

Solar System EXPLORATION



This is the
Solar System
Exploration
Roadmap
for NASA's
Office of
Space Science

2003



Our Solar System *the grand laboratory for*



u n d e r s t a n d i n g o u r o r i g i n s a n d e v o l u t i o n

Our solar system is a place of beauty and mystery, incredible diversity, extreme environments, and continuous change. Our solar system is also a natural laboratory, on a grand scale, within which we seek to unravel the mysteries of the universe and our place within it.

Forty Years *of Solar System Exploration*

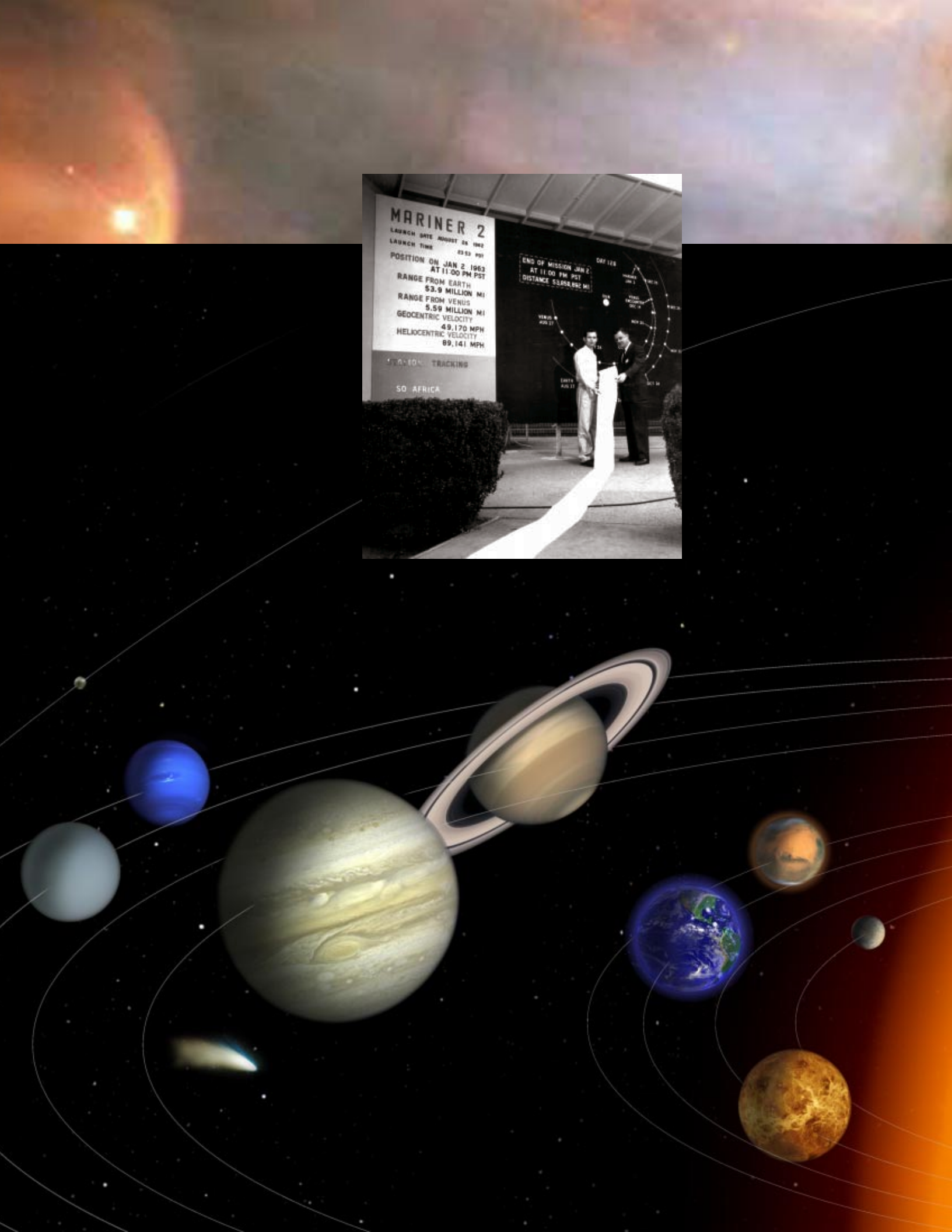
IN THE FORTY YEARS SINCE THE LAUNCH OF MARINER 2, THE FIRST INTERPLANETARY PROBE, OUR KNOWLEDGE OF THE SOLAR SYSTEM AND OUR ABILITY TO EXPLORE IT HAVE INCREASED AT AN ASTONISHING PACE. WE BEGAN WITH SMALL STEPS AND MODEST GOALS, ATTEMPTING TO DO WHAT HAD NEVER BEEN DONE BEFORE.

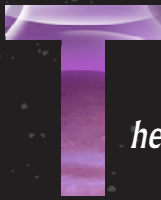
TODAY OUR ROBOTIC EXPLORERS HAVE TRAVELED THROUGHOUT THE SOLAR SYSTEM, REVEALING LEVELS OF COMPLEXITY AND DIVERSITY THAT WERE UNIMAGINABLE PRIOR TO THE ADVENT OF SPACE EXPLORATION.

MARINER 2 (1962)

*OUR FIRST STEP INTO
OUR PLANETARY NEIGHBORHOOD*







T

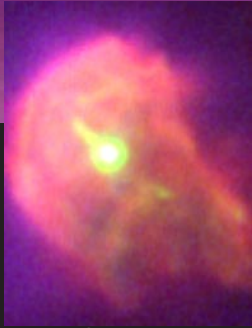
he exploration of our solar system is founded upon the pursuit of three simple yet profound questions:

Where do we come from?

Where are we going?

Are we alone?

Contents



With broad input from the planetary science community, NASA's Solar System Exploration Division and Mars Exploration Program Office have developed this roadmap to describe the foundation, the scientific goals, and the strategy for the coming years of exploration and discovery.

ABOUT THE ROADMAP

2

SUMMARY OF KEY ELEMENTS

4

C H A P T E R 1

SCIENCE OBJECTIVES

6

C H A P T E R 2

MISSION ROADMAP

28

C H A P T E R 3

TECHNOLOGY

42

C H A P T E R 4

RESEARCH AND ANALYSIS

54

C H A P T E R 5

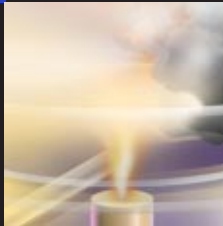
EDUCATION AND PUBLIC OUTREACH

60

APPENDIX — ROADMAP FRAMEWORK

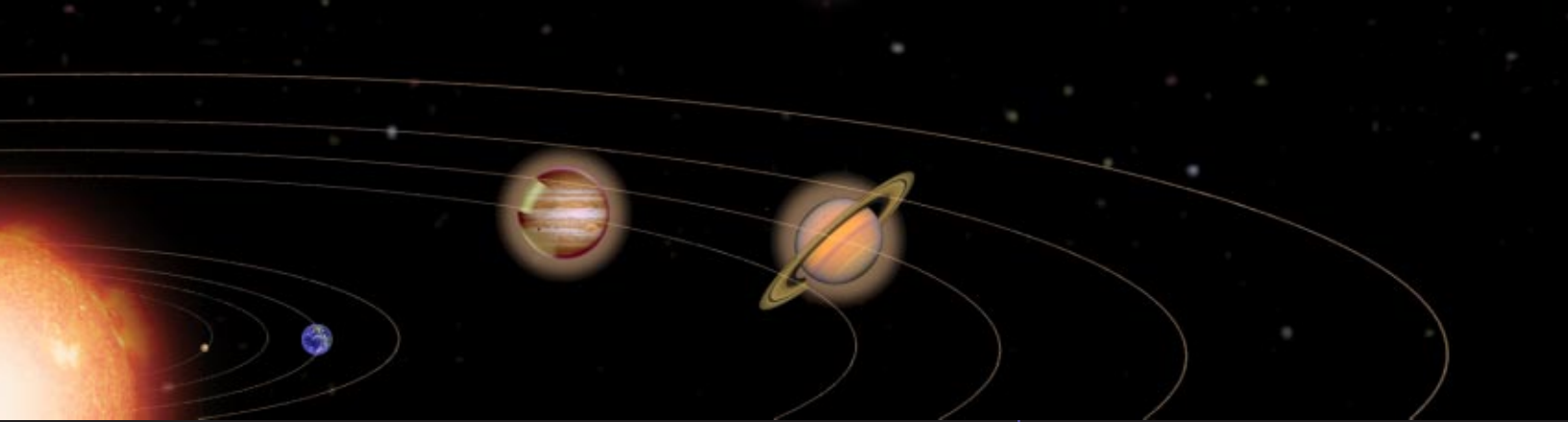
64

About **The Roadmap**



This roadmap draws its intellectual foundation from the recently released draft report “New Frontiers in the Solar System: An Integrated Exploration Strategy,” prepared by the National Research Council at NASA’s request. It also draws on the deliberations and conclusions of the Solar System Exploration Subcommittee, the Mars Exploration Program Assessment Group, and the Astrobiology Working Group.

The eight science objectives outlined in this roadmap represent the most important directions for the exploration of our solar system in the coming decades. They will guide the activities of Solar System Exploration and Mars Exploration — two of NASA’s strategic themes — in fulfillment of NASA’s goals. They also provide the context through which we formulate our specific research objectives and define the science investigations and missions that address them.



The roadmap provides a scientific framework for solar system exploration, with emphasis on the near-term (2003–2008) and mid-term (2009–2013). Our *Science Objectives* and the *Research Focus Areas* and *Investigations* that flow from them are discussed in Chapter 1, and their relationships are summarized in tabular form in the Appendix. The *Missions* that respond to this science strategy are described in Chapter 2, and the key *Technologies* that enable the mission set are summarized in Chapter 3. Chapter 4 describes the science *Research and Analysis* programs through which we analyze data and plan for the future, as well as important elements of infrastructure. Chapter 5 articulates our unique approach to *Education and Public Outreach*, through which we share the wonders of our solar system and the excitement of exploration with the nation’s youth, the American public, and all the people of planet Earth.

The eight science objectives outlined in this roadmap represent the most important directions for the exploration of our solar system in the coming decades.

Summary of Key Elements



- A balanced set of small, medium, and flagship missions is required in order to meet the wide variety of scientific and technical challenges.
- A diversity of vantage points — flyby, orbital, aerial, surface, and returned sample — provides the optimum scientific value for the overall program.
- Education and public outreach is one of the primary responsibilities and major focal points of the Solar System Exploration and Mars Exploration Programs. Every mission will be fully exploited as an opportunity to engage the public and to inspire and educate the nation's youth.
- The Discovery Program and the Mars Scout family of competed small missions allow focused investigations and rapid response to new discoveries, and will be vigorously pursued.
- The New Frontiers Program of competed medium missions represents a critical step in the advancement of solar system exploration. The first New Frontiers mission is New Horizons, which will conduct the first reconnaissance of the Pluto–Charon system and the Kuiper Belt. Subsequent New Frontiers missions should address lunar deep composition and chemistry, Jupiter structure and deep atmospheric composition, Venus in situ exploration, and comet surface sample analysis.
- NASA will pursue the initiation of important new flagship missions at the appropriate times. The top-priority flagship mission objective is the study of possible subsurface oceans on Europa and other Galilean satellites. Other high-priority flagship mission objectives have been identified and will be selected for flight based on scientific discoveries and technological progress.

- Advanced power and propulsion systems can revolutionize solar system exploration and enable fundamentally new types of science. NASA is studying a Jupiter Icy Moons Orbiter as the potential first use of fission power and propulsion technology. Such a mission would represent a major step in our understanding of habitable environments and life in the solar system.
- NASA is developing optical communications technology to dramatically increase the scientific return from our missions. The first application will be on the Mars Telesat in 2009.
- The Mars exploration strategy recommended by the Mars Exploration Program Assessment Group will be pursued, with mid- and far-term missions to be defined on the basis of discoveries made by preceding missions.
- Technology developments that enable and enhance upcoming missions, and that provide new capabilities of broad benefit, will be aggressively pursued.
- Basic scientific research and analysis will continue to be funded at significant levels. These investments support the analysis of mission data, help to frame scientific goals and mission scenarios for the future, and establish a training ground for the next generation of planetary explorers.
- Investments will be made in facilities and infrastructure, including the Deep Space Network, laboratory equipment, the Planetary Data System, and new equipment for safe handling, curation, and analysis of returned samples.



Our key programmatic

tenets — science-driven, broad

engagement, peer-reviewed

competition, and a broad systems

approach to technology invest-

ments — will continue to guide

our exploration of the solar system.



Science Objectives

Today's Solar System Exploration Program is the product of forty years of intensive research, engineering ingenuity, and scientific insight. It reflects a maturity and focus that stems from many successful investigations, as well as a sense of excitement and mystery that is born out of many humbling surprises. Our science objectives are founded on the fundamental human drive to understand our beginnings, our place in the cosmos, and the evolution and destiny of our home and ourselves. Taken together they tell a story, written in the language of the planets, of how our solar system formed and developed and how life arose within it.



This section describes the eight Objectives that form the core of our exploration strategy. Each Objective is addressed by several Research Focus Areas, which represent key areas of scientific emphasis. Identified within each of these research areas are Investigations, shown in italics, that indicate the specific scientific advances to be pursued in the near- and mid-term. Farther-term activities that may represent important follow-on activities are also identified where possible. The Investigations form the framework for identification of specific Missions, described in Chapter 2. The Appendix shows the linkages among these elements and the end-to-end flow from Objectives through Research Focus Areas and Investigations to specific recommended Missions.

OBJECTIVE 1 Learn how the Sun's family of planets and minor bodies originated.

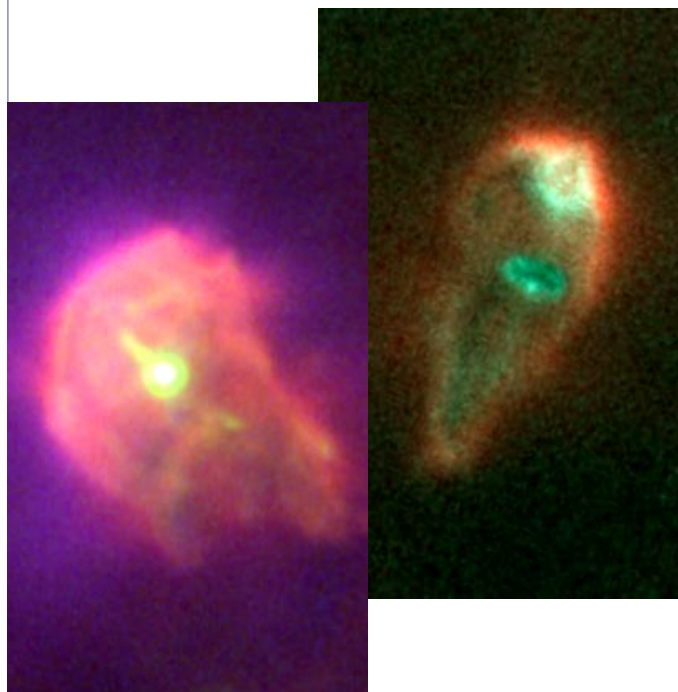
Our solar system began to take shape about 4.6 billion years ago, as the primordial solar nebula of dust and gas began to coalesce around the infant Sun. Within the first billion years or so, the planets formed and life began to emerge on Earth — and perhaps elsewhere. Many of the current characteristics of the solar system were determined during this critical formative epoch — but because of the tremendous changes that Earth and the planets have undergone over the intervening eons, most physical records have been erased and our understanding of this period is fragmentary at best. Fortunately, however, vital clues are scattered throughout the solar system — from the oldest rocks on the Moon and Mars to the frozen outer reaches of the Kuiper Belt. They allow us to look back in time, and to understand the physical setting within which the story of life's origins would unfold.

Understand the initial stages of planet and satellite formation.

The process of planet formation proceeds according to physical principles that are generally well understood. Less well known, however, are the ingredients and initial conditions that resulted in the solar system we know today. Beyond Neptune, the material that became the building blocks of the planets never accreted into major bodies, and it remains relatively unaltered even now. This region, known as the Kuiper Belt, is believed to represent the best available record of the original interstellar materials that formed the solar nebula. Pluto and its moon Charon are the largest known Kuiper objects and the only ones for which we have significant telescopic observations. This region is also the birthplace of the short-period comets, still smaller bodies that have been gravitationally dislodged from the Kuiper Belt. As the comets enter the inner solar system, they not only become visible from Earth but they also become accessible targets for intensive robotic exploration. *Determination of the chemical composition and physical characteristics of Pluto, other Kuiper objects, and short-period comets will give us unique insight into the materials and processes that dominated the initial stages of planet and satellite formation.*

Protoplanetary Disks

These disks appear to be a common feature of young stellar systems and reveal the earliest stages of planet formation. If conditions are right, the action of gravity will cause planets to coalesce from this material — and a new solar system is born.



Study the processes that determined the original characteristics of the bodies in the solar system.

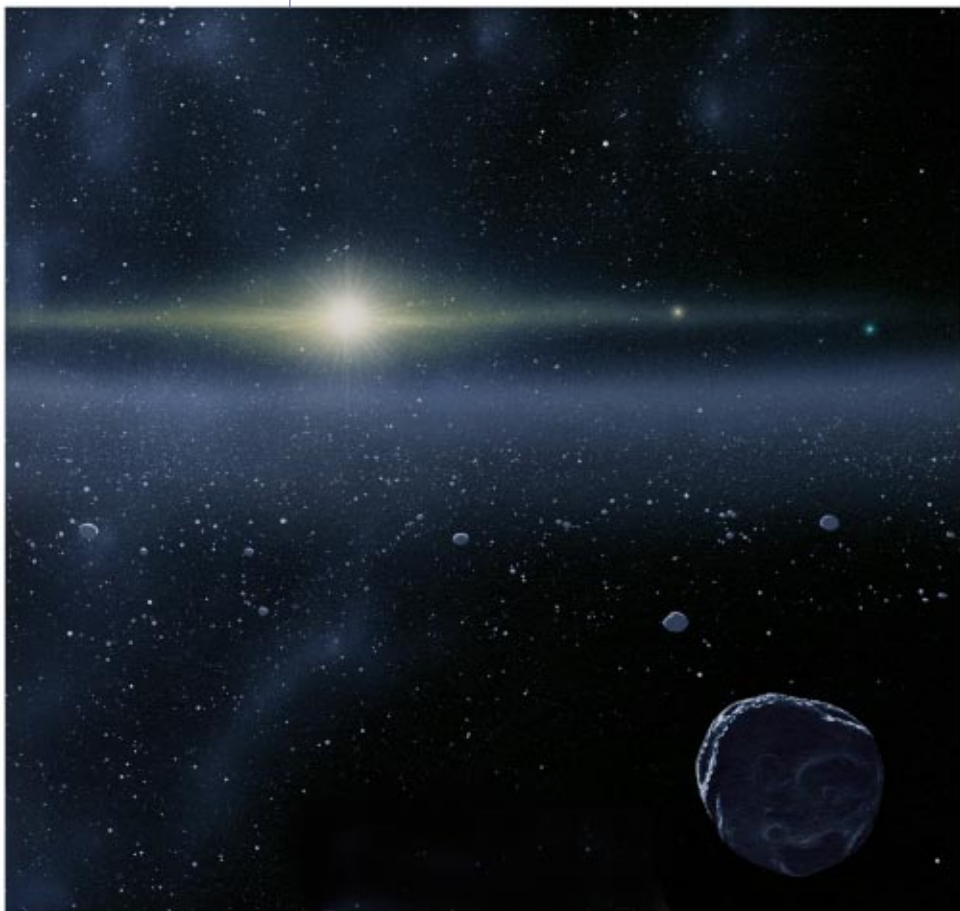
Of particular importance is the way that these formative processes, active during the first billion years or so, manifested themselves in the inner solar system. Unfortunately, the very early geological history of Earth has been nearly completely obliterated by the actions of tectonics, weathering, and biology; on our home planet the earliest rock records date back about 3.8 billion years but no further. The Moon, however, still retains some of the earliest records of the formation of the Earth–Moon system. Leading models suggest a very early origin of the Moon as a result of the collision of a Mars-sized body with the newly formed Earth. Samples from the Apollo and Luna programs elucidated some of this history, but the nature of these samples, limited to equatorial regions of the lunar near side, leaves many key questions unanswered. The Moon’s South Pole–Aitken Basin, one of the largest impact structures known within the solar system, exposes material from deep within the crust and possibly even the upper mantle that was excavated by the impact. In addition, the floor of this basin probably retains impact melt rocks created by the giant impact. Apollo experience shows that such melt rocks provide insight into the average composition of the basin, and that by dating such samples we can infer the age of the basin itself. This will help to resolve questions that are raised by the observed cratering record of the lunar highlands, with important implications for the early history of the Moon and all of the terrestrial planets, including Earth.

Analysis of ancient lunar material will thus provide critical insights into the processes that occurred on Earth and the other terrestrial planets during their early history.

The formation of the giant planets had a major effect on the events and processes at work in the early solar system. The gravita-

Kuiper Belt

Not all protoplanetary material is incorporated into newly formed planets; some remains as smaller icy bodies. The Kuiper Belt at the edge of our solar system is a reservoir of such ancient debris, and is also the source of comets that may have brought water and organics to the inner solar system.



tional influence of Jupiter in particular governed much of the dynamical behavior that in turn determined many key features of the inner planets. An understanding of the processes and timescale of Jupiter's formation is thus of central importance to our study of the early solar system. Informed and constrained by the recent Galileo mission's probe and orbiter investigations, today's models indicate that critical clues to giant planet formation can be found in the structure and masses of their rock–ice cores, and in the composition of their deep atmospheres and interiors. *Characterization of the gravitational and magnetic fields of Jupiter, and measurement of its deep atmospheric composition and water abundance*, will enable us to determine the processes and timing of Jupiter's formation. In the longer term, comprehensive exploration of the ice giant Neptune will permit direct comparison with Jupiter and more complete modeling of giant planet formation and its effects on the inner solar system.

O B J E C T I V E 2 Determine how the solar system evolved to its current diverse state.

We now know that the solar system is exceedingly dynamic. Virtually everywhere we look we find continual change — predictable or chaotic, physical or chemical, subtle or catastrophic. Only by observing solar system bodies under different conditions and from a variety of vantage points can we begin to understand the processes by which they evolved from their initial formative states to the wide diversity we see today. Planetary processes such as impacts, volcanism, tectonics, climate change, and greenhouse-gas warming are difficult to comprehend when their study is confined to just one body — Earth, for example — but by comparing how these processes operate and interact in a variety of planetary settings, we can gain insight into their variations and effects. As we move into the era of discovery and study of extrasolar planets, our efforts in our own neighborhood provide context for our observations of these newly found, distant solar systems.

Determine how the processes that shape planetary bodies operate and interact.

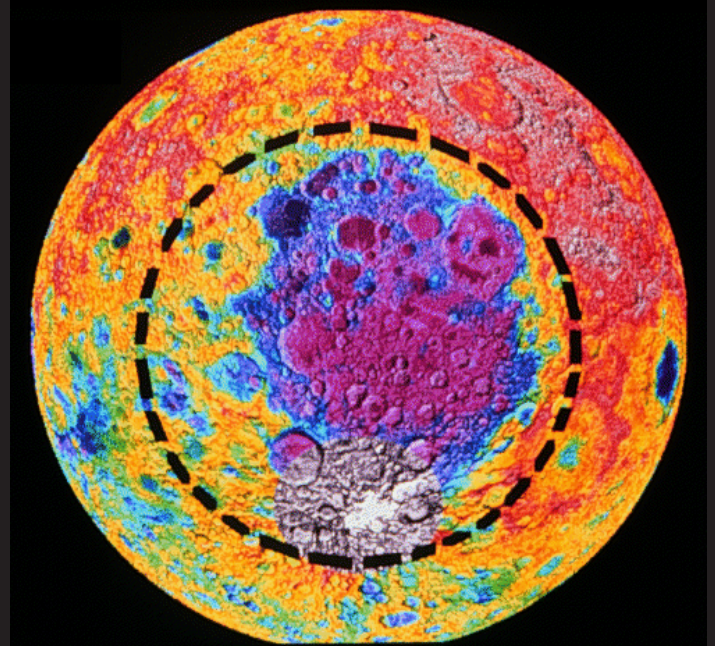
Four decades of exploration have shown us that the underlying physical, chemical, geological, and biological processes that shape the solar

Our science objectives tell
a story, written in the
language of the planets,
of how our solar system
formed and evolved and
how life arose within it.

Science Objectives

system interact in complex and surprising ways. Planetary interiors, surfaces, atmospheres, and magnetospheres are now known to be highly interdependent. Earth's magnetic field, for example, which is generated by processes within the planet's molten core, shields us from fatal high-energy radiation. Recent observations suggest that Mars may have had a similar protective magnetosphere early in its history. Io's eccentric orbit causes tidal flexing, which drives volcanoes that feed charged particles into Jupiter's magnetosphere, producing lethal radiation; by contrast, Europa's eccentric orbit and tidal flexing may keep an ocean from freezing, which may provide a habitable environment. Comprehending these interactions requires *multidisciplinary, comparative studies of planetary atmospheres, surfaces, interiors, and satellites*. This relies on a robust program of scientific research and analysis that allows the nation's best scientists to fully and creatively utilize the data returned by our spacecraft.

Impact processes clearly played a crucial role in bringing the solar system to its present state. The young solar system contained a significant amount of non-accreted material left over from the formation process. A collisional environment very different from today's probably dominated the period following planet formation, as the gravitational influence of the newly formed giant planets cleared out the surviving smaller debris from vast volumes of space. This solar system-wide rain of projectiles had a profound effect on all of the planets, delivering volatiles and organic material from the colder outer solar system to the inner planets while at the same time causing frequent, catastrophic impacts. This impact environment must have had a major effect on the emergence of life on Earth, perhaps delaying its expansion or "resetting" the evolutionary clock with periodic global extinctions. The geologic record of this period has long since vanished from Earth, but important links to this era still exist on the Moon and in the outer reaches of the solar system. While the record of cratering deduced from lunar samples shows a precipitous decline in the impact rate starting about



Clues to the Early Earth

The nature of the early Earth may be preserved only on the Moon. The South Pole–Aitken Basin, shown in this compositional map from the Clementine mission, is the largest impact structure in the solar system. Samples of the lunar interior, and thus of the young Earth from which the Moon formed, are believed to be accessible within this basin.

3.5 billion years ago, we have as yet no direct data relating to the flux in the preceding billion years. Thus a critical step is to *determine how the impactor flux varied in the early solar system*. Competing models have vastly different implications for the conditions under which life might have emerged on Earth. The study of material from the lunar South Pole–Aitken Basin will provide a vital reference point for constraining models of the early impact history, while comparative studies of the cratering records on Pluto, Charon, and other Kuiper objects will allow determination of the impact flux that emanated from that region.

Understand why the terrestrial planets are so different from one another.

The terrestrial planets formed at about the same time, in the same general region of space, and experienced similar forces and processes during their development. Yet today they are different in very fundamental ways, for a complex set of reasons that we are only beginning to understand. The atmospheres of Mars, Venus, and Earth reflect differences in initial volatile content and subsequent atmospheric evolution, with comparison of Mars and Venus providing particularly compelling evidence for completely different developmental pathways. The causes of such climate change are complex and their interactions not fully understood, but they are clearly of tremendous importance to our home planet. *Comprehensive, comparative studies of the atmospheric chemistry, dynamics, and surface–atmosphere interactions on both Mars and Venus* will allow us to better understand their evolutionary pathways and the implications for habitability, both within our solar system and in other solar systems. Of particular interest at Venus are the elemental, mineralogical, and geochemical nature of surface materials, combined with detailed investigation of noble and trace gases in the atmosphere.

Learn what our solar system can tell us about extrasolar planetary systems.

We now know that our solar system is one of many planetary systems in the galaxy. The characteristics of extrasolar planets are raising new questions about the history of our home solar system and how typical



The Search for Other Planetary Systems

The exploration of our solar system is proceeding in parallel with efforts to identify and explore planets around other stars. NASA's Office of Space Science is engaged in a long-term search for and study of extrasolar planetary systems. While today's technology is capable of detecting only Jupiter-size planets, new spaceborne techniques planned for the next decade should enable the detection of planets more akin to Earth. Once found, these planets will be studied spectroscopically to determine if their atmospheres bear any of the telltale signatures of life. The exploration of our solar system establishes "ground truth" that will inform and guide our studies of extrasolar planets; conversely, examination of a variety of planetary systems provides valuable insight into the general processes that govern them. The combined knowledge gained from these complementary endeavors will enable us to reach a much more complete understanding of the formation and evolution of planetary systems and habitable environments.

it might be. For instance, the apparent abundance of large gas giant planets, in orbits very close to their stars, has led to new theories of how the forming planets in our system may have migrated or become frozen in their present locations. Models also suggest that giant planet formation is a critical feature of planetary systems in general, and may govern the formation and early evolution of rocky inner planets that can possess habitable environments. Since our current understanding of extrasolar planetary systems depends in large part on our observations of the largest planets within them, study of the gas giants represents an important tie point between those systems and our own. *Detailed study of the gas giants Jupiter and Saturn, ring systems, and the Kuiper Belt* — our solar system's best analogs for the presently observable features of extrasolar planetary systems — will significantly enhance our understanding of the general processes of solar system formation and evolution.

OBJECTIVE 3 Determine the characteristics of the solar system that led to the origin of life.

In our solar system, the formative and evolutionary processes that acted on the planets made at least one of them a platform for the development of life. Was this an inevitable outcome of solar system evolution, and therefore potentially a common phenomenon, or was it merely an accident of chemistry, dynamics, and timing, unlikely to be reproduced elsewhere? And why did it happen so quickly — the first signs of life on Earth possibly emerging just a few hundred million years after the planet cooled? Where else in our solar system were the conditions right for the formation and development of life?

The essential requirements for life are a source of usable energy and basic nutrients, organic material, and liquid water. There is strong evidence that these ingredients have been present and in contact with one another on bodies other than Earth. Water and organics appear to have been originally condensed or acquired in the outer reaches of the solar nebula where low temperatures favored their retention. Transported aboard cometary and asteroidal materials that were accreted by the planets, these essential ingredients of life were then effectively incorporated into the forming planetary environments. The planetary



Interplanetary Delivery

Water has been transported from the cold outer reaches of our solar system to the inner planets, possibly aboard comets. This is comet Hyakutake in 1996.

system we know today — and the questions of habitability — are thus intimately linked to the original distribution and transportation of water, other volatiles, and organic material.

Determine the nature, history, and distribution of volatile and organic compounds in the solar system.

Most models of the solar nebula suggest that the conditions within it were too hot, at the time and place of Earth's formation, to retain the relatively large proportion of volatiles seen in the current Earth. Delivery of volatile-rich material from more distant, colder parts of the solar system is commonly invoked to explain this discrepancy. There are reasons to believe that even Jupiter received much of its volatile inventory in this way. However, the total quantity of volatile material, the relative proportion delivered from different possible sources, and the time period over which it was delivered all remain uncertain.

Today's short-period comets are the dynamical survivors of the much larger original population of comets that played a role in volatile distribution, and thus knowledge of their composition is crucial to understanding this process and its results. We know that comets delivered volatiles and organics to the inner planets, contributing to the formation of Earth's hydrosphere, atmosphere, and biosphere. Since comets spend the vast majority of time far from the Sun, their surfaces preserve accessible remnants of the primordial chemical constituents from which the entire solar system formed. *Laboratory analysis of the elemental and isotopic abundances in short-period comets* will elucidate the history and transport mechanisms of water, other volatiles, and organics in the solar system. Analysis of returned samples will also allow us to determine the chemical, physical, and mineralogical properties of their non-volatile components.

The abundance of water in the deep interior of Jupiter is a key to understanding the processes by which volatile materials were added to the planet as it formed. Water ice carried other condensed volatiles with it as planetesimals were accreted by Jupiter. However, the water abundance in Jupiter's deep atmosphere and interior remains highly uncertain, because the Galileo atmospheric probe descended in a dry,



Water is all around us — on Earth
and throughout the cosmos. It is
the presence of liquid water, per-
sisting for long periods of time, that
has allowed life to flourish on our
planet. It is probably also the key to
the presence of life elsewhere.

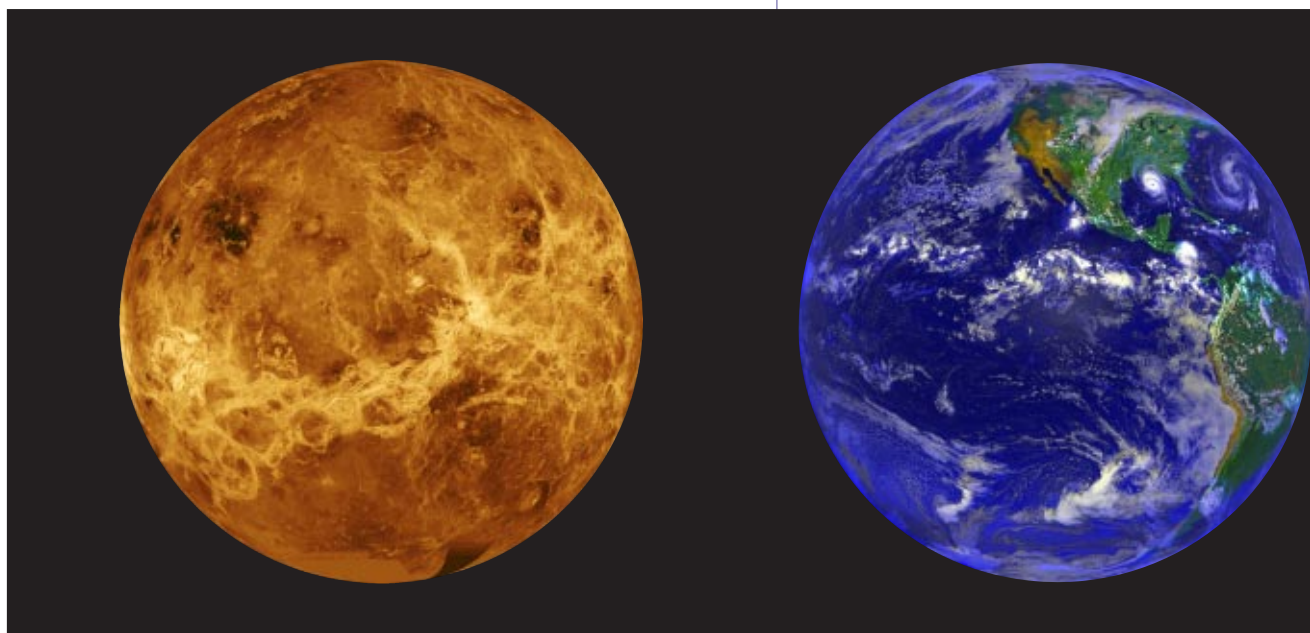
Science Objectives

downdraft region where the water content was not representative of the planet as a whole. *Determination of Jupiter's water abundance at significant depth* will enable us to estimate the planet's overall water content, and thus better understand the mechanisms that delivered water and volatile components to the forming planets in the early solar system.

Once delivered to the planets, volatiles may be sequestered in surface and interior reservoirs, partitioned into the atmosphere, or lost to space. The volatile evolution of the three large terrestrial planets — Earth, Venus, and Mars — apparently took radically different paths with fundamentally different outcomes. These differences hold vital clues to understanding both the history and future of Earth and the potential that other planets may have been habitats for life at some point in their histories. One key means of understanding these differences is to trace the volatile history of Venus, and in particular the processes that led to the loss of the water that should originally have been present. Pioneer Venus and Venera provided some insight into the composition of the atmosphere and surface, but more detailed *measurement of the chemical and isotopic composition of Venus' surface and atmosphere* is required if we are to fully understand its evolutionary history.

Worlds Apart

Although similar in size, mass, and solar distance, Venus and Earth could hardly be more different. When and why did they take such divergent evolutionary paths? Venus has experienced what is sometimes called a "runaway greenhouse effect," rendering the planet hot, toxic, and lifeless.



We know that carbon dioxide on Mars is cycled between the atmosphere and the winter polar caps. At the poles there is evidence of a long history of frozen volatiles, which may preserve evidence of different climatic regimes and possibly of life-supporting environments. Current missions such as Mars Global Surveyor and Mars Odyssey are revealing striking evidence of past and present reservoirs of water on Mars — frozen at the poles and beneath the surface today, but possibly pooled in large ponds, lakes, or oceans in the past. *Determination of the evolutionary processes, sources, and reservoirs of key volatiles on Mars* will allow comparison with Earth and Venus and complete the picture of the original distribution of volatiles in the solar system.

Identify the habitable zones in the solar system.

Recent discoveries suggest that life’s “habitable zones” are defined not just by a planet’s distance from its parent star, but by a complex relationship involving external and internal energy sources, chemical inventories, and geophysical processes. The chemical building blocks of life and complex organic chemistry are known to exist throughout our solar system, and there are tantalizing hints that liquid water may be present in a few key environments. This has significantly expanded our view of the number of solar system environments that might be or might have been conducive to life. Mars is widely regarded as a planet on which the conditions for habitability could have been met. *Determination of Mars’ volatile history and study of its geological and climatic evolution* will tell us whether martian environments ever became habitable. Remote and in situ investigations, as well as analysis of returned samples, will all provide important data for understanding the habitability of Mars.

Other recently recognized potentially habitable environments are the inferred subsurface liquid oceans on several major satellites of Jupiter, especially Europa. Considered at least a theoretical possibility for nearly three decades, the existence of global liquid layers under the icy crusts of the larger moons has received major support from the Galileo mission’s exploration of the jovian system. Although the evidence for its existence is as yet indirect, there is wide acceptance that Europa does today possess a subsurface global ocean of liquid water. While there are many uncertainties regarding the geology and chem-



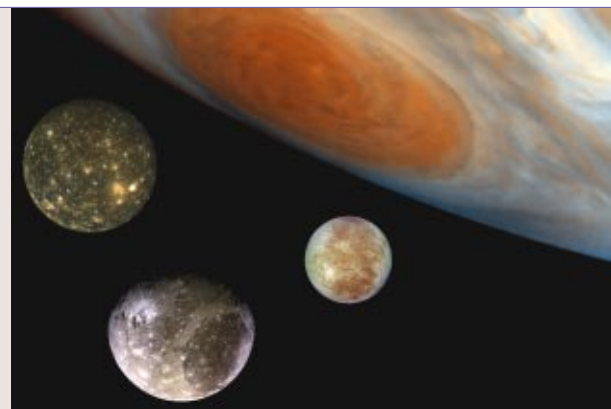
The Sun–Earth Connection

A complete view of the evolution of the solar system and life within it is not possible without an understanding of the evolution and variability of the Sun. The Sun–Earth Connection Division within the Office of Space Science focuses on solar physics, the plasma environments in the solar system, and the effects of the Sun on Earth and the planets. These data provide important context for interpretation of planetary mission investigations. Virtually all solar system exploration spacecraft include instruments to study the fields and particles that stem from solar interactions. These measurements are crucial to understanding how these interactions have affected the climatic and geological history of the planets. The past and present radiation environments experienced by the planets may also be an important factor in determining whether prebiotic chemical processes or biology can arise in a planetary environment.

istry of this environment and potential life-supporting energy sources within it, *confirmation of the existence and determination of the characteristics of Europa's ocean* will allow us to conclude whether it is or ever has been a habitable environment. A positive finding would provide tremendous impetus for future surface and subsurface chemical and geophysical Europa exploration. Although explored less intensively by Galileo, both Ganymede and Callisto show indications of subsurface structure similar to that of Europa. If the formation of oceans is found to be a common phenomenon, the implications for life in the cosmos could be stunning. *Comparative intensive studies of Callisto, Ganymede, and Europa* could therefore prove to be one of the most important contributions we can make to the understanding of habitability in the solar system.

OBJECTIVE 4 Understand how life begins and evolves.

Microbial life forms have been discovered on Earth that can survive and even thrive at extremes of high and low temperature and pressure, and in conditions of acidity, salinity, alkalinity, and concentrations of heavy metals that would have been regarded as lethal just a few years ago. These discoveries include the wide diversity of life near sea-floor hydrothermal vent systems, where some organisms live essentially on chemical energy in the absence of sunlight. Similar environments may be present elsewhere in the solar system. Understanding the processes that lead to life, however, is complicated by the actions of biology itself. Earth's atmosphere today bears little resemblance to the atmosphere of the early Earth, in which life developed; it has been nearly reconstituted by the bacteria, vegetation, and other life forms that have acted upon it over the eons. Fortunately, the solar system has preserved for us an array of natural laboratories in which we can study life's raw ingredients — volatiles and organics — as well as their delivery mechanisms and the prebiotic chemical processes that lead to life. We can also find on Earth direct evidence of the interactions of life with its environments, and the dramatic changes that life has undergone as the planet evolved. This can tell us much about the adaptability of life and the prospects that it might survive upheavals on other planets.



Water Worlds?

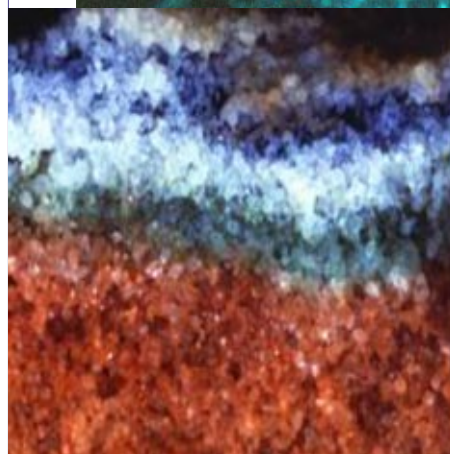
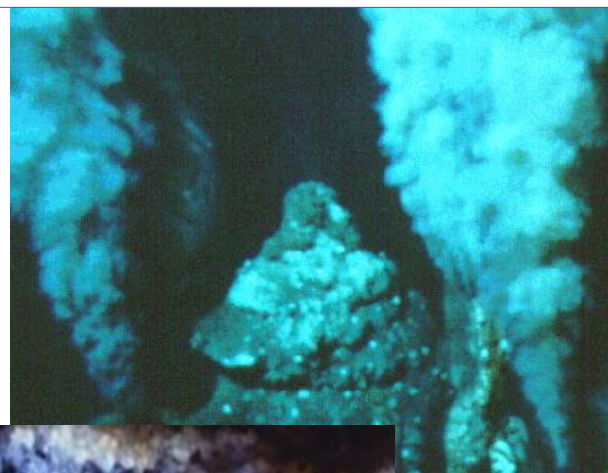
Jupiter and its moons are in many ways like a miniature solar system. The gas giant Jupiter can be thought of as a star that didn't get quite large enough to ignite, and the four largest moons — the Galilean satellites — possess many of the characteristics of small planets.

There is striking evidence that one of them — Europa — and possibly Callisto and Ganymede, hide oceans of liquid water beneath their frozen surfaces. The heat source keeping these oceans liquid, if they exist, is the constant tidal flexing caused by Jupiter's intense gravitational pull. Could this internal heating also power the same types of thermal vents that are known to support life on Earth's ocean floor?

Identify the sources of simple chemicals that contribute to prebiotic evolution and the emergence of life.

Since the outer reaches of the original solar nebula were relatively cool, a variety of volatile compounds could condense from the nebular gas as the solar system formed. Of particular importance were ices containing carbon, nitrogen, and sulfur, as well as organic materials. The outer solar system was thus far richer in organic compounds, essential for prebiotic chemistry as we understand it, than was the inner solar system. Planetesimals that formed in this region probably delivered such materials to the moons of the outer planets and to the inner planets. Comets are volatile-rich and organic-rich samples from reservoirs in the outer solar system, including the Kuiper Belt beyond Neptune and the more distant Oort cloud. By *determining the chemical composition of comets and Kuiper objects* we can directly study chemical building blocks that may have laid the foundation for life.

Saturn's moon Titan is an organic-rich world that is of tremendous importance to our study of prebiotic chemistry. Data from Voyager, as well as from other observations and experiments, suggest that the pathways and products of long-term organic evolution on Titan may bear similarities to those that existed on the early Earth. The atmosphere and surface of Titan are a virtual time machine, presenting us with unique opportunities for studying photochemistry and chemical reactions that are no longer observable on our planet due to the pervasive effects of biology. *A thorough study of Titan's atmospheric chemistry and surface-atmosphere interactions* is a key to determining its chemical history and thus to learning about analogous processes that may have occurred on Earth. In 2004 the Cassini-Huygens mission will initiate an intensive study of Saturn and Titan that is expected to revolutionize our understanding of complex organic chemical processes in the solar system. Based on the anticipated results of this mission, future in situ Titan exploration is expected to be a very high scientific priority.



Life is Resilient and Adaptable

There are now known life forms that can thrive at both high and low temperatures, and in chemical environments that would have been regarded as lethal just a few years ago. Life has recently been found around deep ocean thermal vents (top) and within Antarctic permafrost (bottom). Similar environments may exist elsewhere in the solar system.

Study Earth's geologic and biologic records to determine the historical relationship between Earth and its biosphere.

Recent discoveries attest to the fact that life is remarkably hardy and that it developed surprisingly quickly. Microbial life on Earth may have come into existence nearly 4 billion years ago, shortly after the end of the most violent phase of formation of the planet. Today it thrives wherever liquid water and usable energy exist together. This includes unlikely environments such as hot deep-sea vents, cold Antarctic rocks, acidic hot springs, and rocks many kilometers below the surface. A full understanding of the historical relationships between life and the environment requires a synthesis that draws from many different fields of science. We seek to *investigate the development of biological processes on the early Earth through molecular, stratigraphic, geochemical, and paleontological studies* involving a combination of field and laboratory research. Molecular biomarkers uncovered in such research can help to link biological evolution to past environments. Likewise, biogeochemical cycles of carbon, oxygen, sulfur, and iron are integral to Earth's biosphere, and the isotopic records preserved in Earth's geology and in fossils help us to understand how the biosphere evolved.

Our knowledge of chemistry, physics, and solar system dynamics places constraints on Earth's history of environmental change. With these tools and methodological framework, astrobiologists study the interactions of organisms with the planetary environment. We now know that some of the most cataclysmic disruptions in Earth's history have been due to impacts. By *examining the records of the response of Earth's biosphere to extraterrestrial events*, including comet and asteroid impacts, we can gain substantial insight into the processes by which life adapts and evolves. We can also learn about the role that impacts may have played in determining the habitability of other planets in our solar system and beyond.



Breaking Through

Reddish spots and shallow pits pepper the enigmatic ridged surface of Europa. These features may be evidence that water or warmer ice has gradually risen through the colder surface layers. By studying these surface deposits we might discover evidence of what lies below.

O B J E C T I V E 5 Explore the space environment to discover hazards to Earth.

Once a source of life-giving organics and water, cosmic impacts also have the potential to wreak widespread destruction or even to extinguish much of life — and these events occur regularly on planetary timescales. This sobering conclusion stems from the convergence of many lines of study, from geology to astronomy to paleontology. Evidence continues to mount that the so-called Cretaceous–Tertiary mass extinction event 65 million years ago was caused by the impact of an extraterrestrial body about 10 kilometers in diameter. It has also become apparent that even much smaller objects, which impact Earth much more frequently, are capable of doing serious damage to modern industrialized society. To understand the impact threat posed by asteroids and comets, as well as the feasibility of potential mitigation strategies, we must assess not only the number of potentially hazardous bodies and the frequency of both small and large impacts, but also the physical characteristics of the objects themselves.

Determine the inventory and dynamics of bodies that may pose an impact hazard to Earth.

The interplanetary space between the major bodies in our solar system is far from empty. Although the impactor flux has declined greatly since the early days of the solar system, it is estimated that up to 50,000 objects of diameter at least 50–100 meters still exist in orbits near Earth. Of those, up to 1,500 may have diameters of 1 kilometer or larger. An impactor at the smaller end of this size range could wipe out a city or an entire coastal region; at the upper end of this range it could cause global devastation. Considerable progress has been made in identifying and cataloguing near-Earth objects that could potentially pose a threat to Earth, and it is estimated that about 50% of the near-Earth objects larger than 1 kilometer have now been identified. NASA will continue to play a major role in this search and will seek to *identify and track at least 90% of the near-Earth objects greater than 1 kilometer in diameter by 2008*. This represents a unique contribution to the protection of our home planet that is synergistic with our objectives of understanding key solar system processes.

Building Blocks and Wrecking Balls

Near-Earth asteroids such as Eros have much to tell us about the formation of the planets. They are also the most serious Earth impact threats, so it is imperative that we understand their population, dynamics, and physical structure.



Determine the physical characteristics of comets and asteroids.

The effect that a comet or asteroid impact has on a planetary environment is determined by the amount of energy that is released during the impact. This depends on the velocity of the impact, which is a function of the Earth-relative orbital dynamics, and on the mass and structure of the impacting body. In addition, any possible plan to divert an impactor or mitigate its effects will depend critically on an understanding of its physical characteristics. Since these same scientific parameters — mass, composition, structure, dynamics — are important to understanding the roles that comets and asteroids played in the development of the solar system and the origin of life, our scientific exploration missions are uniquely suited to help clarify the impact hazard. *Measuring the surface and interior composition and structural properties of comets and asteroids* will enable modeling of the effects of impacts and the development of credible mitigation strategies.

OBJECTIVE 6 Understand the current state and evolution of the atmosphere, surface, and interior of Mars.

Our recent missions to Mars have resulted in exciting discoveries, and ongoing analysis of data from these missions, as well as research on martian meteorites, continues to revolutionize our understanding of the planet and its evolution. There are indications that the surface environment of Mars may have evolved from one that was conducive to the formation of life to that which today is dry, cold, and forbidding. The prospect that geological and climatological changes may have extinguished early martian life, or stunted its growth and forced it underground, makes Mars an exceptionally important laboratory for the study of planetary evolution and its effects on the development of life.

Characterize the present climate of Mars and determine how it has evolved over time.

Modern Mars has a thin atmosphere of carbon dioxide that represents one climatic extreme among the terrestrial planets. Atmospheric temperatures are low and the amount of water in the atmosphere is small.

Ancient Expressions

The presence of ancient volcanoes is evidence that Mars was once geologically active. Geothermal energy sources could potentially support habitats for simple life. The large volcano shown here is Ceraunius Tholus.



This may not always have been the case, however. Understanding the climate of modern Mars is the first step in looking back to the time, more than a billion years ago, when Mars may have had a wetter, warmer climate — conditions that may have supported life. *Mapping the structure, water content, and isotopic composition of the atmosphere* will provide the baseline from which evidence of climate change can be assessed.

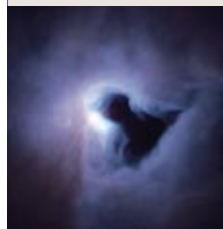
Studies of current climate processes provide insight into long-term martian climate variability. Quasi-periodic climate change — apparent today in sedimentary layering of dust and ice at the poles — is thought to be due to oscillations in the planet's orbit and rotation. Shorter-term seasonal processes provide an observable proxy for long-term astronomical variability. *Studying the mineralogy and weathering of Mars' surface* will elucidate the planet's long-term climate history.

Investigate the history and behavior of water and other volatiles on Mars.

Mars shows strong indications of being or having been habitable. The primary issues facing Mars exploration are to confirm this hypothesis, to understand the evolution of martian habitability, and to determine whether life ever actually existed there. Central to these questions is the presence of liquid water for periods of time sufficient for life to have originated. Following the water on Mars, throughout space and time, is therefore at the core of our science strategy.

Evidence continues to mount that water flowed on or near the martian surface at some time in its past. A key goal is to determine when water was present on the surface in liquid form, how much, for how long, and how it was lost. The history of water on Mars is written today in geological surface records that can be read by our instruments — both locally on the martian surface and globally from orbit. Near-term investigations will *map the sources and sinks of water and characterize aqueous processes acting on the surface*; in the longer term, with the benefit of returned samples, measurement techniques in Earth-based laboratories will extend these studies to much greater precision. Since water is not present on the surface today, it is equally important to un-

The Emerging Science of Astrobiology



Through the science of astrobiology we seek to understand the potential and actual distri-

bution of life in the universe. Astrobiology encompasses scientific and intellectual issues that span both the Earth and space sciences, and provides a scientific organizational structure that encompasses the origins, evolution, and destiny of life and its habitats. Of particular interest for solar system exploration is determination of the history of environmental conditions on the planets and satellites in our solar system, the processes that produced them, whether and where they are capable of supporting life, and whether life actually developed there. Astrobiology thus provides an integrating theme that brings together a substantial fraction of the issues in solar system exploration under the common thread of understanding planetary habitability. It also provides a compelling connection between the exploration of our planetary system and the universe beyond. As we learn about planets around other stars we seek features and processes in common with our own solar system, with a goal of someday determining whether they might have led to habitable environments and life elsewhere in the cosmos.

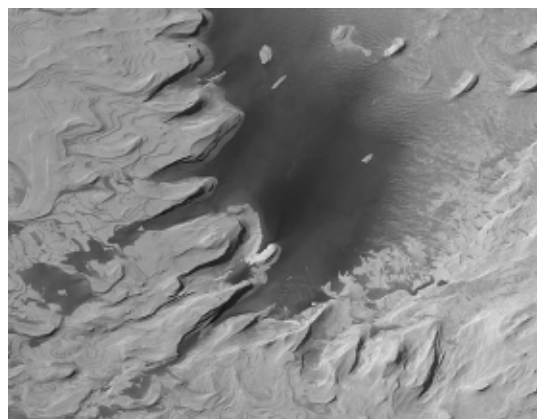
Understand the processes that have led to its disappearance. *Determining the energetics and dynamics of Mars' upper atmosphere* will allow us to calculate the rate at which ancient water was lost to space, and thereby estimate the remainder that must be locked in subsurface deposits or surface rocks and ice.

Study the chemistry, mineralogy, and chronology of martian materials.

As research on Earth has shown, an understanding of a planet's historical habitability requires in-depth study of the origin and evolution of the planet's physical environment. Mars is unique among the terrestrial planets in that the ancient surface is exposed, largely unaltered, and readily observable by orbiters, landers, and rovers. The surface of Mars records its history of violent impacts, volcanic eruptions, crustal tectonics, fluid erosion, and possibly biology. Individual rocks contain a tremendous amount of such information on a microscopic scale, and clues to the ancient climate can also be found in the layer of weathering products that we expect to find on rock samples and in the soil. A critical unknown for Mars is the absolute chronology of the surface. *Compositional and isotopic analysis of surface materials, weathering rinds, and sedimentary deposits* will establish the role of liquid water and uncover evidence of geochemical cycles of biological relevance. These investigations can be performed in situ to a limited degree, but ultimately require the return of surface samples from scientifically compelling locations.

Determine the characteristics and dynamics of the interior of Mars.

According to our current models, after the formation and differentiation of Mars the planet's crust formed and recorded an early period of heavy impact bombardment. A global dichotomy formed between the southern highlands and the northern lowlands, and the massive Tharsis volcano-tectonic complex was emplaced with resulting global deformation. *Long-term global studies of martian seismicity* will allow us to characterize the interior of Mars and better understand the sequence of these events and their implications for martian habitability. The recent discovery of intense remanent magnetic fields, confined largely to the



Martian History: Written in the Rocks

Just as they do on Earth, layers of rock and sediment on Mars may preserve evidence of past climatic conditions. This is a region in Schiaparelli Crater.

The Detailed Study of Mars

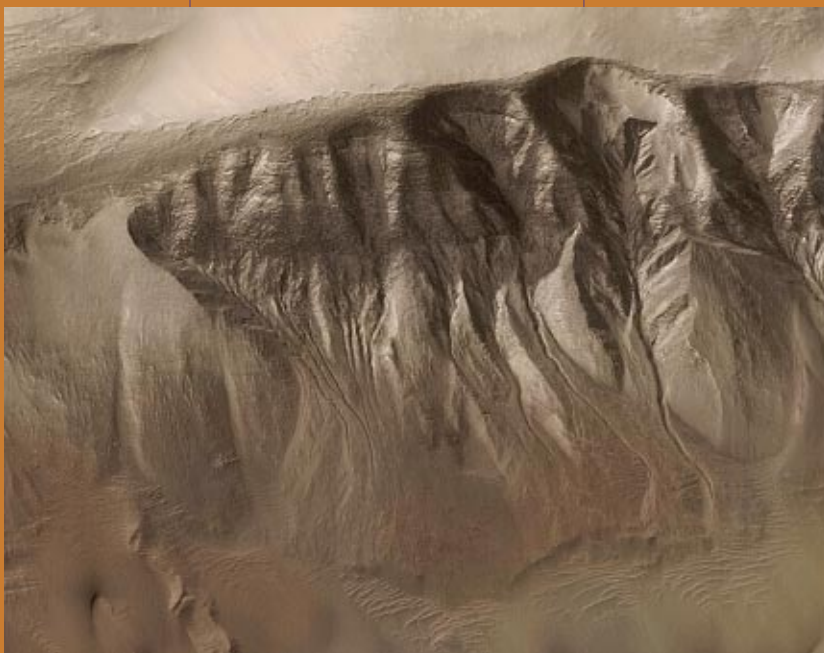
Channels found on martian hillsides, canyons, and crater walls may indicate that liquid water has existed on or near the surface of Mars in the recent past, and may still exist today. These discoveries have revolutionized our view of the planet as a possible abode for life.

Because of the vital role it plays in answering the key questions of our origins and life in the cosmos, Mars receives special emphasis within NASA. It is the only planet, other than Earth, that shows strong evidence of liquid water having coursed over its surface. Contributing to the current view that Mars was once wet — and possibly wet and warm — are numerous sinuous channels, presumably left by flowing water; sedimentary deposits, similar to those that, on Earth, are

indicative of standing water; and subsurface ice and surface features suggestive of permafrost and periglacial landforms. Although our current understanding of life's origins may be limited, we believe that the features we see on Mars today are the relics of environments that may once have been habitable, and that may even have actually harbored life.

While the search for evidence of life is a primary motivation for our emphasis on Mars, it is not

the only one. Mars is the most Earth-like planet in the solar system — it has diurnal and seasonal cycles similar to our own, water-based polar caps that wax and wane, vast volcanoes, deep canyons, shifting sand dunes, and other features with close analogs on Earth. The proximity of Mars permits relatively rapid, discovery-driven exploration of its geological and climate history. It is an accessible natural laboratory within which we can pose and answer questions about the all-important processes of planetary evolution, independent of the questions of life. And Mars has always beckoned as the first, and perhaps the only, planet that is suitable for human exploration and habitation. Our robotic armada seeks evidence that life is on Mars today or that it, perhaps, once was; at the same time, we lay the groundwork for the possible human life on Mars that may yet be.



Science Objectives

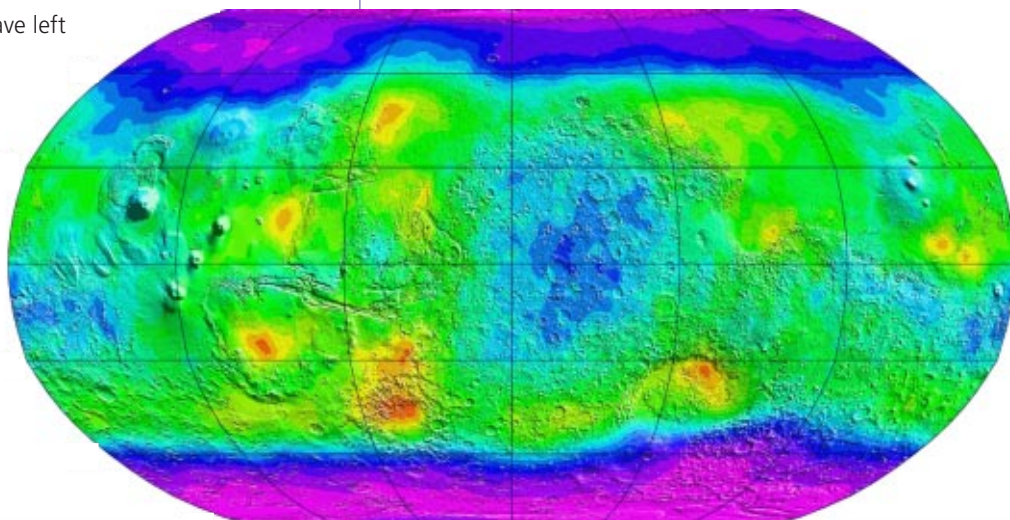
most ancient surfaces of the planet, implies that an early global magnetic field was generated and then vanished. Life on Earth has been protected from damaging solar effects by Earth's global magnetic field, and a similar magnetic shield on Mars could have allowed life to gain a foothold. *Accurate mapping of the martian remanent magnetic field* will help to clarify the nature of the ancient global field and the possibility that early Mars might have been protected — and habitable.

OBJECTIVE 7 Determine if life exists or has ever existed on Mars.

Human speculation on the possibilities for life on Mars has transformed dramatically over the past hundred years. The canals envisioned in the early 1900s by astronomer Percival Lowell are now known to be optical illusions. The waxing and waning dark regions are not the seasonal growth of vegetation, but rather the result of movements of dust across the face of an arid planet. The Martians hypothesized by countless science fiction authors never existed. Even the simple plants envisioned by respected scientists prior to the 1976 Viking missions are now thought to be extremely unlikely in martian history. Yet today we are closer than ever to determining whether the spark of life — however small — arose on Mars, and whether it might still exist today. We now search for evidence that Mars was once warmer and wetter than it is now, perhaps providing the conditions required for life's origins. We seek the habitats where simple life might have prospered and where it might persist today. We are beginning to learn how to search for and identify the signatures that life would have left behind in martian rocks. And if it were found, evidence of any organism — no matter how simple and whether dead or alive — would be no less significant to humankind than the grand visions of the past, for it would prove once and for all that life has existed elsewhere.

Where There's Ice . . . ?

Was Mars warmer and wetter in the past? Today there are large areas of water ice on Mars, frozen at the poles and buried just below the surface. This is a compositional map from Mars Odyssey in which concentrations of hydrogen, presumed to be indicative of frozen water, are shown in purple and blue.



Investigate the character and extent of prebiotic chemistry on Mars.

If there is life on Mars today, it is probably well hidden; if there was ancient life that is now extinct, the direct physical evidence may be difficult to detect in situ. Our near-term exploration of martian habitability focuses instead on the building blocks of life. This carries the added advantage of helping us to understand how close Mars came to producing life, even if organisms never developed; this would be an important scientific result in itself. Thus we *seek evidence of organics and prebiotic molecules in martian materials*, since these are the precursors of life itself. Our search for signs of prebiotic chemistry must be methodical, because it will certainly be difficult. The Viking landers found the surface to be sterile and devoid of organics. As an explanation of that finding and to explain the behavior of samples in the Viking experiments, scientists hypothesize the presence of a powerful oxidant in martian soil that actively destroys organic molecules. The nature and extent of this oxidant is unknown, but it will certainly have major implications for our ability to find and study organic material. We must *characterize the surface oxidant with depth* in order to understand whether the martian subsurface or the interiors of rocks provide the best chances of detecting prebiotic chemical markers and possibly evidence of life.

Search for chemical and biological signatures of past and present life on Mars.

Since the present-day martian surface is hostile to life, current research seeks both past environments in which life might have found a foothold, as well as present-day habitable environments. On modern Mars we see tantalizing evidence that habitats may still exist, including on the margins of and beneath the polar ice caps, within the shallow subsurface where liquid water may persist, and possibly even in association with recently active hydrothermal systems. Fossil evidence of extinct life may be accessible in other locations, such as ancient lakebeds, marine sediments, and outflow regions. Future Mars surface missions will *search in situ for chemical and structural evidence of the biogeochemical signatures of life*. Interest in martian life has been heightened by recent results from Mars meteorite studies that have been



Follow the Water

Today's Mars orbiters are uncovering numerous features that are suggestive of past flows of water or ice. A key to our Mars exploration strategy is to study such regions for evidence of past or present life.


interpreted by some researchers as possible evidence of ancient life. The heated debate that surrounds these investigations, as well as the severe limitations inherent in the scientific instruments that can realistically be sent to the surface of Mars, underscores the need for verifiable studies of martian samples in laboratories on Earth, using the most powerful instruments in the world. Definitive searches for past or present martian life thus require *laboratory analysis of martian samples drawn from scientifically compelling locations* — sites where water once persisted and where conditions are suitable for the preservation of the signatures of life.

O B J E C T I V E 8 **Develop an understanding of Mars in support of possible future human exploration.**

Our robotic exploration of Mars will continue to reveal to us in astounding detail the story of martian history, evolution, and biological potential. The return of samples to laboratories on Earth will allow us to utilize the best instruments and technologies to answer ever more complex questions. In the long term, though, as we delve still deeper into these mysteries, the presence of human scientists and explorers on Mars will enable tremendous advances in our understanding of the planet. Human ingenuity, dexterity, and adaptability will provide capabilities that may forever be beyond the reach of robotic explorers. The eventual human exploration of Mars will require a thorough understanding of the martian environment that can only be provided by our robotic spacecraft. This will not only help to ensure the safety of human explorers, it will also allow us to determine the most cost-effective ways in which humans can contribute to Mars science.

Identify and study the hazards that the martian environment will present to human explorers.

Knowledge of the martian environment is critical to the planning and assessment of safe and effective human Mars exploration. The National Academy of Sciences documented a broad suite of hazards in their 2002 publication, “Safe on Mars.” Of prime importance is detailed knowledge of the radiation environment and whether local landforms could offer geometric shielding for human explorers. There are additional issues associated with toxic elements that may be present at



Our robotic armada seeks
evidence that life is on Mars
today or that it, perhaps,
once was; at the same time,
we lay the groundwork for
the possible human life on
Mars that may yet be.



significant levels in the ubiquitous dust. Thus a top priority is to *characterize the radiation and fine material (dust) at the martian surface*. In addition, landing site hazards such as local slopes, rock distributions, and mechanical properties affect planning for future human exploration. Upcoming Mars exploration missions will provide measurements of many of the important factors associated with identified hazards. The 2005 Mars Reconnaissance Orbiter (MRO) will provide landing site reconnaissance suitable for early planning, and the 2009 Mars Science Laboratory (MSL) may address slope and rock conditions, as well as possible geochemical hazards.

Inventory and characterize martian resources of potential benefit to human exploration of Mars.

Eventual human explorers of Mars will benefit tremendously from the ability to make use of natural resources found on Mars. These could be used for life support, radiation mitigation, or production of propellant and power. Sources of hydrogen and oxygen are critical, so the single most valuable commodity in the early stages of exploration will be water. Upcoming Mars missions will *search for accessible reservoirs of usable water and determine the chemistry and structure of martian surface material*. Identification of any accessible sources of energy on Mars is also important. The reconnaissance capabilities of the 2005 MRO and 2009 MSL missions will provide the first steps in this area. Both missions will dramatically improve our knowledge of key aspects of Mars, including its surface minerals, subsurface volatiles, and the detailed chemistry of accessible materials.

New Vista

One day human explorers may watch the Sun set over the plains of Mars.



Mission *Roadmap*

Planetary exploration missions are conducted by some of the most sophisticated robots ever built.

Through them we extend our senses to the farthest reaches of the solar system and into remote and hostile environments, where the secrets of our origins and destiny lie hidden. The coming years of solar system exploration promise to be the most exciting and productive yet, as we explore entirely new worlds and probe in even greater detail the fascinating environments we have discovered.

This section describes the program elements and high-priority missions that will respond to the science objectives and investigations discussed earlier. It also describes the criteria by which priorities are established and how our missions are woven together into an effective long-term exploration strategy.

Tools of Exploration

Solar system exploration has an increasing variety of tools available with which we can accomplish our science objectives. Planetary spacecraft, both flight proven and in development, now span a wide range of capabilities that can be brought to bear on the top-priority science questions. An important part of planning an effective exploration program is identifying the “right” tool to meet a particular objective; this allows us to properly assess the scientific potential of a mission. The major tools we can consider are:

- Flyby spacecraft for reconnaissance of unexplored objects
- Orbiters to provide global and targeted regional remote-sensing observations
- Landers, rovers, drills, and entry probes for access to surfaces, sub-surfaces, and atmospheres
- Networks and constellations of spacecraft to provide multiple vantage points and increased sensitivity
- Aerial platforms (e.g., balloons or airplanes) to provide higher-resolution regional perspectives
- Sample return systems, including the required infrastructure for sample quarantine, curation, and analysis

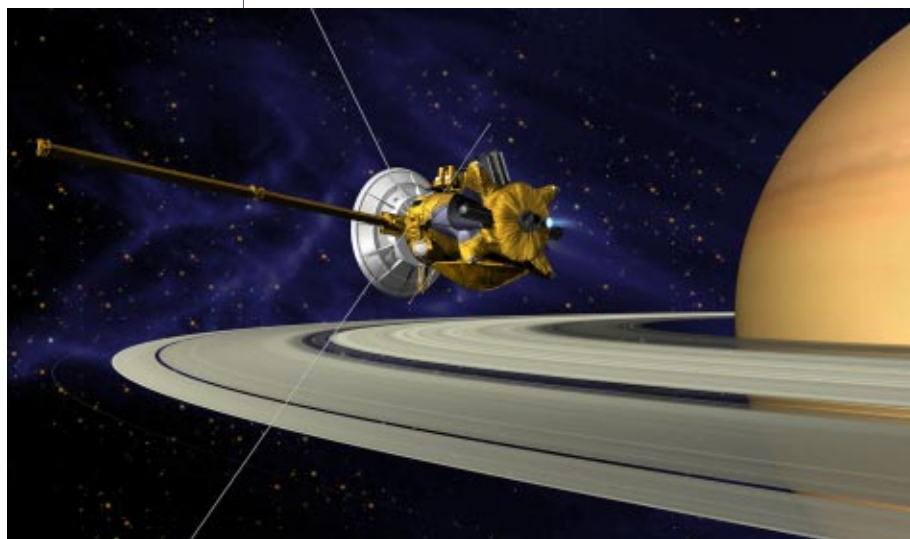
With these tools comes a range of costs, ultimately requiring trades between measurement goals and available resources.

Establishing Priorities

In establishing program priority — that is, a recommended chronological sequence of missions — we must balance the scientific imperative of each investigation against its cost, technological readiness, and other considerations. Thus each potential mission must be studied in sufficient depth to enable comparisons of scientific merit, opportunity, and technological readiness.

At the Ringed Planet

In July 2004, the international Cassini–Huygens mission will arrive at Saturn to begin its four-year mission. A major focus will be Titan, whose atmosphere may be a prebiotic analog to that of the early Earth. The Huygens probe will descend through Titan’s clouds in January 2005.



Mission Roadmap

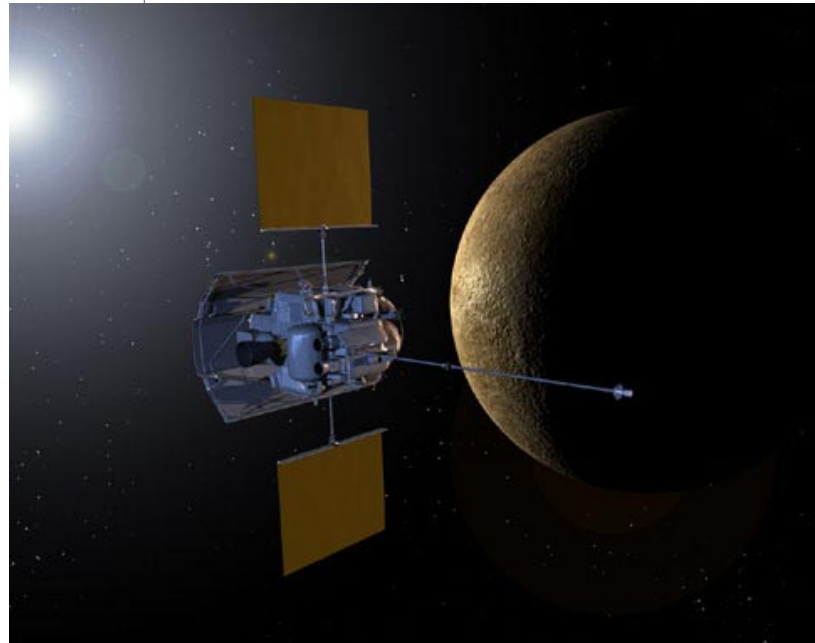
Scientific merit is measured by addressing the following prioritized questions:

1. Does a proposed mission represent significant progress toward achieving the high-priority science objectives of this roadmap and the NASA Strategic Plan?
2. How might the measurements made by a mission create new or change existing paradigms?
3. How would the new knowledge affect the directions of future research?
4. To what degree would the knowledge gained strengthen the factual base of our understanding and improve predictive models?

The research focus areas and investigations described in this roadmap are the product of a rigorous process by the broad planetary science community to address these issues of scientific merit. They broadly follow the recommendations of the National Research Council's "Decadal Survey" of priorities in planetary exploration and represent the activities considered to be the most important, having been derived from a much larger set of possible investigations.

Opportunity comprises a number of factors that can affect mission sequence decisions. These include orbital mechanics, relationships to other missions, public interest, and possible international cooperation. Opportunity can also arise by virtue of a scientific discovery that suddenly makes it the "right time" to undertake a prospective mission.

Technological readiness is frequently the factor that drives choices among missions with relatively equal scientific value and no clear opportunity-based discriminators. It is a major element of the cost vs. risk equation for each mission, and a logical flow of technology from mission to mission is a key factor in building a cost-effective long-term program. Technological readiness can also be the most difficult factor to determine, however, requiring the most intensive mission and system design trades and projections of future technological progress.



Mercury Rises

MESSENGER, a mission in NASA's Discovery Program of focused planetary missions, is being prepared for launch in 2004. As the first Mercury orbiter, it will provide unprecedented insight into the composition, structure, and history of the innermost planet.

Solar System Exploration Missions

At present there are fourteen NASA solar system exploration missions, including five Mars missions, either in flight or in full-scale development. NASA is also developing scientific instruments that will fly on international missions. The discoveries produced by these investigations will not only dramatically advance our understanding of the solar system, they will also allow us to further refine our exploration strategy.

The missions described here are planned for the near- and mid-term, based on the scientific strategy articulated in this roadmap. Far-term missions are conceptual, having been identified based on our expectations of the types of investigations that will be high priority after the turn of the decade. Mars exploration missions are discussed in a later section.

Discovery Program

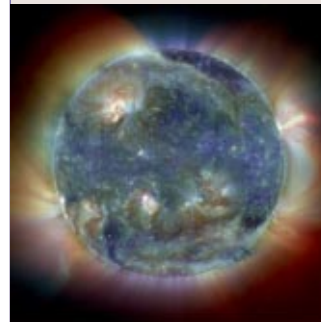
Ten years ago, the Discovery Program was initiated as a means of implementing small, highly focused, competitively selected missions whose costs are capped from the start. Throughout the 1990s, the value of this mission class was amply demonstrated, and now Discovery missions are a key element of our exploration program. They offer flexibility, rapid response, and broad involvement, and they allow us to operate in a region of the risk/reward trade space that might be deemed unacceptable for larger, more costly missions. Discovery missions will continue to be a central element of the Solar System Exploration Program for the foreseeable future and will continue to be launched at their current rate of about two every three years. Since they are competitively selected, it is not possible to specify here exactly what the nature of these missions will be or where they will go; among the criteria for their selection will be the degree to which they help achieve the science objectives and investigations established in this roadmap.

New Frontiers Program

While Discovery has been and will continue to be an extremely valuable source of flight missions, many of the high-priority science investigations we have identified are too complex to be accomplished within

Bringing the Heavens to Earth

By returning samples of solar system bodies to Earth, we can analyze them using the full power of the most sophisticated laboratory instruments. This will provide us with unprecedented insight into the history of the solar system and the physical and chemical processes that govern its evolution. The first two deep space sample return missions, Genesis and Stardust, are in flight now as a part of NASA's Discovery Program. They will return their small yet tremendously valuable samples to Earth in 2004 and 2006, respectively. Together they represent the first of an entirely new breed of planetary exploration missions.



Genesis will acquire and return to Earth samples of the solar wind, a continuous stream of small particles ejected from the outer regions of the Sun. The image above shows the Sun as seen in ultraviolet light.



During a high-speed encounter, Stardust will capture samples of dust and gas from the tail of a comet and return them to Earth.

Mission Roadmap

the constraints of that program. Medium missions, whose life-cycle costs are approximately double those of Discovery missions, will fill an extremely important niche in the spectrum of solar system exploration activities. A new NASA program, New Frontiers, was initiated in 2003 to implement medium-class missions to a variety of targets. New Frontiers missions will be competitively selected, with the first set of selections focused on the specific high-priority investigations identified by the NRC Decadal Survey and reflected in this roadmap. The flight rate is expected to be approximately one mission every three years.

The first planned New Frontiers mission, New Horizons, would be launched in 2006 to conduct the first reconnaissance of the Pluto–Charon system and possibly other Kuiper objects. Four other high-priority investigations have been identified whose implementation may be possible under the New Frontiers Program. *Since the feasibility of these missions within New Frontiers constraints has not yet been fully demonstrated, the details of their implementation and science objectives must remain flexible for the time being.* Science and mission priorities will be regularly reassessed in view of new discoveries and technological advances, with the ultimate sequence of missions to be determined on the basis of technology readiness, program budget, and the results of the competitive selection process. All New Frontiers missions, to be solicited by Announcements of Opportunity, will focus on achieving essential Decadal Survey recommendations while fitting within the New Frontiers Program constraints.

Flagship Missions

Certain high-priority investigations are by their nature so challenging that they cannot be done within the cost constraints of the New Frontiers Program. Examples include comprehensive studies of individual planetary systems, such as those undertaken by Galileo and Cassini; energy-intensive missions that require large propulsion systems and launch vehicles; in-depth studies of outer solar system satellites; and sample return from planetary surfaces. These types of missions generally require significant focused technology developments prior to mission start, as well as extensive pre-decisional trade studies to determine the proper balance of cost, risk, and science return. At a typical

New Horizons

As the first New Frontiers mission, New Horizons would conduct the first reconnaissance of the Kuiper Belt. This will allow determination of the chemical compositions, physical characteristics, and impact histories of Pluto–Charon and other Kuiper objects.



New Frontiers



Lunar South Pole–Aitken Basin Sample Analysis

The impact that produced the lunar South Pole–Aitken Basin excavated much of the Moon’s far-side crust and possibly the upper mantle. Samples of these ancient deep-seated rocks and possibly of the melt sheet may be accessible on the surface. Laboratory analysis of this material can provide a unique window into the composition and formation of the Moon and the history of the Earth–Moon system.

Jupiter’s origin and evolution had a major effect on the development of the rest of the solar system, including the potentially habitable environments of the terrestrial planets. Understanding Jupiter’s internal structure, water abundance, and deep atmospheric composition is a key to unlocking the origin of life and to understanding the dynamics of solar systems in general.

Jupiter Internal Structure and Deep Composition



Venus Surface–Atmosphere Composition and Dynamics

A Venus in situ exploration mission will help us understand the climate change processes that led to the extreme conditions on Venus today, and will lay the groundwork for a future Venus surface sample return.

Detailed examination of returned samples of comet surface material will help us understand the distribution of volatiles and organics in the solar system and how it has evolved over time. It will also provide important insight into the mechanisms by which organic material is transported throughout the solar system, and the structure of potential Earth impactors.

Comet Surface Sample Analysis



cost significantly larger than New Frontiers missions, they represent major national investments that must be selected and implemented in a strategic manner. NASA will strive to gain approval for new flagship missions approximately once per decade, to ensure that the Solar System Exploration Program is properly balanced and can undertake the high-priority, challenging investigations that cannot be done any other way.

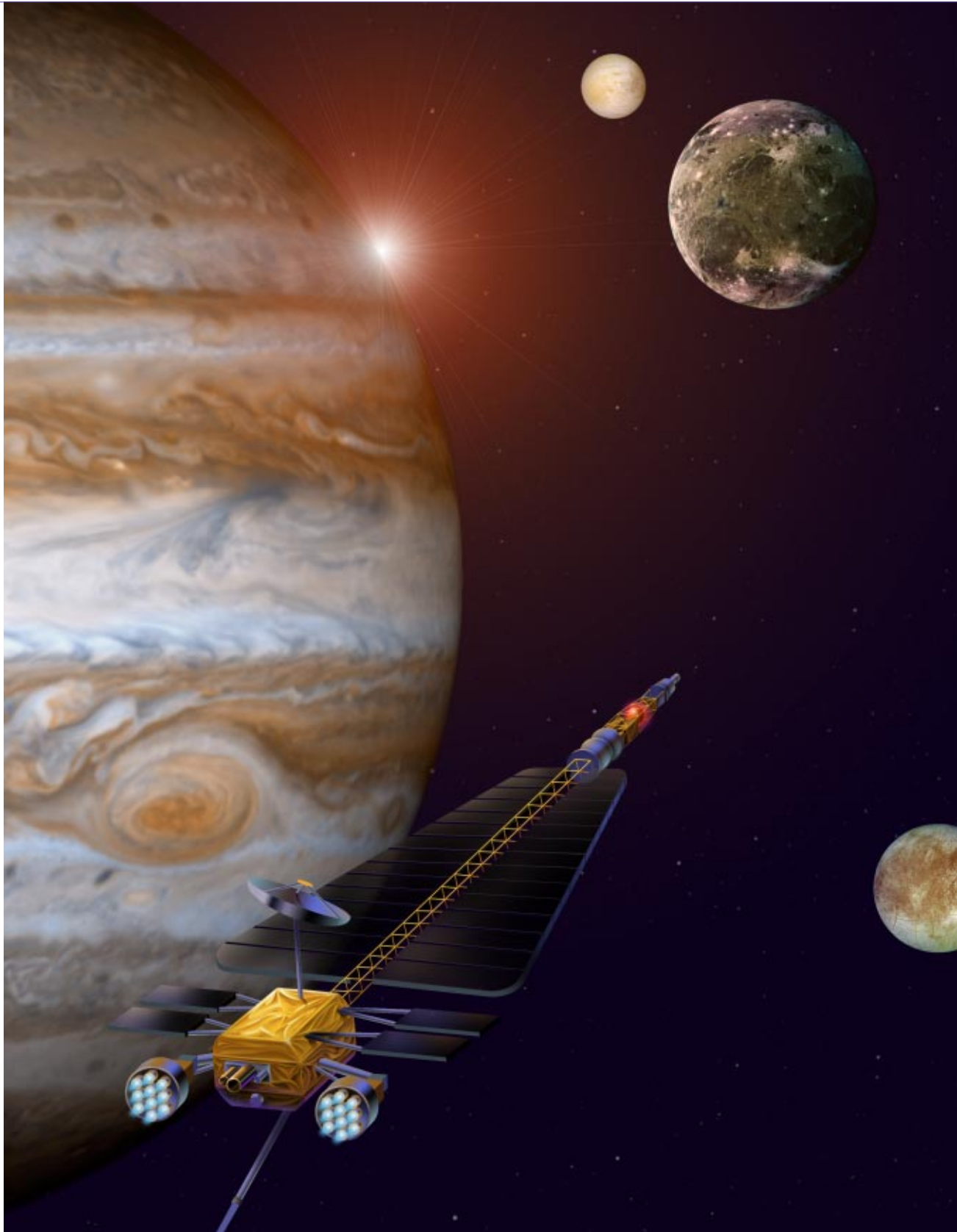
The top priority (non-Mars) flagship mission objective is intensive exploration of potential subsurface oceans on Jupiter's large icy satellites. The Galileo mission has provided strong indications that a liquid ocean may exist beneath the ice crust of Europa, and perhaps beneath the surfaces of Ganymede and Callisto as well. This possibility makes these Galilean satellites among the most fascinating bodies in the solar system from an astrobiological perspective. Verification of the presence of significant amounts of liquid water on one or more of these satellites, study of their surface and subsurface chemistries, and determination of the thicknesses of their ice crusts would allow us to understand the history and biological potential of the Galilean satellites and lay the groundwork for future missions. NASA has recently begun intensive study of a Jupiter Icy Moons Orbiter, which would successively orbit Callisto, Ganymede, and Europa using highly efficient nuclear electric propulsion. Such a mission would achieve the top-priority Decadal Survey objective of focused Europa geophysical exploration and extend it by enabling comprehensive study of this set of three potential water worlds.

In the mid- and far-term, flagship missions will be defined and selected to build on the results of earlier investigations. Examples of high-priority missions that would represent major scientific advances include:

- A *Titan Explorer* that would build on the results of the Cassini–Huygens mission by performing a detailed in situ exploration of Titan.
- A *Neptune Orbiter with Probes* that would perform the first detailed exploration of this ice giant planet and its major moon, Triton.

Jupiter Icy Moons Orbiter

Using highly efficient nuclear electric propulsion, a single mission could successively orbit Callisto, Ganymede, and Europa. This Jupiter Icy Moons Orbiter would represent a major step in our understanding of the nature and extent of habitable environments in the solar system. In addition, as the first application of nuclear electric propulsion, this mission would open a pathway for use of this revolutionary technology throughout the solar system. The large propulsive capability will enable high-energy missions that are otherwise impossible, and the fission power supply allows increased data return as well as fundamentally new types of scientific measurements. NASA is studying the Jupiter Icy Moons Orbiter for a possible launch early in the next decade.



Mission Roadmap

- A *Venus Sample Return* that would provide insight into the causes and effects of the apparent global climate change that Venus experienced in the distant past.

NASA will engage the broad science and engineering community in studies of these and other flagship mission concepts to assess their feasibility and establish technology requirements for near-term investment. One characteristic common to all future flagship missions is that they require significant technology developments before they can be undertaken. The definition of these technology needs and the development of investment plans is one of the most important near-term activities that will lead to the capability to undertake these challenging, scientifically compelling missions.

The Roadmap for Mars: Follow the Water

NASA's Mars Exploration Program seeks to understand the climatological, geological, and potential biological evolution of Mars, and to develop an understanding of the martian environment in support of future human exploration. The common thread among these objectives is the study of water on Mars throughout space and time. Our exploration strategy is characterized by the increasingly refined search for sites that show evidence of past or present liquid water, and for materials that may preserve either biosignatures or paleo-environmental records. Increasingly focused orbital observations are coupled to surface investigations and ultimately sample return from selected sites. The strategy is executed in three overlapping phases:

1. *Seek*: Orbiters map chemical elements, mineralogy, physical properties, and geology at global to local scales.
2. *In situ*: Landers and rovers measure key physical and chemical processes.
3. *Sample*: Vehicles acquire and return to Earth carefully selected samples of rock, soil, and atmosphere for detailed laboratory analysis.

The missions in each phase provide data that help to define the goals, activities, and specific locations for the missions to follow, as well as

Twin Geologists to be Sent to Mars in 2003

They're robots, of course. The Mars Exploration Rovers are sophisticated mobile explorers that will roam Mars for three months or more, searching for and studying evidence of past liquid water and martian climatic evolution. Each rover can travel up to 100 meters per day and can take microscopic images as well as broad panoramas. The MERs are more than ten times the size of the Sojourner rover that fascinated the world in 1997, and will once again revolutionize our view of the Red Planet.



feedback that enables us to continually modify and improve the overall strategy. Each new mission builds on the technological and scientific heritage of prior missions and leaves a legacy for the missions yet to come.

Within the first part of this decade, the Mars Exploration Program will focus on coupled “seek” and “in situ” investigations, integrating results from Viking, Mars Global Surveyor, and Mars Odyssey, as well as upcoming Mars Exploration Rover surface observations. The second part of the decade will focus on a second cycle of observations based on Mars Reconnaissance Orbiter and Mars Science Laboratory measurements, with much greater capability to identify and access high-priority sites with evidence of persistent liquid water and organic materials. At the conclusion of this cycle of observations, shortly after the turn of the decade, we will be prepared to embark on the first set of detailed investigations of a selected high-priority site, careful selection of samples of key martian materials, and their return to Earth for analysis. It is with the advent of this third phase of Mars exploration that we have the potential to provide the greatest leaps in our understanding of the formation and evolution of the terrestrial planets and of life.

Mars Pathways

Our understanding of Mars has advanced dramatically in the past few years, and the pace of discoveries is only expected to increase. In order to most effectively build on these achievements, the Mars Exploration Program must remain flexible and “discovery driven.” This means that the sequence and content of future missions depends critically upon the results of the missions conducted earlier. Given the near certainty that significant discoveries will be made in the future — typified by those already made by Mars Global Surveyor and Mars Odyssey — it would be unwise and inefficient to establish a rigid sequence of highly specific missions extending deep into the next decade. Our future plans must remain flexible enough to take advantage of today’s investments.

The discovery-driven nature of mid- and far-term Mars exploration is reflected in the concept of Mars “pathways.” This is a framework that



Big Eye in the Sky

The Mars Reconnaissance Orbiter, to be launched in 2005, will observe the martian surface with unprecedented precision. By resolving features as small as 8–12 inches across, it will allow us to follow the tantalizing hints of water wherever they lead. MRO will revolutionize our understanding of the planet's geology and will be a key to selecting the best landing sites for future missions.

Mission Roadmap

describes options, or pathways, for the content and sequence of future investigations, based upon a likely range of potential scientific outcomes of current and near-term missions. It allows us to assess the value of potential missions and to look for common denominators, in engineering and science, that can be used to guide technology investments and mission scenario development.

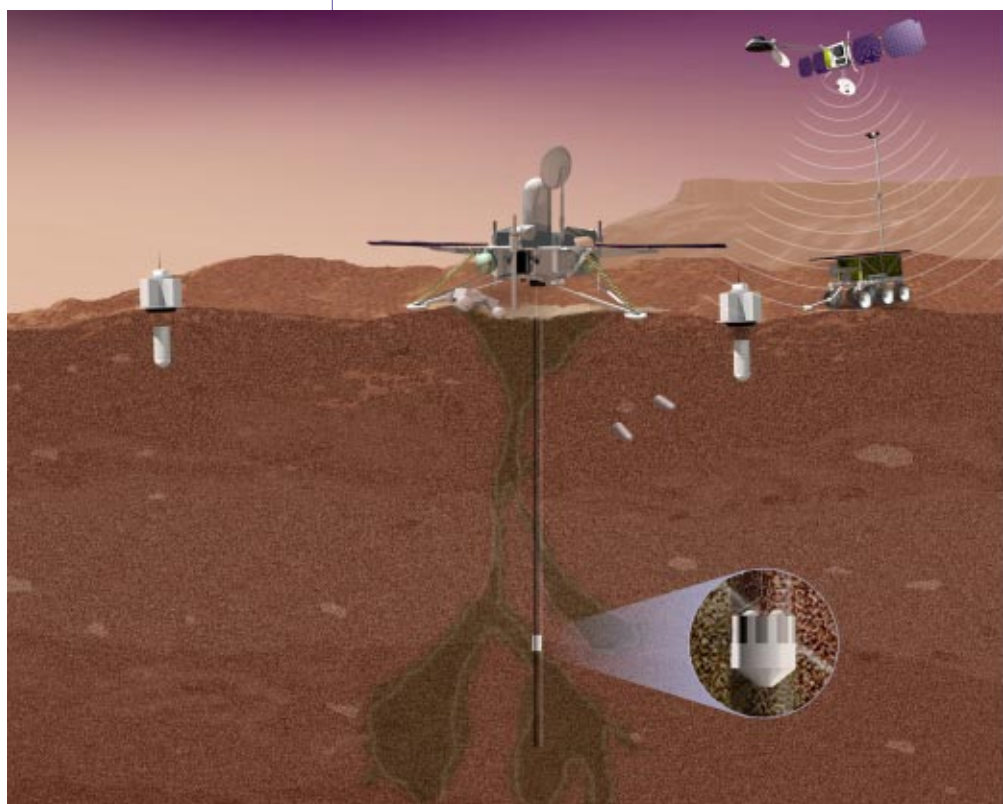
Prominent in a majority of the pathways are highly capable in situ science laboratories coupled with sample return missions. The measurement objectives of these in situ missions, and the specific sites to which they will be sent, will depend on the scientific discoveries made by preceding missions. Another common element shared by all pathways are the Mars Scout opportunities for innovation and rapid response using small missions.

Mars Scouts

The Mars Scouts are a family of small, competitively selected Mars missions analogous to those of the successful Discovery Program; like Discovery, the life-cycle cost for Scout missions is capped at \$325M (FY03). NASA's first Mars Scout will be selected in 2003 for the 2007 Mars launch opportunity. Also like Discovery, the details of Mars Scout investigations will not be known prior to mission selection, but one of the selection criteria will be the degree to which proposed missions advance the state of Mars exploration consistent with the program science strategy. Based on budget projections and scientific need, it is anticipated that Mars Scout missions will be launched at every other Mars opportunity, or about once every four years. The Mars Scout Program will

Beneath the Martian Surface

One Mars exploration "pathway" might focus on exploration of extinct hydrothermal vent systems in the search for evidence of life below the surface.



allow the Mars science community to propose, lead, and participate in exciting small missions that will address focused Mars science questions, some of which may fill key science “gaps” while others will provide critical foundation data sets.

Mars Science Laboratories

The year 2009 will represent another quantum leap in Mars exploration when the Mars Science Laboratory (MSL) is planned to be launched. The revolutionary scientific and technological capabilities incorporated in this mission will make it an appropriate capstone for this decade’s exploration of the Red Planet. At the same time, it will serve as a bridge to the exploration pathways to be followed in the next decade.

The overall objective of MSL is to address issues of martian habitability, which we define as the potential of the planet to have supported life at some time in its history. To accomplish this, MSL would be designed as a mobile platform for suites of instruments that enable it to function as a sophisticated in situ scientific laboratory. Included will be a “contact suite” of instruments that require physical contact with rocks or soil, a “remote sensing suite” for more distant observations, and, most importantly, an “analytical suite” to take in and analyze samples of martian materials. The combination of these data types will allow us to answer critical questions of martian geological and climate history, and will elucidate the nature and extent of potentially habitable environments.

In conducting these new measurements, MSL would represent a major advance in our ability to explore Mars and the other planets. It would incorporate precision landing, by which we can land within a few kilometers of sites of targets of scientific interest, hazard detection and avoidance, and long-range mobility that will allow us to explore specific sites up to several kilometers away in a single mission. MSL may also incorporate a new radioisotope power system that will provide it with an operational lifetime of a year or more, dramatically increasing the scientific capability of this advanced robotic explorer.

The Mars Scout Program

will allow the Mars science

community to propose,

lead, and participate in

exciting small missions that

will address focused Mars

science questions. The first

Mars Scout will be launched

in 2007.

Mission Roadmap

Mars Telesat

In order to maximize the science return from our spacecraft operating on and around Mars, NASA is planning to place a communications relay satellite — a Mars Telesat — into orbit around Mars in 2009. This satellite will be designed for a lifetime of at least six years, with a goal of ten years, and will be placed into a high Mars orbit that will enable it to cover a large fraction of the martian surface every few hours. The Telesat will not only substantially increase the total volume of data that can be returned from Mars, it will also provide essential telemetry relay during critical events such as Mars landings, orbital entries, and the launch of samples from the martian surface.

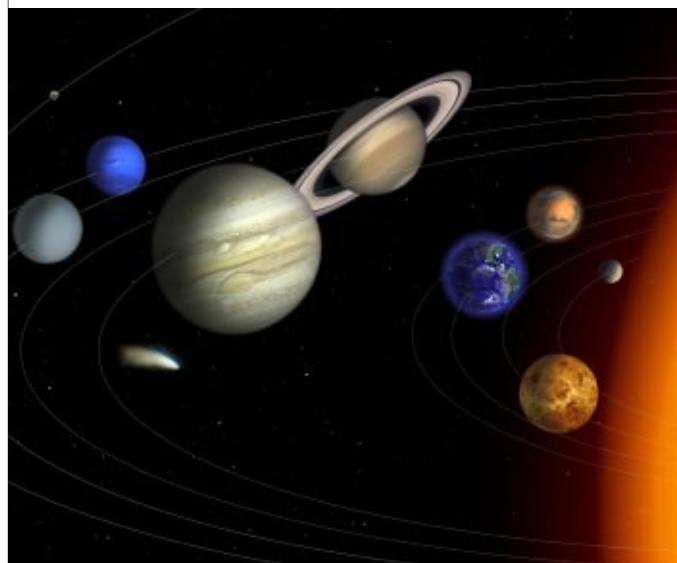
In addition to its role as a relay at various radio frequencies, the Telesat will carry the first deep space optical communications payload. This revolutionary technology utilizes laser light instead of radio waves to dramatically expand the data “pipeline” to Earth. As the first operational test of optical communications for planetary missions, this experiment on the Mars Telesat will help to alleviate one of the fundamental constraints on solar system exploration, and will pave the way for the next generation of highly capable planetary explorers.

Mars Network

Collective monitoring of martian seismic activity and meteorology through a network of landers will provide a unique picture of the three-dimensional, time-varying phenomena associated with the deep interior, weather, short-term climate variability, and hydrological cycles. Such a Mars Network is an important future mission goal of the Mars Exploration Program. Technology investments will seek to develop long-life, lightweight systems capable of three-dimensional sounding for liquid water, interior structure, and climate studies.

Mars Sample Return

More so than any other solar system exploration objective, the return of samples from the surface of Mars has been studied extensively for more than two decades. The reasons for this are twofold: first, analysis of samples from Mars will dramatically advance our understanding of martian climate evolution and habitability; and second, Mars sample



A New Understanding

Our discoveries throughout the solar system in the coming decade will lay the foundation for the new and challenging missions to come. Intensive exploration of planetary environments and analysis of returned samples will bring us to a new understanding of our solar system and our place in the cosmos.

return is a complex and expensive endeavor. Due to this combination of scientific priority and technical challenge, implementation of Mars sample return may be best accomplished using a phased approach. Because the return of even a small amount of martian material will so greatly advance our understanding of the planet's environment and history, a first "groundbreaking" sample return may be flown to allow the return of soil, rock fragments, and atmosphere from a fixed lander. This would considerably reduce mission cost and risk compared to more aggressive implementations. Subsequently, more capable Mars sample return missions would return carefully selected samples using mobile platforms and perhaps multiple site sampling. This could eventually include the return of samples from the subsurface. Current plans call for an initial sample return as early as possible in the next decade, and therefore the Mars Exploration Program is investing in technologies now that will enable this mission. The priorities and plans for subsequent Mars sample return missions will continue to be refined based on the scientific achievements and technological advances of the Mars Exploration Program.

Far-Term Missions

Planning for missions in the post-2016 timeframe is an iterative process that starts by hypothesizing potential discoveries and mission outcomes during the next 15 years. Studies of alternate investigation pathways demonstrate that future Mars Science Laboratories represent a critical capability for sustained presence on the surface. Depending upon the location and environment in which we find potential habitats, long-range rovers, deep drilling, and polar operations will be undertaken using sensitive analytical instruments. Sample return from surface or subsurface habitats of biological potential will very likely be assigned the highest priority for the long-term program. These sample return missions must have a "Go To" capability in which safe precision landing, coupled with mid- to long-range mobility, can acquire key samples retrieved from highly localized surface targets such as an outcrop of sedimentary rock or a drill hole. This robotic exploration and sample return program will lay the groundwork for future scientific expeditions by human explorers.

A balanced set of small,
medium, and flagship
missions will allow us to
best meet the wide variety
of scientific and technical
challenges of solar system
exploration.

Technology

Solar system exploration is a uniquely challenging endeavor. It requires that we build efficient, highly capable robotic vehicles and send them across vast distances with the tools they need to make detailed scientific measurements.

We must furnish them with the power they need to conduct their missions; we must place them into orbit around or onto the surface of bodies about which we may know relatively little; and we must ensure that they survive and function in environments that can be very hostile. We design them to acquire and transmit the maximum amount of information during their mission lifetimes, and sometimes to return safely to Earth with a cargo of planetary samples. The scientific imperatives of solar system exploration have motivated some of the most remarkable engineering achievements of the past four decades.

As solar system exploration progresses, new challenges arise and prior challenges take on new dimensions. The routes of this roadmap demand progress in diverse technologies that enable or enhance future missions. Many of these technologies are of broad benefit across the spectrum of planetary missions, because they enable us to better cope with the challenges common to virtually all destinations and investigations. Other technologies are more specifically tailored to meeting the needs of individual missions or classes of missions. This section will summarize the key requirements and the investment strategy for both categories of technologies.

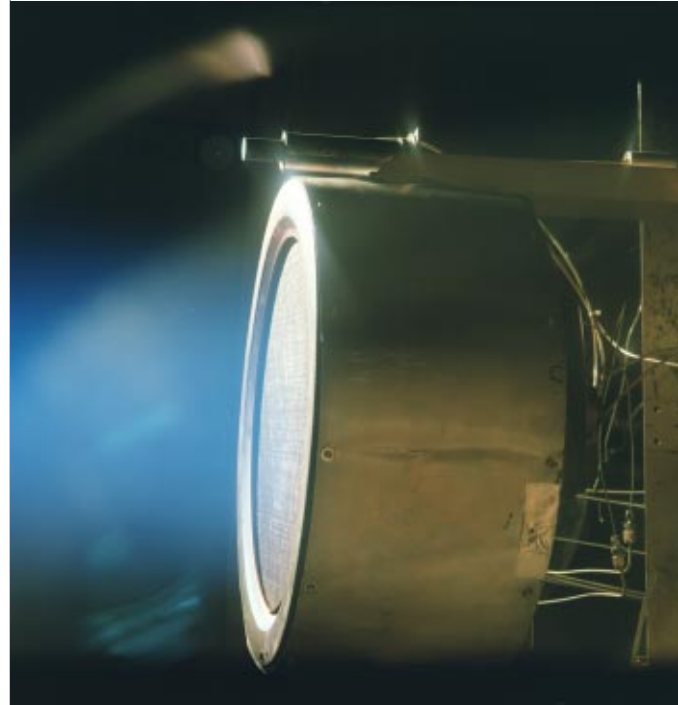


Technologies of Broad Benefit

The challenges common to virtually all planetary missions — large distances, long flight times, and stringent limitations on mass, power, and data rate — mean that essentially all types of missions can derive significant benefit from advances in these areas. Investments in relevant technologies help to reduce mission costs and increase capabilities for exploration and science return. Since technology development timeframes can be long, it is frequently necessary to base technology requirements on the expected general characteristics of future missions in order to provide the greatest benefit. In addition, since the small (Discovery and Mars Scout) and medium (New Frontiers) missions will be competed, their technology needs must be broadly stated as those which are most likely to be beneficial to those classes of missions.

In-Space Propulsion

Chemical propulsion has been used on all previous planetary missions. Many of the more energy-intensive missions planned for the future, however, would be severely constrained by chemical propulsion technology, which is approaching the limit of its capabilities for reasonable flight times. A major step forward in interplanetary transportation technology occurred in 2001 with completion of the space validation of solar electric propulsion (SEP) by the New Millennium Program's DS-1 spacecraft. This technology can reduce the propellant required to reach certain planetary destinations by a factor of 10 or more, and can significantly reduce flight times for high-energy missions. The first planned application of SEP on a science mission will be Dawn, a multi-asteroid orbiter, under development for launch in 2007. Significant improvements in the efficiency and performance of SEP are underway, and the resulting systems may provide substantial benefits to this roadmap's planned missions to small bodies and the inner planets. When coupled with aerocapture (rapid aerodynamic braking within a planetary atmosphere), SEP may also enable rapid and cost-effective delivery of orbital payloads to the outer solar system, as well as the ability to deliver much larger payloads into orbit around Mars and Venus.



Ion Propulsion

Ion propulsion, powered by either solar or nuclear energy, provides continuous low thrust at very high efficiency.

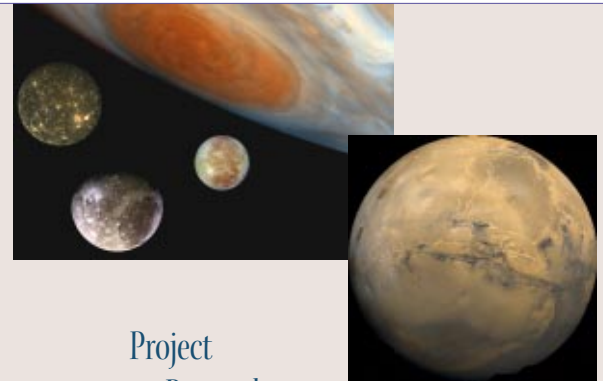
Technology

Mid- and far-term flagship missions to the outer solar system, such as the Jupiter Icy Moons Orbiter, will require a propulsive capability that far exceeds the potential of chemical propulsion or SEP. For these high-priority missions, nuclear electric propulsion (NEP) is an enabling technology. This requires the development of a compact and efficient fission power source coupled to advanced electric propulsion systems. Such a capability will open up the entire solar system to intensive exploration, enabling missions that can visit multiple planets and satellites, deliver large payloads, and return samples from virtually any destination. This and other propulsion techniques are being investigated within the In-Space Propulsion Program and Project Prometheus, formerly known as the Nuclear Systems Program. Technologies will be selected for development based on their benefit to future science missions as well as on safety, cost, readiness, and other factors.

Advanced Power Generation

Solar power is generally insufficient beyond the main-belt asteroids, and limits the lifetime of landed spacecraft on Mars. As a result, radioisotope thermoelectric generators (RTGs) have been used on all of NASA's previous outer solar system missions and on the Viking Mars landers in the 1970s. Future outer solar system missions, as well as other missions for which solar power is insufficient, will require an improved non-solar power generation capability. NASA is developing a new generation of advanced radioisotope power systems that would ultimately provide up to five times the electrical conversion efficiency of prior RTGs in a unit less than half the size. This reduced weight and improved power would greatly enhance mission performance for many of the high-priority missions of this roadmap.

The high power available from fission reactor systems (10–100 kW or larger) would not only enable advanced nuclear propulsion systems, it may also enable new types of active science investigations as well as very high data transfer rates from anywhere in the solar system. Under Project Prometheus, NASA is striving to bring fission power to maturity and infuse it into solar system exploration missions. Studies



Project Prometheus

To meet the needs of the next generation of highly capable planetary explorers, NASA is developing new, safe, reliable power and propulsion systems based on nuclear technologies. Project Prometheus has two primary near-term objectives. First, it will develop a new, more efficient radioisotope power system (RPS) to provide spacecraft electrical power for surface and deep space applications. The first use of this new RPS may be on the Mars Science Laboratory, to be launched in 2009. Project Prometheus is also developing a compact fission reactor that would provide power of up to 100 kilowatts to support nuclear electric propulsion. This technology would revolutionize solar system exploration by enabling high-energy missions that cannot be accomplished using conventional power and propulsion technology. The first utilization of fission power and propulsion would be on the Jupiter Icy Moons Orbiter, which is under study for possible launch early in the next decade. Project Prometheus represents one of the key building blocks of the exciting and scientifically rewarding Solar System Exploration Program envisioned for the future.

are underway to determine the best implementation of these technologies at the earliest possible time. Fission power and the propulsion capability it enables would represent paradigm-altering technologies of great potential benefit to robotic and, eventually, human exploration of the solar system.

Telecommunications

Progress in solar system exploration over the past forty years has required major improvements in deep space telecommunications. The most recent advance is the implementation of communications systems operating at Ka-band. This capability, to be fully demonstrated on the 2005 Mars Reconnaissance Orbiter, will provide a data rate from Mars of more than 2 megabits/second. In order to take full advantage of the potential of future missions, we must further extend the capabilities of the “trunk line” between Earth and planetary destinations.

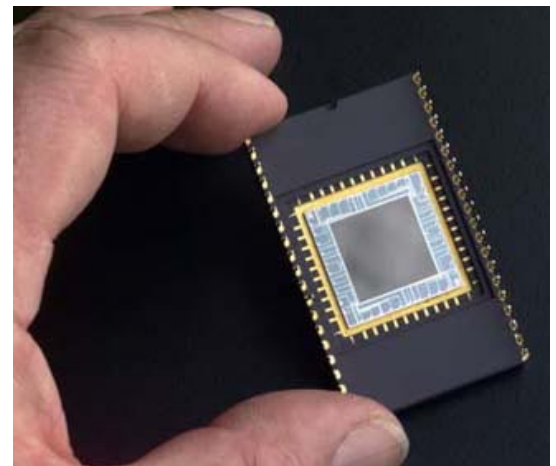
Technology developments underway now will allow improved radio telecommunications performance through the use of large deployable spacecraft antennas and ground-based antenna arrays. In the longer term, the most dramatic leap will come with the development of optical communications. This will enable video-rate communications from Mars and large gains in data rate for exploration of the outer solar system. Advanced optical and/or radio communications should be developed and flight-qualified near the end of this decade for use by the next generation of planetary missions. Investment in the Deep Space Network will be needed to support these capabilities. Along with developments in the proximity links that allow surface vehicles to communicate with relay orbiters, these are major steps toward the goal of enabling real-time access by the science community and the public to our robotic explorers across the solar system.

Avionics

Avionics technology for operating in the intense Jupiter radiation environment has been under development since 1997. This is a critical technology for high-priority missions to the Galilean satellites, and is of

Miniature Components

The need to miniaturize our spacecraft has led to major advances in computer and electronics technologies.



Technology

broad benefit across the Solar System Exploration Program. Newly developed avionics elements are already planned for use on the Discovery Program's Deep Impact mission, the Mars Reconnaissance Orbiter, and the Mars Science Laboratory. The Office of Space Science endorses a competitive environment where innovative approaches to enable avionics to survive high-radiation environments will be encouraged.

Software

As missions have become more complex, software engineering has become one of the most challenging technology development disciplines. New technologies are needed to support the design, modeling, and simulation of flight systems. The expanded use of autonomy in exploration presents new challenges for software verification and system-level validation. Innovative approaches, including the use of Earth environments as analogs for extreme solar system environments and the application of commercially developed software where possible, will enhance software reliability as well as our ability to predict software development costs. Software advances must be applied to the entire mission life cycle, from the definition of initial requirements and mission concept through flight and data analysis.

Data Validation, Archiving, and Analysis

As telecommunications systems are developed to transmit more data, and new instruments are developed to exploit the high power provided by Project Prometheus, new technologies for data validation, archiving, and analysis will be needed. Even in the near-term, the large data volume expected from the Mars Reconnaissance Orbiter will require more efficient archiving than has been previously available. Technologies developed for archiving Earth science data will be explored for adaptation to the specific requirements of solar system missions.

Technologies for In Situ Exploration and Sample Return

In the next decade of solar system exploration, many missions will perform intensive in situ exploration of planetary bodies and, in some cases, return samples to Earth for detailed analysis. These missions require advanced technology tools and system approaches for safe, pre-

Optical Communications

As the number and capability of solar system missions increases, we must expand the capacity of the data return "pipeline" through which our spacecraft communicate their discoveries back to Earth. To achieve this, NASA is exploring the development of a communications capability that relies on laser light instead of radio waves. This "optical communications" system will transform our scientific capability by greatly increasing the amount of data that can be returned from each mission. The first deep space demonstration of optical communications will take place on the Mars Telesat mission around the end of this decade. Laser communications from deep space will be received by simple optical telescopes, operating either on the ground or on platforms above Earth's atmosphere.



Small laser transmitters and onboard telescopes may replace the radio dish antennas that have been a feature of all prior planetary spacecraft.

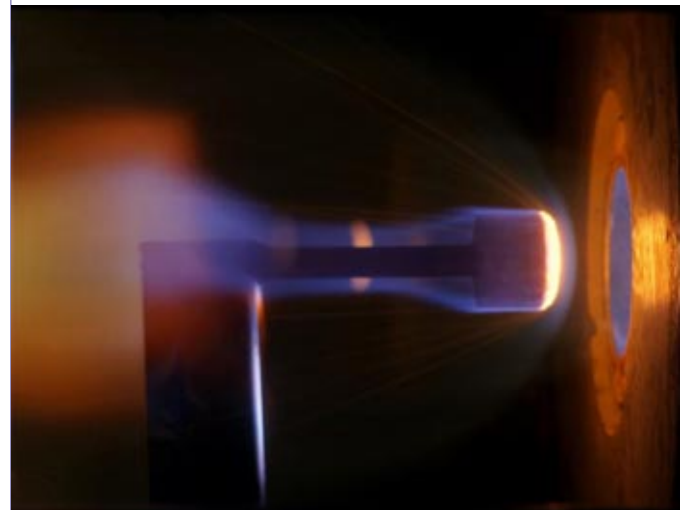
cise landing; autonomous mobility in the planetary atmosphere, surface and subsurface; tolerance of extreme environments; acquisition and return of samples safely to Earth; and protection of the target planet, Earth, and the sample itself from possible contamination.

Entry, Descent, and Landing

Safe and accurate landing of robotic vehicles on diverse solar system bodies is one of the unique challenges of solar system exploration. A number of the missions described in this roadmap have some requirement for descent and landing, and so technology developments in this area are particularly important. The Mars Exploration Program is investing in technologies that will also be applicable to other bodies with atmospheres. The precision guidance technology under development by the Mars technology program will use advanced optical navigation methods and aerodynamic guidance to improve landing accuracy by a factor of 20. This will enable landing within roving range of the scientific sites of greatest interest, while avoiding hazardous regions such as craters, mountains, and canyons. This precision guidance capability will be supplemented by hazard avoidance technology to enable the spacecraft to detect large rocks and steep slopes during terminal descent and maneuver in order to avoid them. Resilient landing systems that involve deployable airbags or pallets further ensure that payloads are safe when landing on the most inhospitable terrain. Although there is no single entry, descent, and landing system applicable to all of the widely diverse types of bodies we seek to explore, the critical advanced technologies for precision landing and hazard avoidance can be utilized as a foundation for the capabilities needed by all missions. Entry into the atmospheres of the outer planets, particularly Jupiter, presents exceptional challenges that will require development of lightweight thermal protection technologies and suitable testing facilities.

Autonomous Planetary Mobility

The ability to move from place to place at a planetary destination dramatically increases the science return of in situ and sample return missions. The primary challenge we face in implementing mobility is latency, the time delay between the sending of a command from Earth and the time at which the results of that command are known. Au-



The Heat Is On

Our spacecraft must survive the searing heat of atmospheric entry before they can explore planetary environments. Here, a high-temperature arc jet is being used to test new thermal protection technologies.

Technology

tonomy technology is a key to meeting this challenge, and significant advances are under study now. The Mars technology program, for example, is developing technologies that will enable a rover to travel to and sample a rock 10 meters away with a single command, thus greatly multiplying the scientific productivity of the vehicle. Autonomy technology will also enable aerial mobility, which may be a key feature of future missions to Mars, Venus, and Titan.

Another dimension of planetary mobility is the exploration of subsurface environments. These may be particularly important to the search for extant life, since it is quite plausible that such life would be found beneath the surface of Mars or Europa, if it exists at all. Advanced drilling, coring, or boring devices, carrying scientific sensors and tethered to a surface platform, will be required to enable in situ exploration of potentially habitable environments.

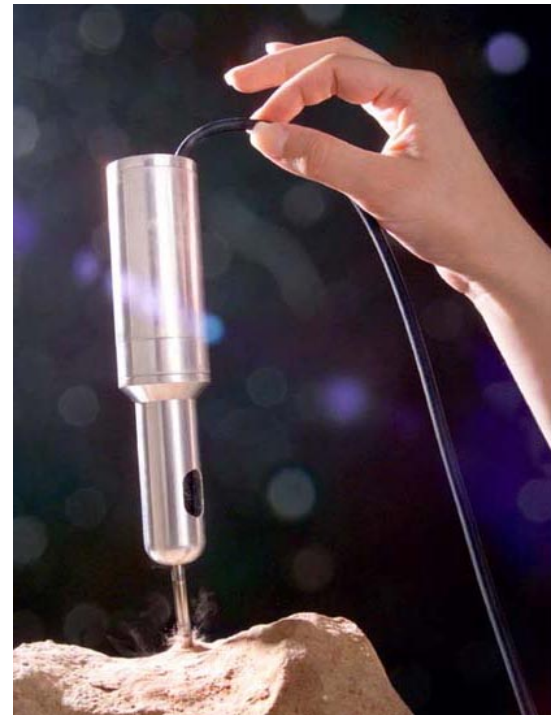
Technologies for Extreme Environments

Future solar system exploration missions will experience a wide range of conditions, from the comparatively benign environment of Mars, to the intense radiation environment around Europa, to the searing heat and crushing pressure within the atmospheres of Venus and Jupiter. The need for spacecraft to survive and make measurements in this wide variety of environments is a major challenge for the next generation of solar system missions.

At the surface of Venus and at the depths we must explore on Jupiter, the convergence of temperature and pressure conditions limits the lifetime of systems built with present technology to just minutes. Improved pressure vessels, thermal control, temperature-tolerant electronics, and low-power systems are needed to prolong the lives of these vehicles.

Sample Return Technologies

NASA's first robotic sample return missions, Genesis and Stardust, are presently in flight and will return their samples to Earth in 2004 and 2006, respectively. Sample return missions to the Moon, Mars, and



Ultrasonic Drill

Technologies such as this lightweight ultrasonic drill will allow us to explore and sample planetary materials with high efficiency.

comets are identified as high priorities in this roadmap, and it is expected that future strategies will continue to identify sample return as a compelling mission objective.

Sample acquisition and return is a very broad system-level capability requiring the interaction of a number of new technologies. Power and propulsion, safe entry and landing, sample selection sensors, sample handling and packaging systems, ascent vehicles, rendezvous and docking, and lightweight Earth entry vehicles are all required. The primary challenge will be to develop an integrated plan that will lead to cost-effective sample return missions to a wide variety of targets, starting with the Moon, small bodies, Mars, and Venus, and ultimately progressing to the outer solar system.

Planetary Protection Technologies

It is both a scientific and a legal requirement that missions to objects of biological interest, such as Mars and Europa, must not contaminate the target body until the biological exploration of the body is complete. Furthermore, biological contamination must not compromise the integrity of life detection experiments. To meet these requirements, cleaning and sterilization of the spacecraft must be carried out before launch. New technologies are needed in order to perform and validate the results of this process in a cost-effective manner.

Sample return missions to bodies of biological interest must also be engineered so that samples are safely contained as they return to Earth, until they can be thoroughly evaluated for potential biological and environmental hazards in a quarantine facility. New technologies and new system design approaches eliminate the risk of inadvertent release of sample materials and permit effective study of the contained sample.

Technologies for Science Instruments

To achieve the scientific objectives of our missions, increasingly capable scientific instruments will be required. Advances in component and detector technologies as well as instrument system architectures will benefit the next generation of scientific instruments. New opportunities for

Learning from Nature

Miniaturized rovers inspired by biological systems are being studied as one way to access key planetary environments. Here, a "spider-bot" undergoes mobility tests in the laboratory.



Technology

novel measurements will be made available by the advent of fission power systems, and new classes of instruments will be required to take advantage of this opportunity.

The payoff from miniaturization of planetary instruments is significant, since the cost of delivering 1 kilogram of payload to a planetary destination may be anywhere from five to thirty times the cost of delivering a comparable amount of payload to Earth orbit. The NASA-developed thermopile detectors to be used on the Mars Reconnaissance Orbiter, for example, reduced the mass of the instrument by 35 kilograms, providing a major benefit to the mission. Reducing landed mass is even more critical due to the additional propulsion and shielding required to place systems on planetary surfaces. Several NASA programs, such as the Planetary Instrument Definition and Development Program, the Mars Instrument Development Program, the Astrobiology Science and Technology Instrument Development Program, and the Astrobiology Science and Technology for Exploring Planets Program are addressing these critical instrument technology needs.

Remote Sensing

Technology developments continue to enable fundamentally new types of remote-sensing measurements from orbit or from aerial and surface vehicles. The Mars Orbiter Laser Altimeter (MOLA) on Mars Global Surveyor, for example, uses a new solid-state laser to acquire extraordinary data on Mars' surface elevation. In the future, new types of laser systems will enable the detection of trace atmospheric species by molecular absorption, mineralogical identification exploiting the Raman effect, and elemental analysis using laser ablation. Active scanning laser systems will enable three-dimensional mapping of landing sites with centimeter-level vertical precision as well as direct detection of ices within shadowed or night-side regions.

The introduction of fission-powered spacecraft will provide the opportunity to utilize high-power instruments using tens of kilowatts. Active remote-sensing instruments employing high-power lasers and radars,



Good Things in Small Packages

Sensors such as this miniature tunable diode laser enable detection of small amounts of water and other compounds in planetary environments.

previously not feasible for planetary applications, will become possible. Investments are being planned now to take advantage of this new capability.

In Situ Exploration

To carry out effective in situ exploration throughout the solar system, sophisticated analytical laboratories will be needed. In particular, the search for evidence of life on other planets requires not only new and more sensitive measurement techniques, but also fundamentally new principles of investigation. The most sensitive techniques require such complex equipment and sample handling that they cannot be implemented in situ in the near term and are only feasible in laboratories on Earth. Over time, however, the development of more sensitive miniaturized in situ laboratories will enable selection of the most interesting samples for return to Earth.

Technology Acquisition

The breadth of technology needs for solar system exploration calls for an aggressive and effective technology acquisition strategy. Because of the scope of our needs, we must leverage work elsewhere in NASA as well as in the government and commercial sectors. We must continually reassess the content of our technology initiatives based on evolving scientific needs and technology development progress. NASA will strive to maximize the payoff from its technology investments, either by enabling individual missions or by enhancing classes of missions. We will also invest in technologies that help us cope with the general limitations on power, communications, and mass that are faced by all planetary missions.

The Office of Space Science works in partnership with NASA's Office of Aerospace Technology to pursue developments in the fields of information technology, low-power electronics, power storage, sensors, and other technologies. A hallmark of this partnership is close cooperation among technologists, scientists, and mission and spacecraft development engineers for identification and research into technologies at the early conceptual stages. Technology investment priorities are guided by the requirements established in mission and system studies. Within the

The scientific imperatives
of solar system exploration
have motivated some of
the most remarkable
engineering achievements
of the past four decades.

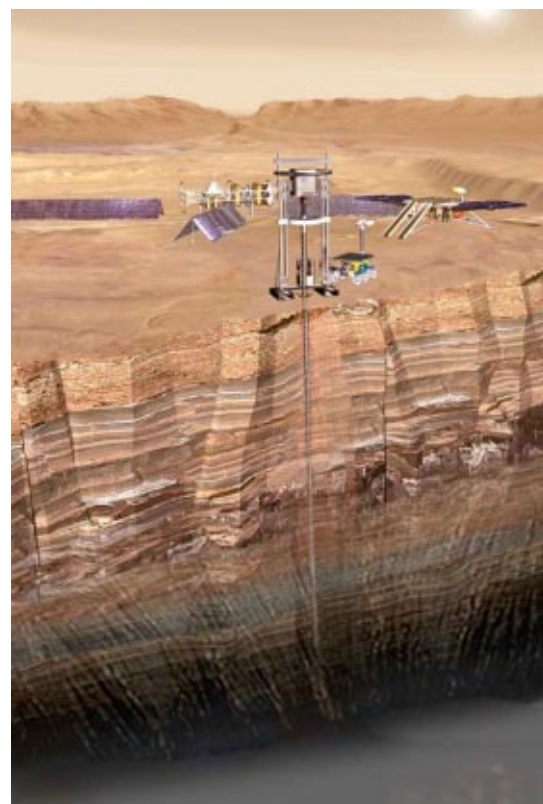
Technology

Office of Space Science itself, technologies of unique importance to solar system exploration are being developed by the In-Space Propulsion Program and Project Prometheus.

Certain technologies are of such a mission-critical nature that space-flight validation is considered a prudent step prior to their actual use. This can be done in two ways: on dedicated technology demonstration missions within the New Millennium Program, or by using other solar system exploration missions as a platform for their validation. New Millennium missions provide opportunities to validate technologies of a broad system nature, such as solar electric propulsion (flight-proven on the Deep Space 1 mission) or aerocapture. They also provide opportunities to validate sets of individual component technologies. Other technologies may be appropriate for validation on actual science missions in a non-mission-critical role. Early flight validation can ensure that the benefits of new technologies can be made available to future missions in a prudent and cost-effective manner.

Summary

The missions described in this roadmap, like virtually all planetary missions, will benefit substantially from advances in power, propulsion, telecommunications, avionics, and software. They also impose unique requirements for survival in extreme environments, safe entry and landing, mobility, science instruments, sample return, and planetary protection. The following table summarizes the key technology investments that will enhance or enable achievement of our future science objectives.



Drilling Down

In the long-term, challenging objectives such as deep drilling on Mars will be enabled by a robust, carefully planned set of technology investments.

Summary of High-Priority Technology Investments

TECHNOLOGY AREA	TECHNOLOGY INVESTMENT AREAS
Technologies of Broad Benefit	
<i>In-space propulsion</i>	<ul style="list-style-type: none"> • High-performance components for electric propulsion • Development and flight validation of aerocapture
<i>Nuclear systems</i>	<ul style="list-style-type: none"> • Advanced radioisotope power: high efficiency and high specific power • Fission power reactors for nuclear propulsion
<i>Communications</i>	<ul style="list-style-type: none"> • Optical communications for high-rate data transfer from the outer planets • Large arrays of ground-based antennas • Lightweight, large-aperture deployable spacecraft antennas • Proximity communications with low-mass/low-power components
<i>Avionics</i>	<ul style="list-style-type: none"> • Avionics for high-radiation environments
<i>Software</i>	<ul style="list-style-type: none"> • Improved development and verification environments for autonomous systems • Enhanced software reliability
<i>Data validation, archiving, and analysis</i>	<ul style="list-style-type: none"> • Automated data validation processes • Advanced archiving, databases, and data mining
Technologies for In Situ Exploration and Sample Return	
<i>Entry, descent, and landing</i>	<ul style="list-style-type: none"> • Precision navigation and approach guidance • Hazard avoidance and pinpoint landing • Anchoring technology for small bodies
<i>Autonomous planetary mobility</i>	<ul style="list-style-type: none"> • Advanced surface navigation with autonomous science • Autonomous aerial exploration for Titan, Venus, and Mars • Robotic probes and drills for subsurface exploration
<i>Severe environments</i>	<ul style="list-style-type: none"> • Tolerance of extremes of high and low temperature and high pressure
<i>Sample return technologies</i>	<ul style="list-style-type: none"> • Sample acquisition systems for diverse environments • Ascent vehicles for retrieval of samples from planets and large satellites • Rendezvous and capture of orbiting sample containers
<i>Planetary protection technologies</i>	<ul style="list-style-type: none"> • Cleaning, sterilization, and validation • Sample containment and monitoring
Technologies for Science Instruments	
<i>Remote sensing</i>	<ul style="list-style-type: none"> • Instrument components (detectors, lasers) enabling revolutionary measurements including microscopic imaging
<i>In situ exploration</i>	<ul style="list-style-type: none"> • High-power remote-sensing instruments • Analytical instruments for life detection and absolute age determination • Miniaturization of instruments

Research *and Analysis*

An essential part of solar system exploration is conducted every day in laboratories and offices on Earth. This is where the data that returns from our missions are analyzed and interpreted, and where information is turned into understanding.

It is also where the fundamental research and modeling is done that helps to define future investigations and flight missions. This forms the foundation upon which our understanding of the solar system is built, and relies on the talents of numerous scientific experts and students from universities and laboratories around the country.



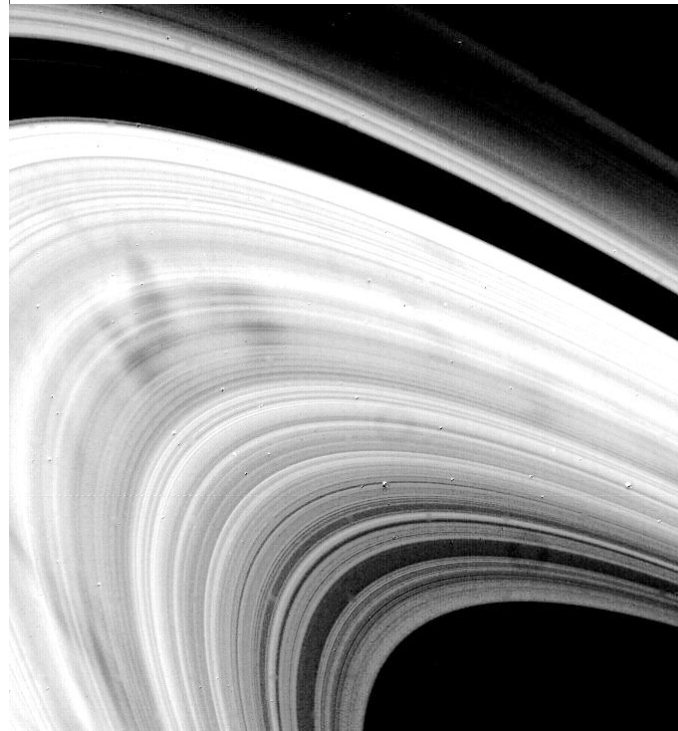
This section describes the NASA-funded research and data analysis programs that translate spacecraft data into knowledge and lay the theoretical groundwork for future investigations. It also describes infrastructure needs such as laboratory and computational facilities that enable our missions and research.

Solar System Exploration Research and Data Analysis

Solar system exploration is founded upon a robust program of research and data analysis. This covers areas of basic research in planetary science — theoretical studies, experimental and field research, laboratory studies, telescopic observations, and sample analyses — as well as supporting facilities such as ground-based telescopes, instrument development, laboratory facilities, computing centers, and the Planetary Data System. These Research and Analysis (R&A) programs are discipline-oriented and are not tied to specific missions. Data Analysis (DA) programs, by contrast, are tied to specific missions or data sets, and focus on reducing and processing data and drawing conclusions relative to the phenomena being observed. DA programs derive much of their focus and a cadre of expert researchers from the ongoing R&A programs, and in turn feed their results back into the next generation of research to spark new concepts, missions, and investigations. Research and data analysis programs represent an essential complement to flight missions, providing the scientific research and theoretical foundation that allows the nation to fully utilize the unique data sets returned from the solar system.

Research and Analysis Programs

Discoveries and concepts developed in the R&A programs are the genesis of missions, investigations, and instruments. The R&A programs are the primary interface with NASA for university faculty and graduate students; they allow training of the next generation of mission team members, principal investigators, and project scientists. Although not tied to specific missions, R&A programs frequently provide additional value to missions in the form of observations required for mission design, mission support, and joint scientific campaigns. Increasingly this support has expanded to include international, multidisciplinary campaigns in conjunction with spacecraft observations, greatly increasing the value of data from all platforms by combining observations and comparing different data types. Recent examples include the massive campaigns organized to support observations and characterization of the impact of comet Shoemaker–Levy 9 at Jupiter, and coordination of the joint



Rings and Spokes

Theories of planetary evolution and behavior have been revolutionized by intriguing and unexpected discoveries. The puzzling dark spokes in Saturn's rings were first seen by Voyager 2.

Research and Analysis

Galileo–Cassini encounters with Jupiter. In each case, massive computing and theoretical resources were devoted to the opportunities and a large fraction of the available Earth- and space-based observational assets supported the campaigns. Clearly, the last forty years of solar system exploration and the vision for future exploration contained in this roadmap could not exist without a vigorous R&A program.

Planetary research occupies an unusual niche in the scheme of federal funding for science in that a relatively large fraction of active planetary scientists are supported entirely on NASA grants. With increasing competition for limited funds, many scientists must submit multiple proposals to obtain full-time support; this tends to inflate the scope of the entire peer review process and detracts from the time available for scientific research. Growth in this area to keep up with the expanding range of flight missions, and timeliness of grant funding, are issues which NASA is committed to addressing.

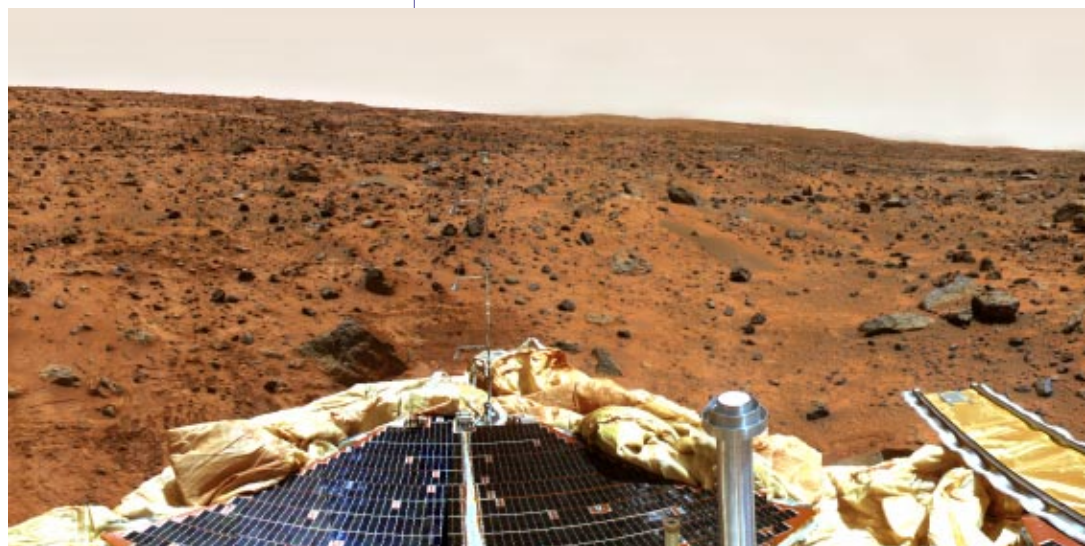
Data Analysis Programs

DA programs supplement the R&A programs and become active as soon as mission data begin to flow to Earth. They may also draw on data that were returned years earlier, enabling use of new analysis techniques and allowing older data to be reviewed in the context of new discoveries and theories.

Three years after the Galileo probe descended into Jupiter's atmosphere, for example, it was realized that the relative abundances of volatile elements and noble gases pose a very challenging puzzle for theories of planetary origin — they indicate that Jupiter's solids formed at temperatures much lower than the freezing point of water. To effectively utilize the data

Beyond the Rock Garden

The data returned from planetary missions are analyzed over periods of years. As new techniques and theories develop, even older data sets can yield new discoveries. Recent Mars surface images, for example, are used for comparison with older Viking data. They also help us to interpret today's ongoing orbital observations. This panorama of Mars was taken by Mars Pathfinder in 1997.



from planetary missions and integrate them with the broader research community, DA programs have been made an integral part of future mission plans.

Infrastructure and Facilities

Solar system exploration mission and research goals require a number of unique infrastructural elements. Maintaining and improving these elements, identifying and funding new developments, and making them available to all qualified researchers is an important part of maintaining a healthy exploration program.

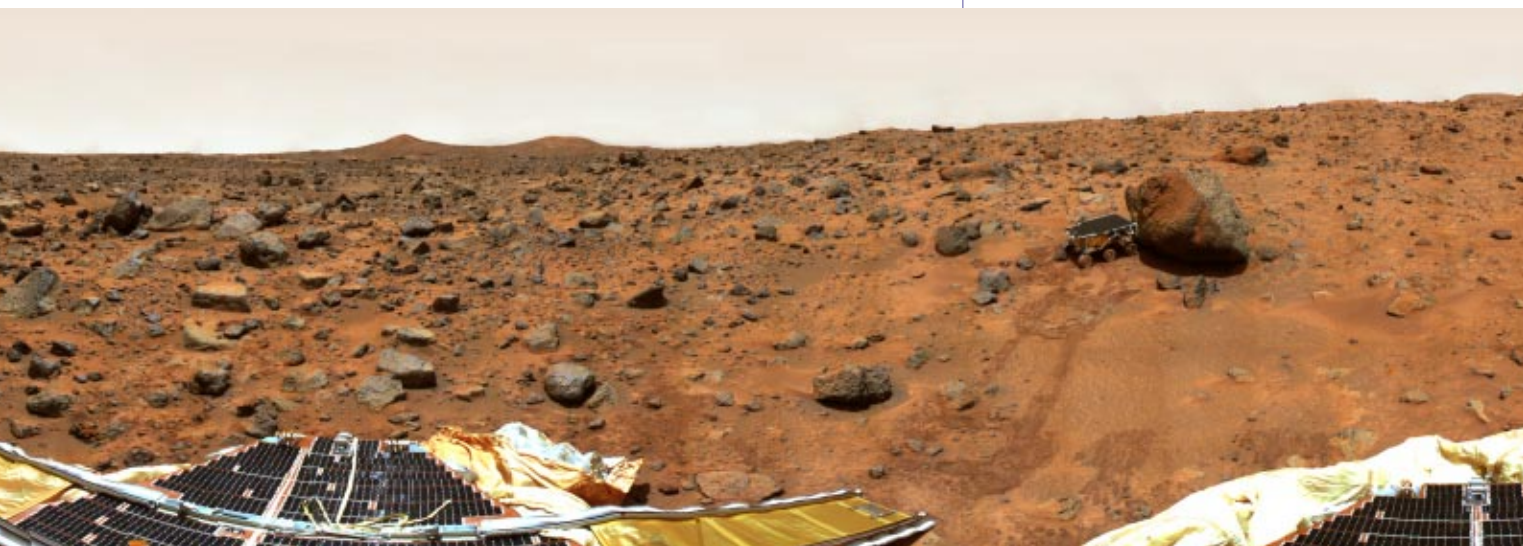
Planetary Data System

Archived data from solar system exploration missions is a vital resource for generations of scientists and represents the product of substantial national investment. The Planetary Data System (PDS) is NASA's facility for validating, archiving, and releasing data to the research community. Given the huge volume of planetary data soon to be returned by upcoming missions, and the number, variety, and complexity of instruments to be flown, the task of the PDS is substantial. Furthermore, with the success of Discovery and the initiation of the New Frontiers Program, there will be an increase in the number of Principal Investiga-



Sample Curation

Clean-room facilities for handling and analysis of planetary samples ensure scientific integrity and long-term availability for future scientists.



Research and Analysis

tor-led missions rather than NASA center-led missions. NASA will work aggressively to ensure that data archiving and PDS issues are addressed at an early stage in every mission. NASA will also work to upgrade the PDS by developing and adapting new technologies and methodologies for data validation, archiving, and distribution.

Laboratory and Computational Facilities

Comprehensive preparation for new investigations and complete interpretation of the data returned from our spacecraft are not possible without adequate support of complementary activities in laboratory science and computation. Laboratory activities include the determination of material properties under conditions encountered in the solar system, as well as the development and testing of analytical techniques to characterize natural or analog materials from other bodies. The techniques and instruments that are developed in the laboratory can then be applied to flight missions for in situ or returned sample analysis. Similarly, continual improvements in computational capabilities are essential if we are to fully understand and interpret the complex and interrelated data sets that are returned by solar system missions.

Sample Return Facilities

A particularly critical aspect of laboratory analytical facilities centers on the handling and analysis of samples returned from planetary bodies. Sample return from comets is scheduled to begin with the return of comet dust from the Stardust mission in just a few years, and samples of the solar wind will be delivered by Genesis in 2004. These will be followed during the next decade by lunar and comet surface samples, as well as by at least one and perhaps multiple Mars sample returns. Existing sample facilities for curation and analysis of extraterrestrial material were primarily developed during the Apollo era and have also been used for major meteoritic studies. These will require both regular maintenance and significant upgrades to be ready for new classes of samples and the much more capable analysis that will be required.

Just Passing Through

During its flyby of Jupiter in December 2000, the Cassini spacecraft captured this image of Io silhouetted against Jupiter's cloud tops. Cassini's observations provided new information on Jupiter's atmospheric dynamics and Io's volcanic activity. These data sets will help researchers to refine their models of these important planetary phenomena.



Deep Space Network

The Deep Space Network (DSN) provides the capability to communicate with spacecraft throughout the solar system. It consists of complexes of large radio antennas at three primary locations around the world, as well as the supporting infrastructure, software, and data distribution systems through which spacecraft transmissions are provided to mission operations teams and scientists. The DSN represents a major national investment and a unique capability for deep space communications, and the maintenance and continuous improvement of the DSN is critical to achievement of our goals for solar system exploration. To accommodate the increasing number of planetary spacecraft and the large data volume expected, NASA is upgrading the DSN to operate at higher radio frequencies and to improve its ability to track multiple spacecraft. NASA is also studying methods of electronically arraying large numbers of smaller radio dishes to increase the total antenna aperture. As optical communications becomes operational during the next decade, the DSN will evolve to accommodate this new technology that will transform our capability for deep space communications.

Near-Earth Object and Kuiper Belt Object Surveys

Ground-based telescopes represent a tremendous resource for solar system exploration, and continuing improvements are providing an ever-expanding range of research opportunities. In particular, our appreciation for the importance of Kuiper objects and near-Earth objects has increased dramatically in the past few years, and ground-based telescopes represent one of the most effective near-term methods to carry out the required observations. NASA will continue to use ground-based observations when required to support the investigations conducted by its spaceflight missions.



Deep Space Network

Planet Earth communicates with its explorers across the solar system using NASA's Deep Space Network. This is the DSN complex at Canberra, Australia.

As we explore our planetary neighborhood, striving to unlock the secrets of the solar system and of life itself, we have an equally important opportunity to make lasting contributions to the education of our nation's youth and the scientific literacy of the American people. The intrinsic excitement of exploration, coupled with the beauty and mystery of the planets, provides a unique and compelling context for direct participation by students and the general public in this long-term journey of discovery. Through this participation we will enable the next generation of explorers to write new and exciting chapters in the story of the solar system and our place within it. By engaging the public in this adventure, we seek to make solar system exploration a part of the shared human experience on Earth, and through it to contribute to the long-term growth of America.



Education *and Public Outreach*

Common Principles

Five cross-cutting principles are applied to all solar system exploration education and public outreach activities. Together these allow us to reach the largest possible number of students and citizens with engaging and meaningful programs tailored to their needs and experiences.

These principles are applied to the design and implementation of our formal and informal education programs, as well as to our public outreach activities. They allow us to communicate with our audiences effectively and use our resources efficiently, helping to maximize the impact of our initiatives on students and the public.

Formal Education: Reaching Out to the Next Generation and Those Who Teach Them

NASA has recently reinforced its long-standing commitment to education by making it a part of the Agency's core mission. Indeed, one of the ten NASA-wide goals is to "Inspire and motivate students to pursue careers in science, technology, engineering, and mathematics." Solar system exploration has been and will continue to be one of the most valuable scientific disciplines through which NASA fulfills this responsibility to the nation. The planets, moons, and other objects in our solar system offer a fun and familiar entry point into all areas of science. The bodies in our solar system — Mars, the rings of Saturn, the tail of a comet — are already a part of the popular consciousness and imagination, representing many of the most widely recognized and easily identifiable natural phenomena within our human experience. They provide an ideal context for the introduction of scientific principles to students at all levels.

Solar system exploration offers unique opportunities for inspiring an interest in learning, offering accessible, real-world examples of how science and math are applied to achieve exciting discoveries. Classroom activities bring the scientific process into student experiences and provide opportunities for students to solve engineering and design challenges within real-world constraints. By providing them with direct access to actual solar system data and mission results, we can help stu-



Cross-Cutting Principles

- **Work thematically:** Organize solar system education and public outreach along themes that have enduring human meaning.
- **Infuse and use planetary science data and technology:** Engage our audiences using real missions and real discoveries.
- **Involve scientists, engineers, and NASA staff:** Train and utilize the people actually doing science and exploration to explain its relevance and communicate their excitement.
- **Reach diverse audiences:** Customize and orient programs based on audience needs and interests.
- **Work closely with partners:** Make engaging material readily available and leverage the capabilities of libraries, museums, and science centers.

Education and Public Outreach

dents to see how fundamental principles of science and math can be applied to solve the complex problems of exploration. The breadth of solar system exploration allows us to tailor educational programs to various grade levels to provide the most meaningful learning opportunities.

Informal Education: Bringing Exploration to Life in Our Home Communities

Informal education covers all of the enriching experiences found in museums, science centers, planetariums, libraries, parks, youth groups, and community organizations. Research shows that informal educational experiences significantly enhance classroom learning and influence career choices. Research also indicates that the family's role in the education of children is vital, and informal educational settings provide the opportunity for adults and children to learn and explore together. Once again, the scientific breadth and the highly visual nature of solar system exploration make it an ideal forum for education of people of all ages. NASA's missions provide content around which entire displays and interactive programs can be based.

By partnering with the informal education community on projects of mutual benefit, solar system exploration can reach and inspire larger and more diverse audiences. These organizations provide places where people can gather for shared experiences and lifelong learning. They have the power and the expertise to create lasting memories and experiences for people, and are venues where the public can "ride along" on missions to the planets and other intriguing destinations. The informal education community is essential for bringing to people the virtual experiences of other worlds and interpretation of scientific results. This is done through local, community-based programs that leverage public facilities, large-screen formats, and other immersive, experiential exhibits and activities. Informal programs can be tailored to the capabilities and needs of widely varying facilities and groups.

Formal Education

Target Grade Level	Educational Focus
<i>K–4</i>	<i>General scientific literacy</i>
<i>5–8</i>	<i>Interdisciplinary studies</i>
<i>9–12</i>	<i>Specific Earth science, biology, chemistry, and physics coursework</i>
<i>13–16</i>	<i>Direct participation in mission research</i>
<i>Pre-service and inservice educators</i>	<i>Systemic educator training</i>

Informal Education

Target Facility/Audience	Educational Focus
<i>Museums, science centers, planetariums, libraries</i>	<i>Visualization of mission data</i> <i>Professional development of informal educators</i>
<i>Youth and community groups</i>	<i>Professional development: "Training the trainer"</i> <i>Hands-on, immersive experiences</i>

Public Outreach

Target Medium/Audience	Public Engagement Focus
<i>Internet</i>	<i>Science and technology literacy</i> <i>Lifelong learning</i>
<i>Media support</i>	<i>Non-traditional media opportunities</i>
<i>Speaker support</i>	<i>Stories that communicate exploration themes</i> <i>Personal connection with scientists and engineers</i>
<i>Public engagement payload and mission experiences</i>	<i>Direct participation</i> <i>Personal experiences and broad involvement</i>

Public Outreach: Solar System Exploration in Your Living Room

Solar system exploration objectives and results are communicated to the general public through a variety of traditional and non-traditional means. Television and the Internet are ideally suited to the visual nature of the solar system, and thus represent the most effective means of reaching large numbers of people. They allow for regular updates on missions that can sometimes last for years, and they provide opportunities for enhanced focus on special events such as launches, planetary landings, and key discoveries. The Internet in particular has proven to be a tremendous resource for public engagement; since the days of the Mars Pathfinder landing in 1997, when new records were set for individual Web site hits for a single event, we have seen ever-increasing public interest in Web-based participation in solar system exploration. Such nontraditional media can also enable us to reach diverse audiences that otherwise might not have access to solar system-related news and knowledge.

The Solar System Exploration Program makes extensive use of speakers, whose presentations bring the public into contact with scientists and engineers for personal, behind-the-scenes views into the challenges and excitement of exploration. The advent of smaller, more frequent missions also allows us to include public engagement or education-focused payload elements on certain spacecraft. This can vastly enhance the direct connection of solar system exploration with the general public. While such programs are still relatively new, significantly increasing opportunities for public engagement payloads on future missions is one of our major programmatic goals.

Learning by Doing

Solar system exploration provides students with opportunities to actually participate in solar system research. This allows them to connect fundamental principles of science and math with real-world, hands-on learning experiences in an exciting environment.

Through the Mars Student Imaging Project, student groups study data being returned from the Mars Odyssey mission, and then get to select sites for a new set of images to be acquired by the spacecraft and analyzed by the students themselves. The Goldstone Apple Valley Radio Telescope (GAVRT) project allows students to use a 34-meter dish antenna to probe the solar system and the galaxy. And the Robotics FIRST! program gives student teams an opportunity to design and test robotic vehicles in a friendly competition, with NASA help. These programs show students the end-to-end connections between science and engineering in a way that no textbook can.



Students plan to acquire an image using the Mars Odyssey THEMIS camera.

High school students compete using robots they constructed in the Robotics FIRST! program.



Appendix *Roadmap Framework*

Objectives	Research Focus Areas
1. Learn how the Sun's family of planets and minor bodies originated.	1. Understand the initial stages of planet and satellite formation. 2. Study the processes that determined the original characteristics of the bodies in our solar system.
2. Determine how the solar system evolved to its current diverse state.	3. Determine how the processes that shape planetary bodies operate and interact. 4. Understand why the terrestrial planets are so different from one another. 5. Learn what our solar system can tell us about extrasolar planetary systems.
3. Determine the characteristics of the solar system that led to the origin of life.	6. Determine the nature, history, and distribution of volatile and organic compounds in the solar system. 7. Identify the habitable zones in the solar system.
4. Understand how life begins and evolves.	8. Identify the sources of simple chemicals important to prebiotic evolution and the emergence of life. 9. Study Earth's geologic and biologic records to determine the historical relationship between Earth and its biosphere.
5. Explore the space environment to discover hazards to Earth.	10. Determine the inventory and dynamics of bodies that may pose an impact hazard to Earth. 11. Determine the physical characteristics of comets and asteroids.
6. Understand the current state and evolution of the atmosphere, surface, and interior of Mars.	12. Characterize the present climate of Mars and determine how it has evolved over time. 13. Investigate the history and behavior of water and other volatiles on Mars. 14. Study the chemistry, mineralogy, and chronology of martian materials. 15. Determine the characteristics and dynamics of the interior of Mars.
7. Determine if life exists or has ever existed on Mars.	16. Investigate the character and extent of prebiotic chemistry on Mars. 17. Search for chemical and biological signatures of past and present life on Mars.
8. Develop an understanding of Mars in support of possible future human exploration.	18. Identify and study the hazards that the martian environment will present to human explorers. 19. Inventory and characterize martian resources of potential benefit to human exploration of Mars.

Investigations	Missions
1. Determine the chemical composition and physical characteristics of Pluto and Kuiper objects. 2. Determine the chemical composition and physical characteristics of short-period comets.	Reconnaissance of Pluto and KBOs Return samples from comet surface
3. Analyze ancient lunar material. 4. Characterize Jupiter's gravity and magnetic fields and deep atmospheric chemistry.	Return samples from lunar Aitken basin Jupiter polar orbiter and deep probes
5. Conduct multidisciplinary comparative studies of atmospheres, surfaces, interiors, & satellites. 6. Determine how the impactor flux decayed in the early solar system.	Theoretical modeling, research, and analysis Lunar Aitken basin sample return Study cratering record on Pluto and KBOs
7. Study Venus' atmospheric chemistry and surface/atmosphere interactions 8. Study Mars meteorology and geophysics.	Probe Venus' atmosphere and sample surface Mars orbital and in situ exploration
9. Conduct detailed studies of the gas giants and ring systems. 10. Determine the structure of the Kuiper Belt.	Jupiter/Saturn orbital observations Reconnaissance of Pluto and KBOs Orbit Neptune and probe atmosphere
11. Analyze the chemical and isotopic composition of comets. 12. Determine Jupiter's water abundance and deep atmospheric composition. 13. Determine the chemical and isotopic composition of Venus' surface and atmosphere. 14. Determine the sources and reservoirs of key volatiles on Mars.	Return samples from comet surface Probe Jupiter's atmosphere to ~100 bars Probe Venus' atmosphere surface Venus sample return Mars orbital and in situ exploration
15. Determine Mars' climate evolution and volatile history. 16. Confirm the presence and study the characteristics of Europa's subsurface ocean. 17. Conduct comparative studies of the Galilean satellites.	Orbit Europa and map surface Successively orbit Callisto, Ganymede, Europa Mars in situ exploration and sample return
18. Determine the chemical composition of comets and Kuiper objects. 19. Study Titan's atmospheric chemistry and surface/atmosphere interactions.	Titan surface studies and atmospheric probe Titan in situ exploration
20. Investigate the development of biological processes on the early Earth through molecular, stratigraphic, geochemical, and paleontological studies. 21. Examine the records of the response of Earth's biosphere to extraterrestrial events.	Earth-based lab and field studies
22. Identify, model, and track near-Earth objects down to 1 km diameter.	Search for and model dynamics of NEOs
23. Measure the surface & interior composition and structural properties of asteroids and comets.	Comet/asteroid in situ exploration and sampling
24. Map atmospheric structure, water vapor, and isotopic composition. 25. Study the mineralogy and weathering of Mars' surface.	Mars orbital atmospheric remote sensing Mars polar orbital and in situ exploration
26. Map the sources and sinks of water and characterize aqueous processes acting on the surface. 27. Determine the energetics and dynamics of Mars' upper atmosphere.	Mars orbital and in situ exploration Mars aeronomy observations from orbit
28. Perform compositional and isotopic analysis of surface materials, weathering rinds, and sedimentary deposits.	Mars in situ exploration and sample return
29. Conduct long-term global studies of martian seismicity. 30. Accurately map the martian magnetic field.	Mars orbital and in situ network science Mars global and regional remote sensing
31. Search for preserved biosignatures in martian rocks and characterize the surface oxidant with depth. 32. Seek evidence of organics and prebiotic molecules in martian materials.	Mars in situ exploration and sample return
33. Search in situ for chemical and structural evidence of the biogeochemical signatures of life. 34. Perform laboratory analysis of martian samples drawn from scientifically compelling locations.	Mars in situ exploration and sample return
35. Characterize the radiation and fine material (dust) at the martian surface.	Mars surface laboratories and monitoring
36. Search for accessible reservoirs of usable water and determine the chemistry and structure of martian surface material.	Mars subsurface mapping, in situ exploration, and sample return

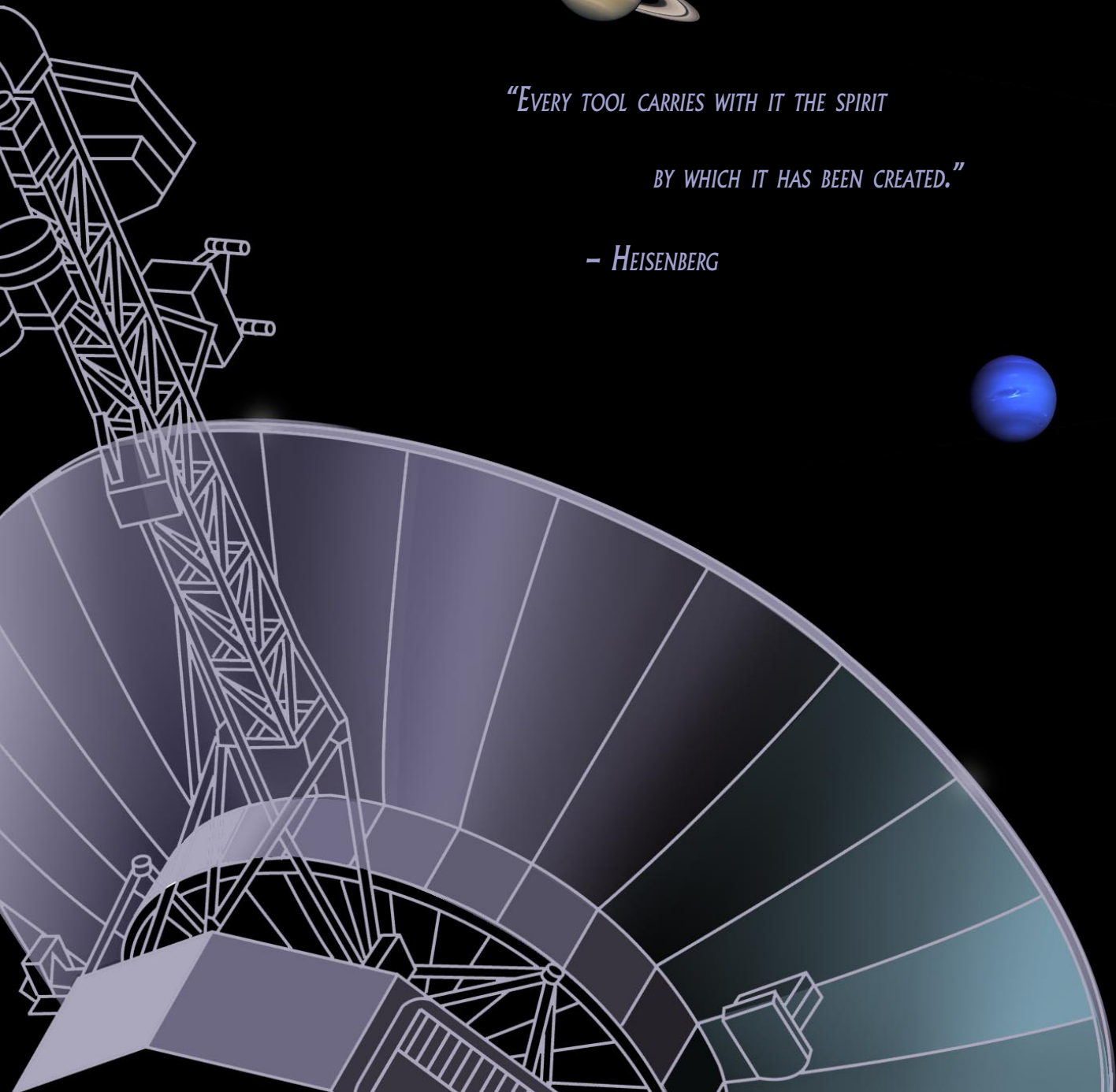
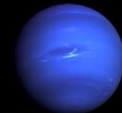
Understanding *Our Origins and Evolution*




"EVERY TOOL CARRIES WITH IT THE SPIRIT

BY WHICH IT HAS BEEN CREATED."

– HEISENBERG






OUR ROBOTIC EXPLORERS ARE EXTENSIONS OF OURSELVES. THEY CARRY WITH THEM HUMANITY'S THIRST FOR KNOWLEDGE AND THE UNQUENCHABLE DESIRE TO PUSH OUTWARD INTO THE NEW FRONTIER. WE INSTILL IN THEM OUR INNATE SENSE OF CURIOSITY AS WE BID THEM LOOK OVER THE NEXT HILL OR UNDER THE NEXT ROCK.

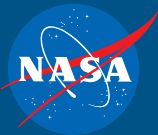
IT IS JUST 100 YEARS SINCE THE DAWN OF POWERED FLIGHT, YET ALREADY OUR FIRST EMISSARIES HAVE LEFT OUR SOLAR SYSTEM FOR INTERSTELLAR SPACE. TWELVE YEARS AGO, VOYAGER 1 LOOKED BACK AT THE SOLAR SYSTEM IT WAS LEAVING AND TOOK ONE FINAL PICTURE, A FAMILY PORTRAIT WHICH IT DUTIFULLY RETURNED TO US — AND THEN CLOSED ITS EYES FOR THE LAST TIME. NOW 25 YEARS OLD, THE TWIN VOYAGERS ARE SPEEDING TOWARD THEIR FUTURE IN THE GALAXY, STILL TELLING US — FOR A WHILE LONGER — WHAT THEY SENSE ALONG THE WAY.

THIS ROADMAP IS BUILT ON THE FOUNDATION OF WHAT THE VOYAGERS, AND ALL OF OUR OTHER ROBOTIC EXPLORERS, HAVE TOLD US ABOUT THE NATURAL LABORATORY THAT IS OUR SOLAR SYSTEM. IT REPRESENTS A PART OF OUR LEGACY TO FUTURE GENERATIONS, WHO WE HOPE WILL GROW UP WITH A DEEPER UNDERSTANDING AND APPRECIATION OF THE COSMOS AND OUR PLACE WITHIN IT.





*leaving the safe harbor
to sail uncharted waters*



National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL 400-1077 5/03