyby
		Saturn	12 November 1980	Flyby
Voyager 2	20 August 1977	Jupiter	9 July 1979	Flyby
		Saturn	25 August 1981	Flyby
		Uranus?	1986	Flyby
		Neptune?	1989	Flyby
Pioneer Venus	20 May 1978	Venus	4 December 1978	Orbiter
	8 August 1978	Venus	9 December 1978	Probes
Galileo?	1986	Jupiter	1988	Orbiter
		Jupiter	1988	Probe

Recommendations by the Space Science Board

In formulating a mission strategy, the SSEC has depended on scientific priorities for space science articulated by the National Academy of Sciences through its Space Science Board. Created in 1958, the Space Science Board has advised NASA throughout its history on overall scientific priorities (*11*). During the past several years, specific recommendations in planetary science have been developed by the Board's Committee on Planetary and Lunar Exploration (COMPLEX) and published in three reports (*12*). These reports are viewed as being of equal priority in shaping the scientific basis for the planetary exploration program.

For the inner planets, COMPLEX recommended a major focus on studies of the triad Venus, Earth, and Mars. These terrestrial planets, which are roughly similar in size, location, and composition, have followed strikingly different evolutionary tracks, and comparative studies should lead to a profound advance in knowledge, particularly with respect to our own planet. COMPLEX emphasized the gap in our knowledge represented by the unknown surface of Venus, and it accorded highest priority to the acquisition of a surface map with a resolution of ~ 1 kilometer.

The comets and asteroids represent the major planetary area in which spacecraft studies have not yet been initiated, and COMPLEX emphasized the urgency of beginning their study in order to probe the earliest periods of solar system history. Exploratory missions should sample the diversity of both comets and asteroids, as well as measure a few objects in detail.

Outer solar system studies are the one area of the planetary program that has retained a fair degree of momentum, with the forthcoming Voyager 2 flybys of Uranus and Neptune and development of the Galileo mission for a 1986 launch to Jupiter. For the next step, COMPLEX endorsed in-depth study of the Saturn system from an orbiter and a follow-up to the Voyager discoveries for Saturn's cloud-shrouded satellite Titan.

While COMPLEX and the Space Science Board have established the scientific objectives for future planetary exploration, they have not addressed the specific means by which these objectives should be accomplished. The development of a mission plan, with appropriate attention to technological and fiscal constraints, is the task of the SSEC.

Technological Considerations

Choice of missions has always depended in part on technological capability, and improvements in technology have led to more ambitious missions of increasing complexity, such as Viking, Voyager, and Galileo. In a period of budgetary constraint, it could be argued that the planetary community was pricing itself out of the market (*13*). Further, a cycle was developing in which the long intervals between flights decreased the opportunities for cost-saving use of hardware and designs from previous missions ("inheritance"), while increasing the pressure to include the maximum science payload in each flight. One of the first priorities of the SSEC was to break this cycle, increasing the opportunities for new missions by reducing their individual costs and phasing them together more efficiently (Fig. 1).

A first step was to identify the key elements that drive mission costs. There are three primary factors: (i) the degree of hardware and software design inheritance from mission to mission, (ii) the scientific scope and hence complexity of any given mission, and (iii) the degree of change that occurs after the mission is approved. The first two of these factors appear to be reinforcing, as noted above. The SSEC decided to limit its recommendations for a core program to missions that are restrained and focused in scope and where high inheritance can be achieved (*14*).

The missions in the core program must be insulated as far as possible from costly changes and delays once they are approved. In the past, many such changes have been outside the control of planetary program management, as in the delays and redirection in Galileo that arose from repeated launch vehicle changes. To avoid such costly problems, the SSEC has restricted its recommendations to missions that do not require new enabling technologies, such as specially designed upper stages, low-thrust propulsion systems, mobile landers, or sample return capabilities. Instead, it recommends vigorous utilization of the basic mission types that have been successful in the past: flybys, orbiters, and atmospheric entry probes. Such an approach promises a maximum scientific return on investment and a minimum probability of costly and disruptive delays.

Essential to the realization of the mission plan is the availability of the high-performance Centaur upper stage for the Shuttle. The Shuttle/Centaur brings within reach a number of missions, including comet and asteroid rendezvous, that were once thought to require such new technologies as low-thrust propulsion. Many missions in the core program require Shuttle/Centaur, but none demand more performance than will be provided by this combination (*15*).

Additional savings can be achieved in spacecraft design. For the inner solar system, the SSEC recommends the modification of spacecraft developed by aerospace companies for a variety of commercial applications in Earth orbit (*16*). Although there are few true production lines for spacecraft, the production rates within this industry are such that the costs of high-capability spacecraft are modest compared with those of the specialized spacecraft generally used for planetary exploration. Such spacecraft are limited to the inner solar system, however, since their thermal control, power, and communications systems would generally prove inadequate for more distant operations.

For exploration of the small bodies and the outer planets, the most efficient approach is to develop a modular spacecraft free of unnecessary complexity and designed for maximum inheritance and ease of reconfigurability. If the mass of this spacecraft (excluding fuel) can be held below 600 kilograms, a number of missions are possible that cannot be achieved with the larger Galileo-class vehicles. This new spacecraft, which would be similar in power, guidance, pointing, and communications capabilities to the Mariners and Voyagers, has been informally termed the Mariner Mark II. Its design, including the development of an integrated ground support system, is under way at Jet Propulsion Laboratory (*17*).

Additional efficiency for probe missions to the outer planets can be achieved by taking advantage of the highly capable Galileo entry probe. The Jovian entry problem will be the most demanding one; having solved it, we can use the same probe design for Saturn, Uranus, Neptune, and Titan. For these missions, the Mariner Mark II could serve as a probe carrier.

The use of derivatives of commercial Earth satellites for inner planet missions and of the Mariner Mark II for missions beyond Mars should lead to significant savings in both mission development and operations. Efficiency will be increased in both cases if the science objectives for each mission are carefully controlled and the frequency of launches is high. These approaches provide the key to carrying out planetary exploration within a constrained budget.

Proposed Missions for the Core Program

Consistent with its conviction that our understanding of the solar system is best served by a balanced exploration program, the committee recommends missions in all three major areas: inner planets, small bodies, and outer planets. For the core program discussed here, only modestly priced missions that do not require new enabling technology are proposed (see Table 2).

Inner planets. A principal scientific objective of inner solar system exploration is to understand the nature and evolution of the interiors, surfaces, and atmospheres of Earth, Venus, and Mars. It has been apparent for some time that the single largest gap in our data base for these planets is our ignorance of the geology of Venus. While the Pioneer Venus Orbiter was able to produce a global altimetry map with a maximum horizontal resolution of 50 to 75 km (*18*), there is virtually no information on the surface topography on scales that might reveal most geological processes and history. The SSEC assigns its highest mission priority to a Venus Radar Mapper (VRM), which will provide a global reconnaissance of the surface equivalent to that carried out by cameras on the first Mars orbiter, Mariner 9 (*19*). The objectives of this mission are to (i) obtain a near-global map by using synthetic aperture radar with subkilometer resolution, (ii) provide global and local topographic

Table 2. Missions in the SSEC core program. These are not listed in order of priority, except as noted in the text.

Inner planets	Small bodies	Outer planets
Venus Radar Mapper	Comet Rendezvous	Titan Probe/Radar Mapper
Mars Geoscience/Climatology Orbiter	Comet Atomized Sample Return	Saturn Orbiter
Mars Aeronomy Orbiter	Main Belt Multiasteroid Orbiter/Flyby	Saturn Probe
Mars Surface Probe	Near-Earth Asteroid Rendezvous	Uranus Probe
Lunar Geoscience Orbiter		
Venus Atmospheric Probe		

information with a radar altimeter, and (iii) extend the global gravity field measurements obtained by Pioneer Venus. This mission is proposed for launch in 1988 and will complete its primary phase after 243 days in Venus orbit (*20*).

The VRM mission has been derived from studies of a more complicated, twice as expensive mission, the Venus Orbiting Imaging Radar (VOIR) (*21*). As presently conceived, it capitalizes on a number of the cost-saving measures, including (i) limited science objectives (focused on radar mapping, to the exclusion of various atmospheric studies planned for VOIR), (ii) high hardware inheritance (for instance, use of a spare Voyager antenna for both the radar mapper and Earth communications), and (iii) use of new technology to reduce costs (advances in synthetic aperture radar allow imaging from an elliptical orbit, providing major cost and weight savings relative to the low circular orbit planned for VOIR).

The highest priority scientific objectives for Mars require the return of a surface sample to Earth and therefore lie outside the boundaries of the core program. However, many objectives that are basic to understanding Mars are attainable within the SSEC guidelines. These include studies of surface composition and mineralogy, of the distribution and atmospheric transport of volatiles, of global atmospheric dynamics, and of the structure and photochemistry of the upper atmosphere. All these investigations, which would produce major advances over the limited measurements made by the two Viking orbiters, can be carried out with relatively simple spacecraft derived from commercial Earth satellites.

The SSEC recommends early initiation of a Mars orbiter, emphasizing investigation of the geology and climate of the planet. The Mars Geoscience/Climatology Orbiter, the first of the new class of low-cost inner planet missions, should be launched in 1990 into a 300-km polar orbit, where it would operate for one Mars year. Its objectives are to obtain global maps of elemental and mineralogical surface composition and of the planet's figure and surface topography, to deduce the nature of the magnetic field (if any), to measure the seasonal cycles of carbon dioxide, water, and dust, and to study the interactions between volatile reservoirs (such as the polar caps) and the atmosphere. High-resolution imaging is not a part of this mission. The Viking orbiters have already given us excellent maps of Mars, and our greatest scientific need now is for quantitative data of the type discussed for this mission.

If humans are to consider the establishment of a permanent and self-sufficient presence in space, we must learn more about our nearest neighbors, the moon and the near-Earth asteroids. The same spacecraft and instruments used to map the figure, surface topography, and composition of Mars can also be used to carry out similar studies of the moon from polar orbit (*22*). The SSEC recommends that a Lunar Geoscience Orbiter be included as a follow-up to the Mars orbiter to realize the maximum savings from hardware inheritance and joint mission operations. A similar early opportunity exists to send a geochemical spacecraft, supplemented by imaging cameras, to rendezvous with an Earth-approaching asteroid and initiate our exploration of this new class of objects (*23*).

Other inner planet missions in the SSEC core program are a Venus Atmospheric Probe, a Mars Aeronomy Orbiter, and Mars hard landers or penetrators. These are all missions to be initiated in the 1990's, and it is hoped that one or more of them might be carried out by other nations, either independently or in collaboration with NASA.

Small bodies. Comets and asteroids compensate for their diminutive size by their large numbers and by the extraordinary interest they hold as chemically primitive objects, little modified since their presumed formation 4.6×10^9 years ago. The diverse populations of comets and asteroids have been much studied by telescope in recent years (*24*), but no mission has been launched to any of these objects, in spite of studies and recommendations that go back to the early days of NASA (*25*). To maintain a balanced perspective on the planetary system and particularly to probe the conditions of its birth and early evolution, the SSEC concurs with COMPLEX and other advisory bodies in recommending early initiation of missions to comets and asteroids.

An essential element of comets and asteroids is their diversity. No one object holds the key to either class. However, there is sufficient information about the characteristics of the major classes of comets and asteroids to permit an intelligent selection of targets, while the Shuttle/Centaur has the capability to launch spacecraft that can visit more than one target in a single mission. Thus we are technologically and scientifically poised to begin the direct exploration of these smaller worlds.

Following the fast flybys of Comet Halley in 1986, the next step in cometary exploration should be a rendezvous mission with a short-period comet. The spacecraft would match orbit with its target many weeks before perihelion and follow it through its activity cycle as it is heated by sunlight and then recedes again into deep space. Among the accessible short-period comets, three suitable targets have been identified: Encke, Tempel 2, and Honda-Mrkos-Pajdusakova (HMP). Each has a period of less than ten years, and each has suitable apparitions during the late 1980's and the 1990's (*26*). The spacecraft would carry cameras and other remote sensing instruments (similar to those on Voyager or Galileo) in addition to direct sensing instruments to study the gas and dust in the cometary atmosphere. Comet HMP presents one of the first opportunities for a rendezvous, with a 1990 launch, 1994 arrival, and 1995 perihelion. En route to its primary target, the spacecraft would fly by a main-belt asteroid, initiating a study of this class of objects. A comet rendezvous is the first Mariner Mark II mission in the core program.

Complementing a rendezvous is the acquisition and return to Earth of a sample of cometary material. It is usually assumed that sample returns can be attempted only after a sequence of reconnaissance and exploration missions. For comets, however, a novel kind of sample return can be carried out even within the restrictions of the SSEC core program. A simple fast-flyby spacecraft can acquire an atomized sample return of dust particles that are vaporized by impact on a foil diaphragm and recondense on the walls of a collection cell, which is returned to Earth for laboratory analysis.

In this way, a detailed analysis of the elemental and isotopic composition of the nonvolatile component of cometary dust can be carried out. For Comet HMP, a 1994 launch would yield an encounter in 1995 and a return to Earth in 1996 (*27*).

For initial exploration of the asteroids, the SSEC recommends a Main Belt Multiasteroid Orbiter/Flyby Mission. A combination of flybys and orbiters is required to achieve the necessary depth and breadth, but these functions can be combined in a single Mariner Mark II spacecraft with Shuttle/Centaur launch (*28*). The objectives are Voyager-class imaging and remote sensing studies of several asteroids en route to (or following) a 60- to 90-day orbit of the primary target. During orbit, more detailed elemental and mineralogical analysis of the asteroid surface can be carried out. One mission studied for a 1992 launch would have as its primary target asteroid 4 Vesta, one of the largest and most interesting main-belt objects (*29*), with additional flybys of 313 Chaldaea and 101 Helena, two objects of differing compositional type with diameters of 120 and 70 km. In general, opportunities for good main-belt asteroid missions recur at two-year intervals throughout the 1990's.

Outer planets. In the giant outer planets and their systems of rings and satellites are found more than 99 percent of the planetary system's mass, 45 of the 48 known satellites, the only ring systems, and (in the case of Jupiter and Saturn) magnetospheres that are vastly larger and more complex than those associated with the inner planets. During the rest of this decade, Voyager 2 will continue its mission to Uranus and Neptune, while Galileo will provide a much more detailed investigation of the Jupiter system. The next step, beyond Voyager and Galileo, will be the in-depth exploration of the Saturn system, especially its largest satellite, Titan.

The SSEC's first priority mission to the outer solar system is a Titan Probe/Radar Mapper, ideally to be carried out in conjunction with a Saturn Orbiter. Titan is unique, having an evolved reducing atmosphere that contains more nitrogen than our own, in addition to methane, carbon monoxide, and more complex organic compounds. The surface of Titan is cold enough for methane to condense, possibly forming pools or oceans. A Titan probe could be a modification of the Galileo Jupiter probe, with an instrumented package to sound and sample the atmosphere as it descends by parachute to the surface. At the same time, radar on the probe carrier could provide an image of part of the cloud-shrouded surface at a resolution of a few kilometers.

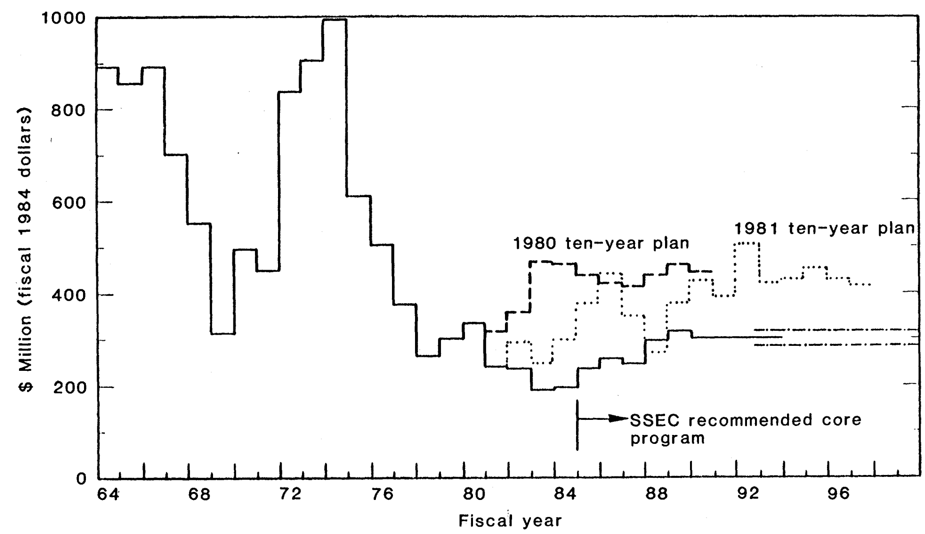

Fig. 1. History of planetary exploration funding: annual budgets of NASA's Planetary Division since FY 1964, expressed in constant value (FY 1984) dollars. Three future projections are shown: the NASA ten-year plan of 1980, the NASA ten-year plan of 1981, and the SSEC core program of 1983. Note that the annual expenditures in the SSEC core program are one-third the high levels of funding of the middle 1960's and 1970's.

If the Titan probe carrier is a full-scale Saturn Orbiter, a mission analogous to Galileo could be carried out in the Saturn system, with detailed study of the atmosphere, magnetosphere, satellites, and rings. Launches can be accomplished every 13 months, with a flight time of six to eight years (*30*). A combined Titan Probe and Saturn Orbiter has been considered an excellent candidate for international cooperation.

The other outer planet missions in the SSEC core program are atmospheric probes based on the Galileo probe design. The objective of these missions is the direct comparative study of the atmospheres of Saturn, Uranus, and Neptune with instruments similar to those being sent to Jupiter. The probe carriers could be instrumented for flyby remote sensing more advanced than that of Voyager; such a capability would also provide a backup in case Voyager 2 fails before it completes the initial reconnaissance of the outer two giant planets (*31*).

Mission summary. The recommended core program includes 14 missions, to be launched between 1988 and 2000. The first four missions in this sequence have been analyzed in some detail and can be firmly recommended at this time. These are (i) the Venus Radar Mapper (1988 launch), (ii) the Mars Geoscience/Climatology Orbiter (1990 launch), (iii) the Comet Rendezvous with Asteroid Flyby (1990 launch), and (iv) the Titan Probe/Radar Mapper. The Titan mission would probably be launched in the early 1990's, but international cooperation could result in an earlier mission, perhaps in conjunction with a Saturn Orbiter.

The sequence of other missions in the core program will be determined by programmatic issues that cannot be foreseen at this time. Major considerations in their execution should include the need to maintain scientific balance and the desire to realize maximum efficiencies in cost and utilization of manpower. These additional missions are, in no order of priority: Mars Aeronomy Orbiter, Venus Atmospheric Probe, Lunar Geoscience Orbiter, Mars Surface Probe, Near-Earth Asteroid Rendezvous, Main-Belt Multiasteroid Orbiter/Flyby, Comet Atomized Sample Return, Saturn Probe, Uranus Probe, and Saturn Orbiter. The SSEC recommends that all of these moderate-cost missions be undertaken between now and the year 2000, by the United States alone or in collaboration with other nations (*32*).

Costs of the Core Missions

In developing the core mission program, the SSEC considered it unrealistic to anticipate a return to planetary budgets of $500 million or more a year. On the other hand, it recognized that if the launch rate of planetary missions becomes too low, then economies resulting from inheritance and common operation systems will evaporate.

The missions in the core program that follow the Venus Radar Mapper fall very roughly into two cost categories: the inner planet missions based on derivatives of Earth-orbital spacecraft, which are estimated to cost on the order of $100 million to $150 million, and the Mariner Mark II missions, which approach $250 million to $300 million in recurring costs (*33*). To sustain momentum in either program a launch about every two years is required. This is also the launch rate required to carry out most of the recommended core missions between 1988 and 2000. We therefore estimate an annual cost for flight programs, exclusive of mission operations or data analysis, of about $150 million to $200 million.

Two other essential elements of the planetary budget, in addition to flight missions, are funds for basic research (including analysis of data from past missions and planning for future flights) and for mission operations. The minimum for data analysis and research is about $100 million per year, while mission operations can, with implementation of a common operating system and use of new technology to reduce costs, be held to about half this value. Both of these items must be added to the cost of flight missions in establishing the base cost of planetary exploration.

The SSEC core program requires a sustained annual funding level of $300 million to $350 million in current (FY 1984) dollars. This level, which is about one-third of the high level of a decade ago, is sufficient to support a vigorous program of individually modest missions, and it promises to return a great deal of high-quality scientific data in a cost-effective manner.

Management Implications

The proposed core mission program represents a new approach to NASA's planetary program, and its success will depend on certain modifications of current practice. Primarily these reflect the interrelations among the proposed missions. Much of the efficiency of the approach can be realized only if the individual missions are closely spaced and planned to make maximum use of human and material resources, including the unique capabilities of the NASA centers. If treated as episodic, isolated events, these missions are unlikely to be accomplished in a cost-effective manner. Therefore, the recommended SSEC core program assumes a long-term commitment to planetary exploration with reasonably constant funding levels.

For these goals to be accomplished, the core program should be judged in terms of overall effectiveness and managed for maximum return from the entire program, not from each mission individually. The SSEC strongly urges that the inner planet missions in particular be treated as a continuing series, modeled after the highly successful Explorer program in the NASA Astrophysics Division (*34*). We endorse the concept of a similar Planetary Observer effort, funded as a level-of-effort program at about $60 million per year (in FY 1984 dollars), out of which the proposed inner planet missions would be supported. (These funds include about $10 million per year to be used for support of U.S. investigators on international planetary missions.) We urge that a similar management approach be taken for the Mariner Mark II missions, although we recognize that the magnitude of these missions makes it likely that each will require scrutiny as an individual "new start" when full-scale development begins (*35*). We recommend the rapid development of a common mission operations system in the planetary area, to be used for both Observer and Mariner Mark II missions.

Missions Beyond the Core Program

Many important scientific goals are excluded from the core program on the basis of cost and technological challenge. These include the return of samples from Mars, the exploration of the martian surface with mobile landers, the return to Earth of pristine fragments from a comet, and the operation of a buoyant station in the atmosphere of Titan. Such missions would provide scientific data fundamental for understanding the origin and evolution of the solar system, and they could generate the kind of public enthusiasm and international acclaim associated with Apollo, Viking, and Voyager. In addition, meeting such challenges would contribute to the strength of high technology in the United States. Challenging larger missions should be accepted (*36*). However, our first priority is to restore and maintain the health of planetary exploration in this nation, and we believe the core program approach advocated by the SSEC contributes to this goal.

References and Notes

1. M. M. Waldrop, *Science* **217**, 1012 (1982).
2. The NASA planetary budget reached record lows of $210.0 million in fiscal year (FY) 1982 and $186.4 million in FY 1983. For comparison, the funds appropriated in peak years FY 1973 and FY 1974 (when the Viking and Voyager missions were under full-scale development) were each over $900 million in FY 1984 dollars.
3. The last opportunity for a U.S. mission to Halley passed in FY 1982. However, fast-flyby spacecraft are being sent to the comet by the U.S.S.R. (Vega), the European Space Agency (Giotto), and Japan (Planet B).
4. The membership in the SSEC is: A. Albee, Caltech–Jet Propulsion Laboratory (JPL); K. Anderson, University of California, Berkeley; J. Arnold, University of California, San Diego; C. Barth, University of Colorado; G. Briggs, NASA headquarters; T. Donahue, University of Michigan; M. Duke, NASA/Johnson Space Flight Center; L. Fisk, University of New Hampshire; L. Haskin, Washington University; N. Hinners, NASA/Goddard Space Flight Center; D. Hunten, University of Arizona; H. Klein, NASA/Ames Research Center; E. Levy, University of Arizona; J. Martin, Martin Marietta Corp.; H. Masursky, U.S. Geological Survey; D. Morrison, University of Hawaii; J. Naugle, Fairchild Space and Electronics Corp.; J. Niehoff, Science Applications, Inc.; T. Owen, State University of New York Stony Brook; D. Rea, Caltech–JPL; L. Soderblom, U.S. Geological Survey; E. Stone, Caltech; J. Veverka, Cornell University; and L. Wilkening, University of Arizona. An additional 40 planetary scientists participated in the preparation of the SSEC report through service in five topical working groups or through supporting studies carried out at NASA centers.
5. A detailed report on the SSEC core program [*Planetary Exploration Through Year 2000: A Core Mission Program* (NASA, Washington, D.C., in press)] should be available by 1 June.
6. The number of workers in this field is estimated from such data as the 1983 membership in the Division for Planetary Science of the American Astronomical Society (450), 1981 membership in the Planetology Division of the American Geophysical Union (694), attendance at the 1982 NASA Lunar and Planetary Science Conference (557), and number of principal investigators in the NASA planetary research grants programs (422).
7. As a result of its assessment of the rationale for planetary exploration, the SSEC recommends the addition of the following fourth objective: "to provide a scientific basis for the future utilization of resources available in near-Earth space." The committee rejected recommending a narrower overall focus for the program, such as concentration on missions leading to manned exploration of Mars, since it believes the primary aim should continue to be broad scientific exploration of the planetary system.
8. For example, data on the concentrations of isotopes of the noble gases in the atmospheres of Venus, Earth, and Mars, which are critical for understanding the origin and early evolution of the terrestrial planets, were not obtained until 1976 for Mars and 1979 for Venus—11 and 17 years, respectively, after initial flybys of these planets. See, for example, T. Donahue and J. B. Pollack, in *Venus*, D. M. Hunten and L. Colin, Eds. (Univ. of Arizona Press, Tucson, 1983), pp. 1003–1031; L. M. Mukkin, in *ibid.*, pp. 1037–1045.
9. Mariner 10 photographed half the surface of Mercury during its flybys in 1973 and 1974. The surface of Venus, hidden beneath thick clouds, has been probed by ground-based and Pioneer Venus radar, but their best resolution of ~ 50 km is insufficient to reveal any but the grossest topographic features.
10. Voyager 2 is on a trajectory that will yield a flyby of Uranus in 1986 and of Neptune in 1989; the spacecraft was not designed for operation beyond the 1981 Saturn encounter, so the anticipated results from the Uranus and Neptune flybys remain uncertain.
11. H. E. Newell, "Beyond the atmosphere," *NASA Spec. Publ. SP-4211* (1980).
12. *Report on Space Science 1975*; *Strategy for Exploration of the Inner Planets: 1977–1987*; and *Strategy for Exploration of Primitive Solar System Bodies—Asteroids, Comets, and Meteorites: 1980–1990*; the three reports were published by the National Academy of Sciences, Washington, D.C.
13. In fact, costs of planetary missions in recent years have increased only modestly relative to inflation. Much of the high cost for Galileo has resulted from repeated delays and reconfigurations imposed by the Shuttle and its upper stages; in their absence, Galileo would have cost less than Voyager. However, it is clear that the absolute cost of missions is of great concern, and there has been little emphasis on applying new technology to reduce cost rather than enhance spacecraft capabilities.
14. Inevitably, this constraint eliminates from the core program a number of missions that address high-priority science goals identified by the Space Science Board. Examples are Mars sample return missions and the exploration of the martian surface by mobile laboratories.

15. Modification of the Centaur to carry out planetary missions with the Shuttle is under way, with the first launches scheduled for Galileo and the International Solar Polar Mission in 1986. Many missions in the core program could also be carried out with the solid-fuel Inertial Upper Stage, but with less margin and consequently greater risk of unanticipated costs.
16. Examples of such spacecraft with a potential planetary application are the Hughes Aircraft Co. HS-376, the TRW (Navy) Fleet Communications Satellite (FLTSATCOM), and the RCA Defense Meteorological Satellite Program (DMSP). The SSEC believes that appropriate derivatives of these spacecraft could be acquired for under $90 million (in FY 1984 dollars, and exclusive of scientific instruments and mission operations costs).
17. M. Neugebauer, *Science* **219**, 443 (1983).
18. H. Masursky *et al.*, *J. Geophys. Res.* **85**, 8232 (1980); G. E. McGill *et al.*, in *Venus*, D. Hunten and L. Colin, Eds. (Univ. of Arizona Press, Tucson, 1983), pp. 69–130.
19. Mariner 9 discovered the giant volcanoes, ancient water channels, aeolian deposits, layered polar caps, and other terrain types that reveal the varied climatic and geological history of Mars. Subsequent Viking orbiter photography increased the imaging resolution for much of the planet to $\sim$ 100 m.
20. Development funds of $29 million are included in the Administration's FY 1984 budget request. If approved, VRM will be the first planetary new start since Galileo in FY 1978.
21. The VOIR mission was proposed as an FY 1982 new start in the Carter Administration budget but was dropped from the revised FY 1982 budget of the Reagan Administration.
22. Geochemical mapping of the moon by x-ray and gamma-ray spectrometry was carried out from lunar orbit during the Apollo program but never extended beyond the equatorial regions. Improved instruments in polar orbit would generate the global perspective needed for proper interpretation of the Apollo lunar samples and could also search for postulated reservoirs of frozen water in permanently shaded regions near the poles.
23. The Earth-approachers are small asteroids in relatively unstable orbits (lifetimes $\sim 10^8$ years) that approach or intersect that of Earth. They may be derived from the main asteroid belt or they may represent extinct comet nuclei, or probably both. Their small sizes, unstable orbits, and unknown provenance argue for consideration separate from the larger asteroids in stable orbits between Mars and Jupiter.
24. T. Gehrels, Ed., *Asteroids* (Univ. of Arizona Press, Tucson, 1979); L. Wilkening, Ed., *Comets* (Univ. of Arizona Press, Tucson, 1982).
25. D. L. Roberts, Ed., *Proceedings of the Cometary Science Working Group—Yerkes Observatory (June 1971)* (ITT Research Institute, Chicago, 1971); M. Neugebauer *et al.*, Eds., "Space missions to comets," *NASA CP-2089* (1977); M. Belton, Ed., "A first comet mission," *NASA Tech. Memo. TM-78420* (1977).
26. Encke is the most difficult of the three comets from an engineering point of view because its orbit takes it closer to the sun than Mercury. Tempel 2 has suitable apparitions in 1993 and 1999, and HMP in 1995. Other possible targets include Kopff (1996) and Wild 2 (1997).
27. Atomized (or plasmatized) sample return was first proposed for Comet Halley in 1981. Laboratory simulations suggest that major elemental and isotopic abundances can be measured with sufficient precision to distinguish among major meteorite types and even to yield an Rb-Sr model age.
28. A number of attractive missions would use a Mars-powered flyby for extra propulsive capability [C.-W. Yen, *AIAA Paper 82-1463* (1982)]. These are primarily combinations of a single orbit target with multiple flybys, but in a few cases the spacecraft could orbit two different main-belt asteroids. If a low-thrust ion propulsion system were available, many more such multiorbiter missions would be possible.
29. Vesta, with a diameter of 550 km, has a unique basaltic surface indicative of a complex and dynamic thermal history. Many meteoriticists consider it the parent body of the eucrite group of meteorites [see M. J. Drake, in *Asteroids*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1979), pp. 765–782].
30. To reach Saturn, a Shuttle/Centaur–launched orbiter spacecraft requires a so-called delta-Vega trajectory with gravity assist from an Earth flyby about a year after launch. In contrast, with a direct flyby trajectory it would take only 3.5 years to reach Saturn.
31. Ideal times to launch spacecraft recur at roughly 13-year intervals, when Jupiter is in position to provide a gravity assist. Voyager took advantage of this planetary alignment in 1977. The next opportunity will be in 1992—unfortunately, too early in the sequence of core missions to be utilized. Uranus can still be reached during the 1990's without a Jupiter boost, but we have had to drop Neptune from the targets in the core program.
32. We anticipate that some of the missions in the core program will be carried out by other nations, perhaps jointly with NASA. For example, of the missions under consideration by the ESA, Kepler is similar to our Mars Aeronomy Orbiter and Agora to our Main Belt Asteroid Multiple Orbiter/Flyby, while the U.S.S.R. Venera program could accomplish the objectives of the Venus Atmospheric Probe.
33. Following usual NASA practice, estimated costs, in FY 1984 dollars, exclude the cost of launch vehicles and of the Deep Space Tracking Network. Mission operations and data analysis are also budgeted separately.
34. NASA's Explorers have recently been supported at a level of about $35 million per year, and it is proposed that this be increased to $50 million beginning in FY 1984. Recent examples of Explorers are the UHURU X-ray Observatory, the International Ultraviolet Observatory (IUE), the Dynamic Explorers (DE's), the Solar Mesosphere Explorer (SME), and the Infrared Astronomy Satellite (IRAS).
35. A similar argument for continuity of funding throughout the space science program has recently been made by the Congressional Office of Technology Assessment ("Space science research in the United States," OTA Technical Memorandum, September 1982).
36. During 1983, the SSEC is undertaking a study of larger missions that might be included in an augmented planetary program.
37. The activities of the SSEC are supported by the NASA Advisory Council and the Earth and Planetary Exploration Division of NASA headquarters. We thank the members of the SSEC and its working groups, the supporting staffs at Jet Propulsion Laboratory and Ames Research Center, and especially G. Briggs, executive director of the SSEC, for their invaluable contributions to this effort.