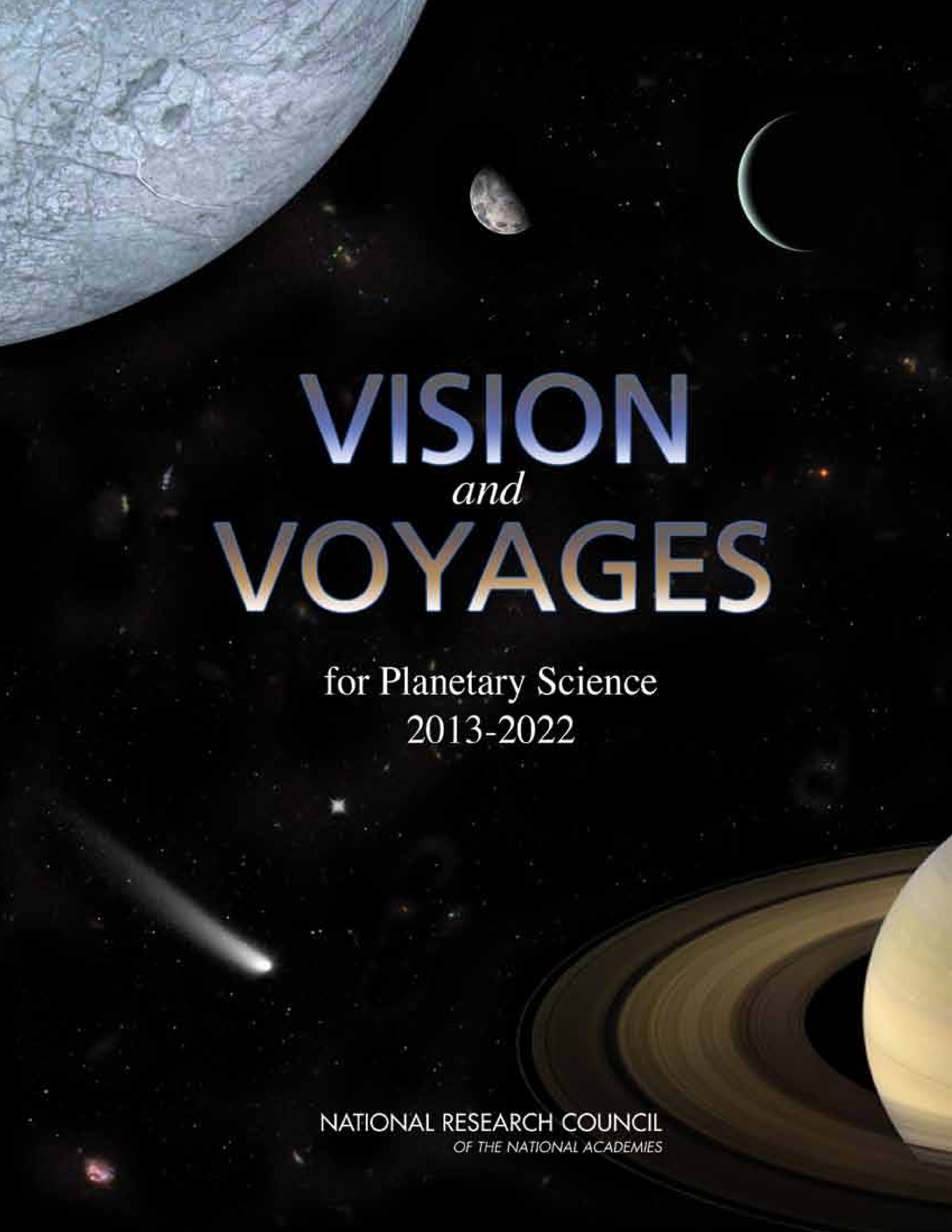

VISION
and
VOYAGES
for Planetary Science
2013-2022
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

This booklet is based on the Space Studies Board report *Vision and Voyages for Planetary Science in the Decade 2013-2022* (available at <http://www.nap.edu/catalog.php?record_id=13117>).
Details about obtaining copies of the full report, together with more information about the Space Studies Board and its activities can be found at <http://sites.nationalacademies.org/SSB/index.htm>.

*Vision and Voyages for Planetary Science in the Decade 2013-2022* was authored by the Committee on the Planetary Science Decadal Survey.

COMMITTEE ON THE PLANETARY SCIENCE DECADAL SURVEY

STEVEN W. SQUYRES, Cornell University, *Chair*
LAURENCE A. SODERBLOM, U.S. Geological Survey, *Vice Chair*
WENDY M. CALVIN, University of Nevada, Reno
DALE CRUIKSHANK, NASA Ames Research Center
PASCALE EHRENFREUND, George Washington University
G. SCOTT HUBBARD, Stanford University
WESLEY T. HUNTRESS, JR., Carnegie Institution of Washington (retired) (until November 2009)
MARGARET G. KIVELSON, University of California, Los Angeles
B. GENTRY LEE, NASA Jet Propulsion Laboratory
JANE LUU, Massachusetts Institute of Technology, Lincoln Laboratory
STEPHEN MACKWELL, Lunar and Planetary Institute
RALPH L. McNUTT, JR., Johns Hopkins University, Applied Physics Laboratory
HARRY Y. McSWEEN, JR., University of Tennessee, Knoxville
GEORGE A. PAULIKAS, The Aerospace Corporation (retired) (from January 2010)
AMY SIMON-MILLER, NASA Goddard Space Flight Center
DAVID J. STEVENSON, California Institute of Technology
A. THOMAS YOUNG, Lockheed Martin Corporation (retired)

The Space Studies Board is a unit of the National Research Council of the National Academies, which serve as independent advisers to the nation on science, engineering, and medicine.

Support for this publication was provided by the National Science Foundation (Grant AST-1050744) and the National Aeronautics and Space Administration (Contract NNH06CE15B).

The Space Studies Board acknowledges David H. Smith, Joseph O'Rourke, and Rachael Alexandroff for drafting the text of this booklet.

Cover images courtesy of NASA/JPL
Cover design by Penny Margolskee
Booklet design by Francesca Moghari



Printed in the United States of America

# INTRODUCTION

Galileo Galilei could not have realized in his wildest imaginings what he was starting when he first trained his crude telescope on the night sky in January 1610. Prior to this, the Moon and the planets were just lights in the heavens. After Galileo's observations these lights were revealed as complex worlds in their own right.

If Galileo's observations mark the birth of the scientific study of the planets and their satellites, then today is its golden age. No clearer indication of this exists than the fact that robotic spacecraft are currently relaying data from vantage points in orbit about all of the planets known to Galileo, except for one. Indeed, as of August 2012, spacecraft are orbiting Mercury, Venus, the Moon, Mars, Saturn, and the asteroid Vesta, an object unknown to Galileo. Jupiter, the solar system's largest planet, is notably absent. However, the Juno spacecraft, launched in August 2011, is scheduled to enter orbit around Jupiter in 2016. Meanwhile, the Mars Science Laboratory has begun its exploration of Gale crater and the New Horizons spacecraft is en route to Pluto. In fact, if missions currently in progress go according to plan, by 2015 the list of planetary bodies examined up close by spacecraft will span the entire solar system—from Sun-scorched Mercury to frigid Pluto.

The same motivation that led Galileo to point his primitive telescope at the heavens inspires the scientists and engineers responsible for Juno and its robotic brethren. The quest for new knowledge, the desire to push the envelope of what is technically feasible, and the enthusiasm to seek what is beyond our earthly horizons are all essential aspects of the planetary science endeavor.

Planetary science is a multifaceted enterprise that collectively seeks answers to basic questions—such as how planets form, how they work, and why at least one planet is the abode of life. The fact that researchers can and do address these deceptively simple questions explains, in part, why planetary science is an important undertaking worthy of public support. Although these questions are deceptively simple, they have inspired a 50-year epic series of exploratory voyages by robotic spacecraft that have visited almost every type of planetary body in humankind's celestial neighborhood. These robotic voyages have been complemented by observations with ground- and space-based telescopes; research conducted in laboratories equipped to study extraterrestrial materials such as meteorites and samples returned to Earth by spacecraft; and complex computer systems programmed to analyze data or run theoretical models and simulations. Last, but by no means least, are the engineering and technical activities that enable all

# PLANETARY BODIES

## A Brief Guide for the Solar System Voyager

The denizens of the solar system are many and varied. Some are well known to all, such as the Moon and Mars. Other planetary bodies are less well known and have exotic names. Moreover, planetary science has now been enriched with the so-called exoplanets, the hundreds of planetary bodies discovered in orbit around other stars.

In approximate order of decreasing mass, the principal solar system bodies featured in this booklet are as follows:

- **Jupiter and Saturn**—the gas giant planets of the outer solar system. They are composed almost entirely of hydrogen and helium. Both have strong magnetic fields, complex rings, and numerous satellites.

- **Uranus and Neptune**—the ice giant planets of the outer solar system. Both have icy cores surrounded by deep, hydrogen-rich atmospheres. Both have strong magnetic fields, rings, and numerous satellites.

- **Mercury, Venus, Earth and the Moon, and Mars**—the terrestrial planetary bodies of the inner solar system. All five have metallic cores and rocky exteriors. Only Earth and Mercury have magnetic fields, and only Earth and Venus possess dense atmospheres.

**SOLAR SYSTEM**
*A montage of the planets explored by NASA spacecraft in the last 50 years.*

- **Io, Europa, Ganymede, and Callisto**—the large or Galilean satellites of Jupiter, Io and Europa are, respectively, slightly larger and slightly smaller than the Moon. Callisto is as large as the planet Mercury, and Ganymede, the biggest satellite in the solar system, is somewhat larger. Ganymede is the only satellite known to have a magnetic field. Io is a rocky body displaying extensive volcanic activity; the other three Galilean satellites contain a fraction of ice.

**GALILEAN SATELLITES**
*The four Galilean satellites: Ganymede, Callisto, Io, and Europa (from left to right).*

of the above to take place. The sum of these diverse contributions has transformed humankind's understanding of the collection of objects orbiting the Sun.

However, planetary science is not purely an academic or technical activity. It has both fiscal and policy dimensions. The basic tools of planetary science, be they spacecraft, telescopes, or laboratories, do not come for free. A "small" planetary spacecraft mission might cost $500 million, so this new venture cannot be started without careful planning and preparation. At a minimum, a new proposal has to be assessed relative to competing activities in other science disciplines and then weighed against the other multifarious demands placed on the federal budget.

Planetary science also has an international dimension. The United States, Russia, Japan, Canada, China, India, and the nations of Western Europe are all capable of mounting planetary missions, either alone or as part of cooperative ventures. But as budgets for space programs come under increasing pressure and the cost and complexity of the missions grow, international cooperation becomes ever more appealing. New alliances and mechanisms to cooperate are emerging, enabling partners to improve national capabilities, share costs, and eliminate duplication of effort. But cooperative plans must be crafted with care, for they also can carry risks. International missions add layers of complexity to their technical specifications, management, and implementation. Different space agencies use different planning horizons, funding approaches,

- **Titan and Enceladus**—the largest and one of the smallest of Saturn's major satellites. Titan is slightly smaller than Jupiter's Ganymede and is the only satellite with a dense atmosphere. Although icy Enceladus is only one-seventh the size of the Moon, it is a geologically active world ejecting plumes of material from large rifts in its southern polar region (*pictured at right*).

- **Triton**—the largest satellite of Neptune. Although only three-quarters the size of the Moon, icy Triton is an active world with geyserlike plumes jetting into very tenuous atmosphere.

- **Asteroids**—a family of primarily rocky and/or metallic bodies. Although their greatest concentration is between the orbits of Jupiter and Mars, they are found throughout the inner solar system. The largest example, Ceres, is less than one-third the size of the Moon. Asteroids are believed to be remnants left over from the formation of the inner planets.

- **Comets**—innumerable, small icy bodies with highly eccentric orbits that periodically bring them into the inner solar system. They develop tenuous atmospheres and characteristic tails as they approach the point in their orbits closest to the Sun. Comets are thought to be remnants left over from the formation of the outer planets.

- **Kuiper belt objects**—another remnant of the population of small icy bodies from which the giant planets formed. They were gravitationally scattered out of the Jupiter-Saturn-Uranus zone into the region beyond the orbit of Neptune during the earliest years of solar system history. They are believed to be related to comets.

- **Centaurs**—small icy bodies with unstable orbits lying between Jupiter and Neptune. There are thought to be Kuiper belt objects in the process of being perturbed into the inner solar system.

- **Trojans**—small objects concentrated around gravitationally stable points located 60 degrees ahead of and trailing Jupiter in its orbit about the Sun. Their locations suggest that they are remnants of the population of rock-ice bodies from which Jupiter formed. Or they may be related to Kuiper belt objects and were captured by Jupiter early in the history of the solar system.

- **Meteoroids**—very small rocky/metallic/carbonaceous fragments of the material from which the planets formed. The frictional heating on entry into Earth's atmosphere causes such objects to glow, and they are seen as meteors. A remnant of a meteoroid that survives to reach Earth's surface is called a meteorite.

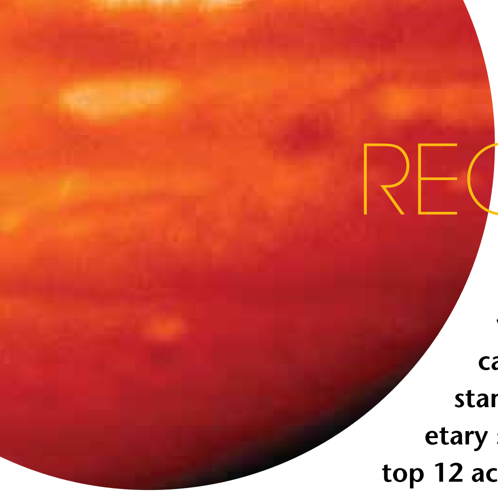
**COMET**
***The Deep Impact mission probed the nucleus of comet Tempel 1 by striking it with an impactor on July 4, 2005, as part of NASA's Discovery program of missions.***

selection processes, and data dissemination policies. Nonetheless, international cooperation may be the only realistic option to undertake some of the most ambitious and scientifically rewarding missions.

So, planetary researchers find themselves the victims of their own success. Never before have they had access to so much new information. But never before have the possible future directions been complicated by a multiplicity of competing options, each with its own unique set of scientific, technical, fiscal, and diplomatic complications. Such times are an ideal point for stopping to take stock of where we stand.

Thus, in 2008, NASA and the National Science Foundation asked the National Research Council to review the current state of knowledge about the solar system, pose the key questions that need to be answered, and outline the major initiatives necessary to find answers in the coming decade.

Three years of effort by some 60 experts, augmented by the input from hundreds of scientists and engineers in universities, research institutions, government laboratories, and aerospace companies in the United States and overseas, resulted in the publication of the report *Vision and Voyages for Planetary Science in the Decade 2013-2022* (The National Academies Press, Washington, DC, 2011). This booklet summarizes the key science questions identified in the report and introduces the spacecraft, telescopes, and other activities that should be undertaken to find the answers.



# RECENT ACHIEVEMENTS

**The past decade has been one of the most successful in the history of planetary science. Data returned from spacecraft missions, observations with ground- and space-based telescopes, laboratory studies, and theoretical investigations have resulted in many significant advances in the understanding of planetary bodies in the past decade. The current vitality of planetary science is clearly evident in the diversity of the topics represented in the top 12 achievements of planetary science in the past decade.**

### Mercury's liquid core

Studies of Mercury's rotation conducted by transmitting radar signals from NASA's Deep Space Network station in California and detecting the echoes with the National Radio Astronomy Observatory's Green Bank Telescope demonstrate that Mercury has a liquid core.

### Recent volcanic activity on Venus

Data from the European Space Agency's (ESA's) Venus Express spacecraft revealed infrared hotspots associated with volcano-like surface features, suggestive of recent volcanic activity. If correct this supports the idea that sulfur dioxide from volcanic eruptions feeds Venus's clouds of sulfuric acid.

### The Moon is less dry than once thought

Recent studies of samples collected by the Apollo astronauts show the Moon's interior is not completely dry, as previously thought. Moreover, data from a variety of NASA spacecraft—e.g., Lunar Prospector, Lunar Reconnaissance Orbiter, Lunar Crater Observation and Sensing Satellite, Deep Impact, and Cassini—and India's Chandrayaan-1 lunar orbiter suggest that small, but significant, quantities of water exist on or near the lunar surface. This lunar water is present as molecules generated by reactions between surface minerals and solar wind protons and ice deposited by impacting comets that gets trapped in the extremely cold lunar poles.

### Mars's extensive deposits of near-surface ice

These deposits and their effects on surface features were mapped by NASA's Odyssey mission. Periodic oscillations in the martian climate, driven by variations in Mars's orbit, might potentially lead to geologically brief periods where liquid water is available in specific locations.

### Martian minerals formed in diverse aqueous environments

Data from various spacecraft missions—e.g., NASA's Odyssey, Mars Reconnaissance Orbiter, Phoenix, and Mars Exploration Rovers and ESA's Mars Express—have identified a broad suite of water-related minerals, including salts, clays, and carbonates, that could only have formed in distinctly different water-related environments at different periods in martian history.

### Dramatic changes in the atmospheres and rings of the giant planets

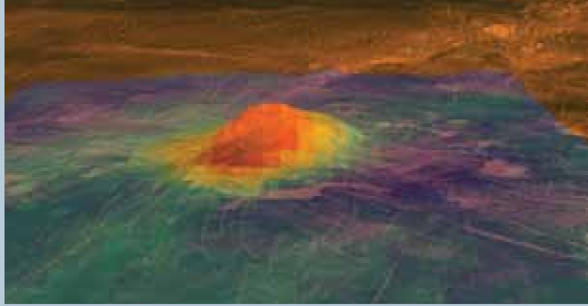
Observations conducted with ground- and space-based telescopes have revealed dynamic changes in the giant planets. Notable examples include three impacts on Jupiter in 2009 and 2010; striking seasonal change in the atmospheres of Saturn and Uranus; vigorous polar vortices on Saturn and Neptune; and rapid changes in the ring systems of Jupiter, Saturn, Uranus, and Neptune.

### Titan's active meteorological cycle

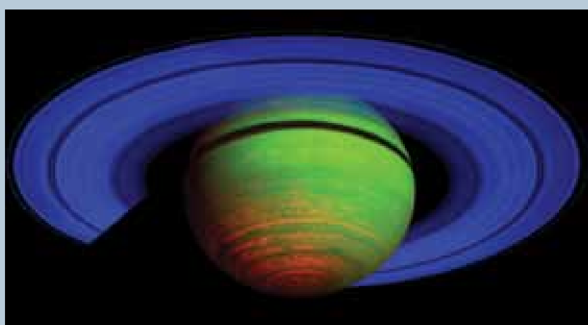
Observations from NASA's Cassini and ESA's Huygens have confirmed the long-suspected presence of complex organic processes on Titan. Moreover, they have revealed that an active global methane cycle mimics Earth's water cycle.

### Enceladus's polar plumes

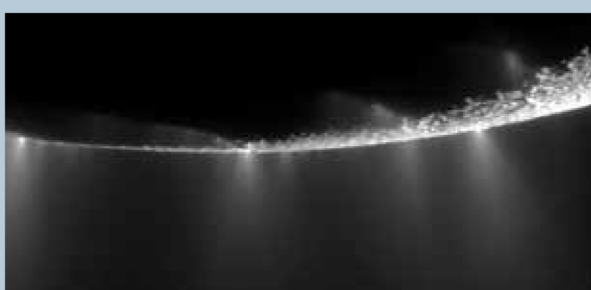
Observations by NASA's Cassini spacecraft have revealed anomalous sources of thermal energy coincident with curious rifts called "tiger stripes" in Enceladus's southern polar region. The energy source appears to be responsible for plumes of ice particles and organic materials that emanate from discrete locations along the rifts.



*The volcanic peak Idunn Mons in the Imdr Regio area of Venus is the site of a surface heat anomaly. Radar and topographic data from NASA's Magellan spacecraft underlie colorful images of heat patterns captured by the Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS) aboard the European Space Agency's Venus Express spacecraft. Red-orange is the warmest area, at the top of the peak. In this image, brown, dark areas are smooth or have shallow slopes, whereas bright areas represent rough or steep terrain.*



*Saturn and its rings as imaged by the Cassini spacecraft.*



*Multiple jets, dominated by water vapor and ice particles but containing a rich mixture of other compounds, emanate from the active warm fractures at Enceladus's south pole. This Cassini image is 130 km across.*


*A schematic illustrating the sizes of some of the smallest known exoplanets relative to Mars and Earth. Kepler-20e and -20f were discovered following the analysis of data from NASA's Kepler spacecraft. The other three exoplanets were discovered using data from Kepler and ground-based telescopes.*

## The differentiated nature of comet dust

Analysis of samples returned to Earth by NASA's Stardust mission indicated that, contrary to expectations, cometary dust contains minerals that can form only at the high temperatures found close to the Sun. This result has changed ideas concerning the physical processes within the protoplanetary disk during the formation of the solar system.

## The Kuiper belt's richness and diversity

Observations from ground- and space-based telescopes revealed that the Kuiper belt includes many objects as large as or larger than Pluto and, intriguingly, a large proportion of binary and multi-object systems.

## The anomalous isotopic composition of the planets

Laboratory analysis of data from NASA's Genesis solar wind sample return mission revealed that the Sun is highly enriched in the isotope oxygen-16 relative to the planets. This suggests that some unknown process must have depleted this isotope in the swirling circumsolar cloud of gas and dust from which the planets formed 4.5 billion years ago.

## Exoplanets galore

The census of known exoplanets increased dramatically from about 50 spotted by ground-based telescopes between 1995 and 2000 to more than 750 in 2012 as data began to stream back from NASA's Kepler and ESA's Corot spacecraft. Moreover, an additional 2,321 Kepler candidates await confirmation. Observations with large ground- and space-based telescopes suggest that most exoplanets are giants. But, there is increasing evidence that Uranus/Neptune-size planets are more abundant than Jupiter-size planets.

# IMPORTANT SCIENCE QUESTIONS

**The deep-rooted motives underlying the planetary sciences address issues of profound importance that have been pondered by scientists and non-scientists for centuries. Such questions cannot be fully addressed by a single spacecraft mission or series of telescopic observations. It is likely, in fact, that they will not be completely addressed in this decade or the next. To make progress in organizing and outlining the current state of knowledge, the *Vision and Voyages* report translated and codified the basic motivations for planetary science into three broad, crosscutting themes:**

**BUILDING NEW WORLDS**
**understanding solar system beginnings**

**PLANETARY HABITATS**
**searching for the requirements for life**

**WORKINGS OF SOLAR SYSTEMS**
**revealing planetary processes through time**

Each science theme brings its own set of questions, based on current understanding of the underlying scientific issues.

## BUILDING NEW WORLDS

*An artist imagines the formation of one of the many planetary systems discovered around distant stars.*

- What were the initial stages, conditions, and processes of solar system formation and the nature of the interstellar matter that was incorporated? Important objects for study include comets, asteroids, Trojans, and Kuiper belt objects.
- How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions? Important objects for study include Enceladus, Europa, Io, Ganymede, Jupiter, Saturn, Uranus, Neptune, Kuiper belt objects, Titan, and ring systems.
- What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play? Important objects for study include Mars, the Moon, Trojans, Venus, asteroids, and comets.

## PLANETARY HABITATS

- What were the primordial sources of organic matter, and where does organic synthesis continue today? Important objects for study include comets, asteroids, Trojans, Kuiper belt objects, Enceladus, Europa, Mars, Titan and the satellites of Uranus.
- Did Mars or Venus host ancient aqueous environments conducive to early life, and is there evidence that life emerged? Important objects for study include Mars and Venus.
- Beyond Earth, are there contemporary habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now? Important objects for study include Enceladus, Europa, Mars, and Titan.

*Mars Science Laboratory Curiosity rover undergoing a test of its sample arm while under construction at the Jet Propulsion Laboratory in September 2010.*

## WORKINGS OF SOLAR SYSTEMS

- How do the giant planets serve as laboratories to understand Earth, the solar system, and exoplanetary systems? Important objects for study are Jupiter, Neptune, Saturn, and Uranus.
- What solar system bodies endanger and what mechanisms shield Earth's biosphere? Important objects for study are near-Earth objects, the Moon, comets, and Jupiter.
- Can understanding the roles of physics, chemistry, geology, and dynamics in driving planetary atmospheres and climates lead to a better understanding of climate change on Earth? Important objects for study are Mars, Jupiter, Neptune, Saturn, Titan, Uranus, and Venus.
- How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time? Important objects for study are all planetary bodies.

*As seen in images returned by the Soviet Union's Venera 13 spacecraft, the surface of Venus is currently a hellish wasteland. But could Earth's sister planet ever have supported life?*

Each question represents a distillation of major areas of research in planetary science, and the questions themselves are sometimes crosscutting. Each question points to one or more solar system bodies that may hold clues or other vital information necessary for their resolution. *Vision and Voyages* explores these questions in detail, dissecting them to identify the specific opportunities best addressed in the coming decade by large, medium, and small spacecraft missions, as well as by other ground- and space-based research activities.

# NASA ACTIVITIES

The principal support in the United States for research related to solar system bodies comes from the Planetary Science Division (PSD) of NASA's Science Mission Directorate. The PSD supports research through a combination of spacecraft missions, technology development activities, support for research infrastructure, and research grants. The annual budget of the PSD is currently approximately $1.0 billion, the bulk of which is spent on the development, construction, launch, and operation of spacecraft.

Two types of spacecraft missions are conducted: large "flagship" missions strategically directed by the PSD and smaller Discovery and New Frontiers missions proposed and led by principal investigators (PIs). The choice and the scope of strategic missions are determined through a well-developed planning process, drawing its scientific inputs from advisory groups both internal and external (e.g., the National Research Council) to NASA. The PI-led missions are selected by a peer-review process that considers the scientific, technical, and fiscal merit of competing proposals submitted in open competition.

The research related to planetary missions begins well before a mission is formulated and funded and continues long after it is over. Research provides the foundation for interpreting data collected by spacecraft, as well as the guidance and context for identifying new scientifically compelling missions. Data from telescopic observations can identify

*The Kepler spacecraft, a NASA Discovery mission, launched from Cape Canaveral, Florida, on March 6, 2009.*

## NASA's Ground- and Space-Based Telescopes

Most bodies in the solar system were discovered using telescopes. Utilization of the enormous discovery potential of telescopes is an essential element of an integrated strategy for solar system exploration. Many spacecraft missions are designed to follow up on discoveries made using telescopes. Telescopes help identify targets to which spacecraft missions can be flown, and they provide ongoing support for such missions. NASA's Infrared Telescope Facility (IRTF) on Hawaii's Mauna Kea, for example, is specifically tasked to assist with flight missions and is providing support for current missions such as Cassini, New Horizons, and MESSENGER.

Although most government-supported observatories in the United States are funded by NSF (see the section "NSF Activities" on page 13), NASA continues to play a major role in supporting the use of Earth-based optical and radar telescopes for planetary studies. Ground-based facilities that receive NASA support, including the IRTF, the Keck Observatory, Goldstone, Arecibo, and the Very Long Baseline Array, all make important, and in some cases unique, contributions to planetary science.

Telescopes mounted in aircraft, balloons, and suborbital rockets provide a cost-effective means of studying planetary bodies at wavelengths that do not penetrate Earth's atmosphere. For example, the Stratospheric Observatory for Infrared Astronomy (SOFIA)—a 2.5-meter telescope mounted in a modified Boeing 747-SP aircraft and operated jointly by NASA and its German counterpart—can fly to altitudes of 13.5 km where it is above 99 percent of the infrared-blocking water vapor in Earth's atmosphere. SOFIA also provides opportunities for rapid response to time-dependent astronomical phenomena (e.g., comets and planetary impacts) and geography-dependent phenomena (e.g., stellar occultations). Similarly, the relatively modest costs and development times of balloon and suborbital-rocket payloads provide training opportunities for would-be developers of future spacecraft instruments.


*The Stratospheric Observatory for Infrared Astronomy in flight.*

Observations from large space telescopes launched by NASA and its international partners not only have made numerous contributions to planetary science but also have revolutionized our understanding of the universe beyond the solar system. Telescopic observations provide scientific advances at a fraction of the cost of deep-space probes, and these facilities are also shared with other disciplines, further new targets for future missions, and experimental and theoretical results can pose new questions for these missions to answer. Research and analysis programs also allow the maximum possible science return to be harvested from missions. Along with analysis of spacecraft data, the portfolios of research and analysis programs include laboratory studies, theoretical studies, fieldwork using Earth analogs, and planetary geologic mapping. All of these efforts and the research infrastructure supporting them—e.g., ground- and space-based telescopes, deep-space communications networks, data-distribution and archiving systems, and sample curation and laboratory facilities—are crucially important to NASA's long-term science goals, and all require funding.

*The New Horizons spacecraft under construction.*

Current NASA research and analysis funding in most programs supporting planetary research is distributed as multiple small grants to individual researchers. An unfortunate and very inefficient aspect of this policy is that researchers must devote an increasingly large fraction of their time to writing proposals instead of doing science. The number of good ideas for planetary research surpasses the funding available to enable that research. While more funding for research and analysis would result in more high-quality science, increased research funding must be tempered by the realization that NASA's resources are finite and that such increases will inevitably cut into funds that are needed to develop new technologies and fly new missions.

reducing cost. Young scientists trained at these facilities will be available to participate in the deep-space missions of the future when scientists trained on Voyager, Galileo, and Cassini have retired.

Observations performed with the Hubble Space Telescope (HST) are important for research on the giant planets (especially Uranus and Neptune) and their satellites and for planning future missions to these systems. HST's ability to observe at ultraviolet wavelengths has been critical for studies of auroral activity on the gas giants, the discovery of the atmospheres of Ganymede and Europa, and investigations of the plumes and atmosphere of Io. During the past decade, HST was also used to discover four moons around Pluto (Nix, Hydra, and two as yet unnamed), and two additional moons (Cupid and Mab) and two new rings around Uranus. HST, although serviced as recently as 2009, has a finite lifetime and will eventually be de-orbited, and no replacement space telescope with equivalent ultraviolet and optical capabilities is currently planned.

*An engineer prepares six of the 18 hexagonal segments that will compose the primary mirror of the James Webb Space Telescope for low-temperature testing at NASA's Marshall Space Flight Center.*

NASA's next major observatory facility is the James Webb Space Telescope (JWST). This 6.5-meter infrared-optimized telescope is currently scheduled to be deployed at Sun-Earth L2 Lagrangian point in 2018. JWST will contribute to planetary science in numerous ways, including diffraction-limited imaging (in the near infrared) of both large and small bodies difficult to match with existing ground-based facilities, spectroscopy of the deep atmospheres of Uranus and Neptune, planetary auroral studies with high spatial resolution, and observations of transient phenomena (storms and impact-generated events) in the atmospheres of the giant planets. Work is currently being done to assess the feasibility of observations of the brighter planets such as Mars, Jupiter, and Saturn.

*NASA's Goldstone complex in southern California is one of three radio telescope facilities that make up the Deep Space Network, which is used to communicate with spacecraft.*

## Deep Space Communications

The Deep Space Network (DSN) is a critical element of NASA's solar system exploration program. The DSN maintains 70- and 34-meter-diameter antennas at Goldstone in California's Mojave Desert and also at sites near Madrid, Spain, and Canberra, Australia. These three facilities are the only asset available for up-linking commands to and down-linking data from spacecraft in the outer solar system. As instruments advance and larger data streams are expected over the coming decade, the DSN's capabilities must keep pace with the needs of the mission portfolio. Future demands on the DSN will be substantial. Missions to the distant outer solar system require access to either 70-meter antennas or equivalent arrays of smaller antennae. The DSN must also be able to receive data from more than one mission at one site simultaneously. If new arrays can only mimic the ability of one 70-meter antenna and nothing more, missions will still be downlink-constrained and will have to compete against one another for limited downlink resources.

## Sample Curation and Laboratory Facilities

Planetary samples are arguably some of the most precious materials on Earth. Just as data returned from planetary spacecraft must be carefully archived and distributed to investigators, so must samples brought at great cost to Earth from space be curated and kept uncontaminated and safe for continued study.

Samples to be returned to Earth from many planetary bodies (e.g., the Moon, asteroids, and comets) are given the designation of "unrestricted Earth return" because they are not regarded as posing any biohazard to Earth. However, future sample return missions from Mars and other targets that might potentially harbor life (e.g., Europa and Enceladus) are classified as "restricted Earth return" and are subject to quarantine restriction, requiring special receiving and curation facilities.

The most important instruments for any sample return mission are the ones in the laboratories on Earth. To derive the full science return from sample return missions, it is critical to maintain technical and instrumental capabilities for initial sample characterization, as well as foster expansion to encompass appropriate new analytical instrumentation as it becomes available and as different sample types are acquired.

## NASA's New Frontiers Program

NASA's New Frontiers program was initiated in 2003 to fill the middle ground between the small and relatively inexpensive Discovery missions and the much larger and more costly flagship missions. Inspired by the success of the Discovery program, New Frontiers missions are selected in a competitive process and led by a principal investigator. However, New Frontiers solicitations are more strategic, restricting proposals to a small number of focused science goals that cannot be implemented within the Discovery cost cap but that do not require the resources of a flagship mission. New Frontiers missions, while complex and challenging, can be executed on timescales of significantly less than a decade and often take advantage of technological developments from recent prior missions. Two New Frontiers missions are currently en route to their destinations, and a third was recently selected for flight at a later date:

- **New Horizons**—A mission to Pluto and beyond, launched on January 19, 2006, with an estimated arrival date of July 14, 2015. Following a flyby of Pluto and its family of five known satellites, the mission team hopes to visit one or more additional Kuiper belt objects.
- **Juno**—A Jupiter polar orbiter launched on August 5, 2011, with arrival anticipated around July 4, 2016. Juno will map Jupiter's gravitational and magnetic fields and characterize its atmosphere for more than a year. A controlled impact into Jupiter will end the mission in October 2017.
- **OSIRIS-REx**—The Origins, Spectral Interpretation, Resource Identification, Security and Regolith Explorer is an asteroid sample return mission that is currently scheduled to launch in September 2016. Arrival at its target, asteroid 1999 RQ36, is scheduled for October 2019. The spacecraft will study and map 1999 RQ36 for up to 505 days before obtaining a surface sample and at least 60 grams of pristine regolith for delivery to Earth in September 2023.

## NASA's Discovery Program

*The Phoenix spacecraft landed on Mars on May 25, 2008. This image was taken on the sixteenth martian day after landing and shows a soil sample in the scoop being delivered to the optical microscope instrument.*

NASA's Discovery program of small planetary missions was initiated in 1992 as a way to ensure frequent access to space for planetary investigations. Although the first two missions were preselected by NASA, all of the subsequent missions were selected via a competitive process from among detailed proposals submitted by scientists from universities, research institutes, industry, and federal laboratories. The relatively low cost and short development schedules of Discovery missions provide flexibility to address new scientific discoveries on timescales of less than 10 years. A parallel program specifically dedicated to martian studies, Mars Scout, was merged with Discovery after the selection of MAVEN, the final Scout mission. The Discovery (and Mars Scout) missions flown by NASA, or scheduled for flight at a later date, are as follows:

- **Near Earth Asteroid Rendezvous**—An asteroid rendezvous and orbiter mission launched on February 17, 1996. The spacecraft flew by the main-belt asteroid Mathilde on June 27, 1997, and entered orbit about the near-Earth asteroid Eros on February 14, 2000. The mission was completed following the spacecraft's landing on Eros on February 12, 2001.
- **Mars Pathfinder**—A Mars lander and rover mission launched on December 4, 1996. The spacecraft landed in the Ares Vallis region of Mars on July 4, 1996. The mission ended when communications were lost on September 27, 1997.
- **Lunar Prospector**—A lunar orbiter that was launched on January 6, 1998, and entered orbit about the Moon 5 days later. Following the completion of its lunar mapping mission it conducted a controlled impact in the Moon's southern polar region on July 31, 1999.
- **Stardust**—A comet coma sample-return mission launched on February 7, 1999. The spacecraft flew by comet Wild 2 on January 2, 2004, and collected dust samples in a capsule that returned to Earth on January 15, 2006. The spacecraft, minus its sample capsule, was renamed Stardust-NExT (New Exploration of Temple 1) and redirected to fly by the comet of the same name on February 14, 2001.
- **Genesis**—A solar wind sample-return mission launched on August 8, 2001. Following a multi-year sample collection mission, the return capsule entered Earth's atmosphere on September 8, 2004. Unfortunately, the sample capsule's parachute failed to deploy. Although the sample collectors were damaged and contaminated, many of the mission's science goals were ultimately achieved.
- **CONTOUR**—The Comet Nucleus Tour mission was launched on July 3, 2002, and was designed to fly by the nuclei of comets Encke and Schwassmann-Wachmann-3. Unfortunately, communications were lost when the spacecraft suffered a catastrophic failure 6 weeks after launch.
- **MESSENGER**—The Mercury Surface, Space Environment, Geochemistry and Ranging mission was launched on August 3, 2004. Following one flyby of Earth, two of Venus, and three of Mercury, the spacecraft settle into orbit about the closest planet to the Sun on March 18, 2011. The spacecraft is currently in the second year of its planned 2-year orbital study of Mercury.
- **Deep Impact**—A comet impactor and flyby mission launched on January 12, 2005. On July 3, 2005, the flyby spacecraft released an instrumented impactor and subsequently observed its collision with the nucleus of comet Temple 1 the following day. Following the encounter with comet Temple 1 the mission was given two new tasks: first, to preview the extrasolar-planet search technique to be used by the subsequent Kepler mission (see below), and second, to fly by a second comet. The former task was conducted between January and August of 2008. The latter task was accomplished on November 4, 2010, when the spacecraft flew by the nucleus of comet Hartley 2.
- **Phoenix**—The first Mars Scout mission, launched on August 4, 2007. Phoenix landed in Mars's northern polar region on May 25, 2008. Its nominal 90-day mission was successfully concluded and contact with the spacecraft was lost on November 10, 2008.
- **Dawn**—A spacecraft launched on September 27, 2007, and designed to conduct orbital studies of two main-belt asteroids. Following a flyby of Mars in February 2009, the spacecraft went into orbit about the asteroid Vesta in July 2011. Following the completion of its observations of Vesta in the summer of 2012, it will break orbit and begin a multi-year cruise to the asteroid Ceres. Arrival at Ceres and the beginning of its planned 4-month-long orbital tour are scheduled for February 2015.
- **Kepler**—An Earth-orbiting telescope, dedicated to the detection of exoplanets, launched on March 6, 2009. By the latest count, the Kepler team has confirmed the existence of 74 exoplanets, and an additional 2,321 candidate planets await confirmation.
- **GRAIL**—The Gravity Recovery and Interior Laboratory mission consists of twin lunar orbiters launched on a single rocket on September 10, 2011. The identical GRAIL-A and GRAIL-B spacecraft entered orbit around the Moon on December 31, 2011, and January 1, 2012, respectively. Precise tracking of the relative motion of the two spacecraft permits the detailed mapping of the Moon's gravitational field, providing information on the Moon's interior structure.
- **MAVEN**—The Mars Atmosphere and Volatile Evolution mission, the second and final Mars Scout, is currently scheduled to launch on November 18, 2013. It will enter orbit around Mars on or about September 22, 2014, and conduct a year-long mission to study the planet's upper atmosphere and ionosphere and their interactions with the solar wind.
- **InSight**—The Interior Exploration using Seismic Investigations, Geodesy and Heat Transport mission is a Mars lander dedicated to studies of the planet's interior. Launch will occur no earlier than 2016.

# NSF ACTIVITIES

Scientists gathering meteorites in Antarctica as part of an annual joint activity of NSF, NASA, and the Smithsonian Institution.

The National Science Foundation's principal support for planetary science is provided by the Division of Astronomical Sciences (AST) in the Directorate for Mathematical and Physical Sciences. The focus of the program is scientific merit with a broad impact and the potential for transformative research. NSF also provides access to telescopes at the various national observatories. In short, NSF supports nearly all areas of planetary science except space missions, which it supports indirectly through theoretical, modeling and computational studies, laboratory research, and analysis of archived data.

The annual budget of NSF/AST is currently approximately $230 million. Planetary astronomers must compete against all other astronomers for access to both research grants and telescope time, however, and so only a small fraction of AST's facilities and budget support planetary science.

Other parts of NSF make small but important contributions to planetary science. The Office of Polar Programs (OPP) provides access to and logistical support for researchers working in Antarctica. OPP's activities are of direct relevance to planetary science because OPP supports the Antarctic meteorite collection program (jointly with NASA and the Smithsonian Institution) and provides access to analog environments of direct relevance to studies of ancient Mars and the icy satellites of the outer solar system. NSF's Atmospheric and Geospace Sciences Division provides modest support for research concerning planetary atmospheres and magnetospheres. And the Earth Science Division and Ocean Sciences Division have supported studies of meteorites and ice-covered bodies.

The Large Synoptic Survey Telescope team gathers around their primary mirror prior to polishing and grinding.

Such grants, although small compared with NASA's activities in similar areas, are important because they provide a vital source of funding to researchers used mostly to support graduate students and postdoctoral fellows. More importantly, they provide a key linkage between the relatively small community of planetary scientists and the much larger community of researchers studying Earth.

## Theoretical, Modeling, and Computational Studies

Significant advances in many areas of the planetary sciences have occurred during the past decade due to the availability of increasing computing power and more sophisticated software. Computer simulations of complex planetary phenomena have strong visual appeal, can clarify complex processes, and can test hypotheses. Theoretical studies also play an important and growing role in planetary science. Theoretical development and numerical modeling are crucial for planning future planetary missions, as well as for maximizing the science return from past and ongoing missions.

General circulation models of the atmospheres of Mars, Venus, Titan, and the giant planets are one of the best examples of the interplay between data and theory. These circulation models are fundamental tools in the study of planetary atmospheric processes. They are also useful as mission planning tools, for example in predicting the winds that will be encountered by planetary entry probes and landers.

Research on primitive bodies is another area heavily dependent on theory and modeling, in part because the objects are so diverse and their numbers so vast. Fundamental theoretical investigations and numerical modeling are, for example, both needed to understand how the structure of the Kuiper belt has evolved through time. Both were also needed to address important processes that cannot be studied directly in the laboratory such as the collisions between planetary bodies.

## NSF's National Observatories

The National Science Foundation is the largest federal funding agency for ground-based astronomy in the United States. NSF-funded facilities of great importance to the planetary sciences include the following:

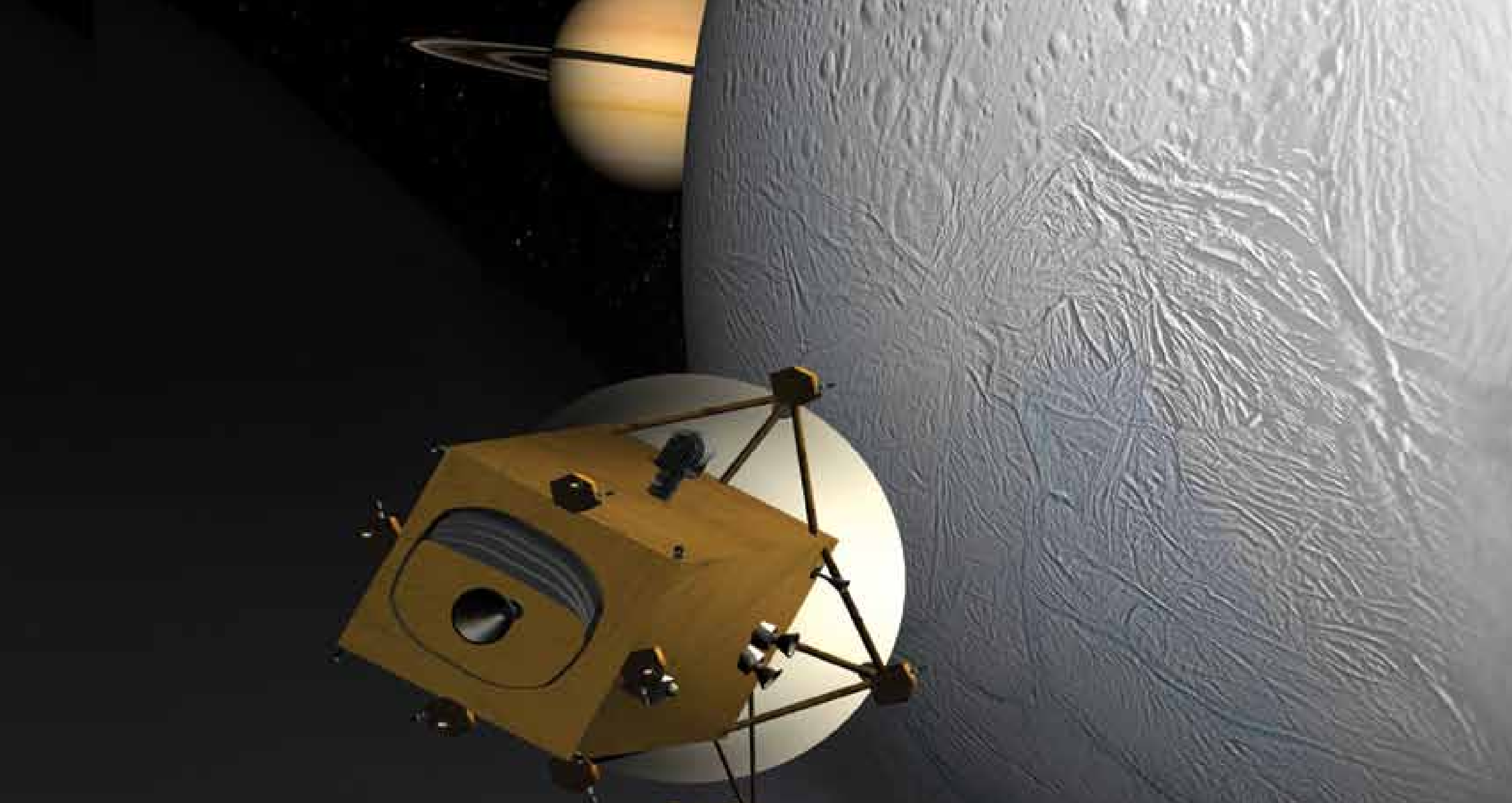
- **The National Optical Astronomy Observatory** operates two 4-meter and other smaller telescopes at the Kitt Peak National Observatory in Arizona and the Cerro Tololo Inter-American Observatory in Chile.
- **The Gemini Observatory** operates two 8-meter optical telescopes, one in the Southern Hemisphere and one in the Northern Hemisphere in an international partnership.
- **The National Astronomy and Ionosphere Center** operates the Arecibo Observatory in Puerto Rico. Arecibo is a unique and important radar facility that plays a particularly important role in studies of near-Earth objects.
- **The National Radio Astronomy Observatory** operates the Very Large Array (VLA) and the Atacama Large Millimeter Array (ALMA). The expanded VLA will produce imaging of the planets across the microwave spectrum and also provide a back-up downlink location to NASA's Deep Space Network. ALMA, an international facility, will operate in the relatively unexplored wavelength region of 0.3 mm to 3.6 mm.
- **The National Solar Observatory** operates telescopes on Kitt Peak, Arizona, and Sacramento Peak, New Mexico, and six worldwide Global Oscillations Network Group stations. In addition, a new facility, the Advanced Technology Solar Telescope, is currently under construction on Mount Haleakala on Maui, Hawaii. Understanding the Sun is critical to understanding its relationship to planetary atmospheres and surfaces.

In addition to access to public facilities, many important advances in planetary research have come from access to private facilities such as the Keck, Magellan, and MMT observatories via NSF's Telescope System Instrumentation Program. The ground-based observational facilities supported wholly or in part by NSF are essential to planetary astronomical observations, both in support of active space missions and in studies independent of (or as follow-up to) such missions. Their continued support is critical to the advancement of planetary science.

Two new ground-based telescope projects are particularly important for planetary scientists. Both involve innovative partnerships between federal agencies (including NSF and the U.S. Department of Energy), private organizations, and international partners. They are as follows:

- **The Large Synoptic Survey Telescope (LSST)**, a wide-field instrument designed to survey the entire sky visible from its observing site in Chile some 1,000 times in a period of 10 years. LSST's ability to study variable phenomena will enable the discovery of many small bodies in the solar system. Some of these bodies are likely to be attractive candidates for future robotic and human spacecraft missions. The timely completion of LSST is the highest-priority new ground-based facility for both planetary scientists and astrophysicists.
- **Extremely Large Telescopes (ELTs)**, that is, telescopes with apertures of approximately 30 meters and larger, will play a significant future role in planetary science. International efforts for ELT development are proceeding rapidly. Preparatory construction work for the 40-meter European Extremely Large Telescope began in 2012. Meanwhile, two such telescopes are in the planning stages in the United States: the Giant Magellan Telescope and the Thirty-Meter Telescope. NSF involvement is needed to ensure that at least one of these facilities comes to fruition with provisions for some public access to observing time.

*A frame from a time lapse movie shows the Gemini North dome under the Big Dipper, along with a shooting star and, to the left, the Pleiades star cluster. The distant domes are part of the Subaru and Keck observatories.*



# RECOMMENDED FUTURE SPACECRAFT MISSIONS

**The authors of *Vision and Voyages* were asked to create a prioritized list of spacecraft missions to be initiated in the decade 2013-2022. Four criteria were used in creating this list. The first and most important was anticipated science return per dollar. The second criterion was programmatic balance in the sense of striving to achieve an appropriate portfolio of mission targets across the solar system and an appropriate mix of small, medium, and large missions. The third and fourth criteria were technological readiness and availability of trajectory opportunities to the intended destinations within the 2013-2022 time period.**

**Operating missions—e.g., Cassini at Saturn, MESSENGER at Mercury, and the various spacecraft on or orbiting Mars—were recommended for continuation, subject to the proviso that they continue to provide new and important scientific results as determined by periodic reviews by NASA. Missions currently in development—e.g., the Lunar Atmosphere and Dust Environment Explorer and the Mars Atmosphere and Volatiles Evolution missions, both scheduled for launch in 2013—were likewise approved for continuation.**

**The principal challenge in assembling a prioritized list of new activities is to assemble a portfolio of missions that achieves a regular tempo of solar system exploration and a level of investigation appropriate for each target object. For example, a program consisting of only flagship missions once per decade may result in long stretches of relatively little new data being generated, leading to a stagnant planetary science community. Conversely, a portfolio of only Discovery-class missions would be incapable of addressing important scientific challenges such as in-depth exploration of the outer planets. To this end, NASA's suite of planetary missions for the decade 2013-2022 should consist of a balanced mix of Discovery, New Frontiers, and flagship missions, enabling both a steady stream of new discoveries and the capability to address larger challenges such as sample return missions and outer planet exploration.**

## Recommended Small Spacecraft Missions

Small planetary missions fall into three categories:

- **The Discovery program** has made important and fundamental contributions to planetary exploration and can continue to do so in the coming decade. Since the missions in this program (see "NASA Activities" section on page 11) are selected via open competition, *Vision and Voyages* makes no recommendations for future specific Discovery flight missions. Because so many important missions can be flown within the program's current cost cap (approximately $500 million) a steady tempo of Discovery competitions and selections is more important than increasing the cost cap.
- **Extended missions for ongoing projects** can be significant and highly productive and may also enhance missions that undergo changes in scope because of unpredictable events. In some cases, particularly the "re-purposing" of operating spacecraft—e.g., as happened with Stardust and Deep Impact—fundamentally new science can be enabled. NASA's current internal review processes are appropriate for deciding the scientific merits of a proposed mission extension.
- **Missions of opportunity** provide a flexible mechanism to facilitate interagency and international cooperation. This mechanism may be used, for example, to enable U.S. instruments to orbit the Moon on India's Chandrayaan-1 spacecraft. A more recent example of a mission of opportunity is the proposed joint European Space Agency (ESA)-NASA Mars Trace Gas Orbiter. The mission would launch in 2016, with NASA providing the launch vehicle, ESA providing the orbiter, and both agencies providing a joint science payload that was recently selected. Unfortunately, NASA withdrew from participation in this joint mission in 2012 due to budget cuts.

## Recommended Medium Spacecraft Mission

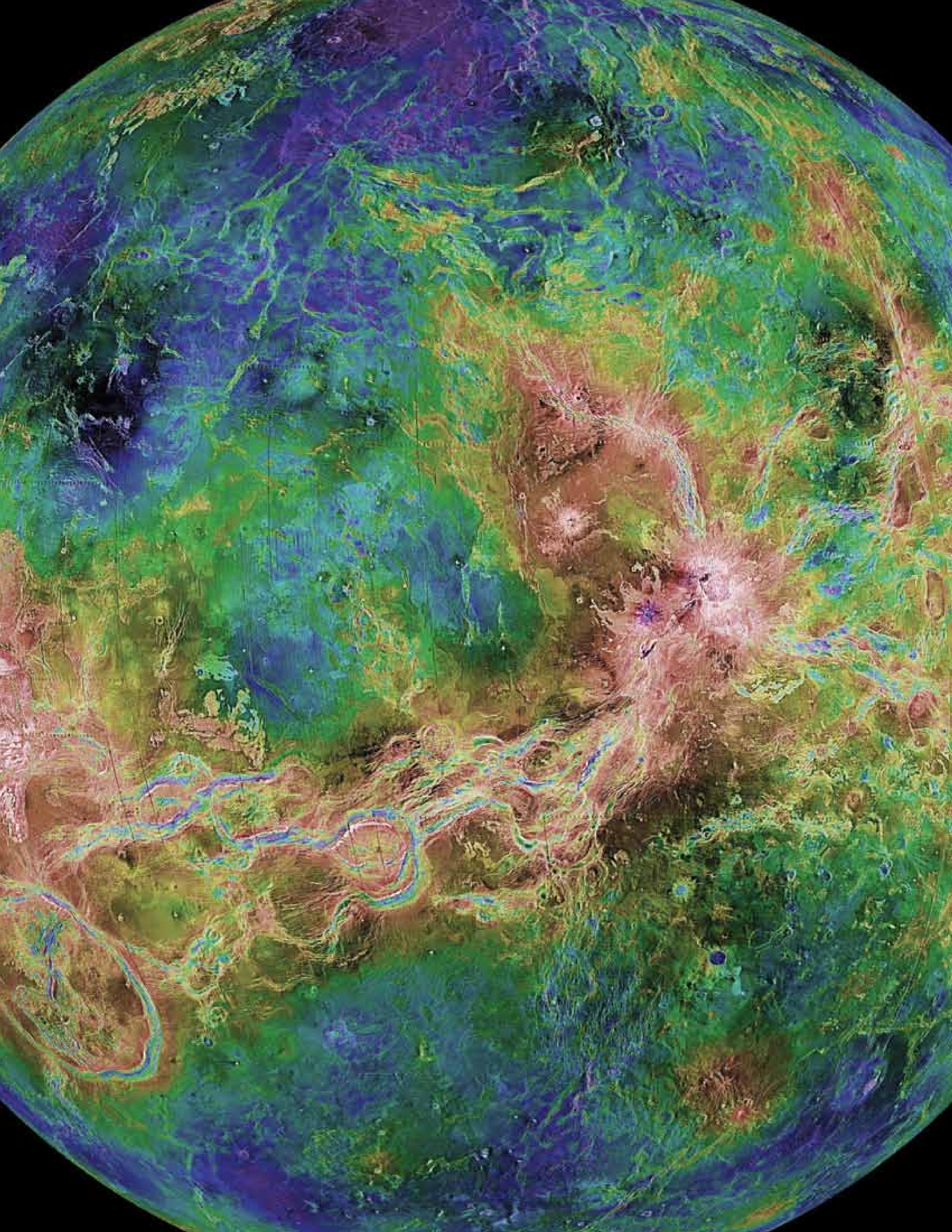
NASA's New Frontiers program of competitively selected, strategic missions fills the middle ground between small spacecraft funded via the Discovery program and multibillion-dollar flagship missions. Two missions of this type have already been launched by NASA—New Horizons bound for Pluto and Juno en route for Jupiter—and a third—OSIRIS-REx—was recently selected for development. The *Vision and Voyages* report identified seven candidate New Frontiers missions. Of these, two are expected to be selected for implementation during the decade 2013-2022. The seven candidates are described in detail in the next section.

## Flagship Missions

*Vision and Voyages* identified five candidate flagship missions for the decade 2013-2022. In priority order, they are as follows:

1. **Mars Astrobiology Explorer-Cacher**—MAX-C, the first of the three components of the Mars sample return (MSR) campaign, is described in detail in a subsequent section.
2. **Jupiter Europa Orbiter**—JEO is discussed at length in a subsequent section.
3. **Uranus Orbiter and Probe**—This mission's spacecraft would deploy a small probe into the atmosphere of Uranus to make in situ measurements and would then enter orbit, making remote sensing measurements of the planet's atmosphere, interior, magnetic field, and rings, as well as multiple flybys of the larger uranian satellites.
4. **Enceladus Orbiter**—This mission (as depicted on the facing page) would investigate that saturnian satellite's polar plumes, habitability, internal structure, chemistry, geology, and interaction with the other bodies of the Saturn system.
5. **Venus Climate Mission**—This mission is designed to address science objectives concerning Venus atmosphere, including carbon dioxide greenhouse effects, dynamics and variability, surface-atmosphere exchange, and origin. The mission architecture includes a carrier spacecraft, a gondola and balloon system, a miniprobe, and two drop probes.

*Vision and Voyages* devoted considerable attention to the relative priorities of the various large-class mission candidates. In particular, both JEO and the MSR campaign (beginning with MAX-C) were found to have exceptional science merit. Because it was difficult to discriminate between the MSR campaign and JEO on the basis of their anticipated science return per dollar alone, other factors came into play. Foremost among these was the need to maintain programmatic balance by ensuring that no one mission takes up too large a fraction of the planetary budget at any given time.



# RECOMMENDED NEW FRONTIERS MISSIONS

NASA's New Frontiers program of principal-investigator-led missions differs from the Discovery program in two important ways. First, with total costs capped at approximately $1 billion each New Frontiers mission is more than twice as expensive as a Discovery mission. Second, New Frontiers missions are strategic in scope. Whereas principal investigators may propose Discovery missions to any and all solar system destinations, New Frontiers missions can only address a restricted number of very-high-priority planetary science goals.

The NRC's 2002 planetary science decadal survey identified an initial list of five high-priority missions and their associated science goals. Following NASA's selection of the New Horizons and Juno missions to Pluto and Jupiter, respectively—which address the science goals of two of the five candidates on the NRC's 2002 list—and prior to NASA's competition to select the third New Frontiers mission, the NRC convened a group of experts to expand the list of candidate missions beyond the remaining three. The third competition resulted in the selection of the OSIRIS-REx—Origins, Spectral Interpretation, Resource Identification, Security and Regolith Explorer—asteroid sample return mission.

The *Vision and Voyages* report reassessed all of the remaining New Frontiers candidates and considered more than a dozen new options. On the basis of their science potential and a conservative assessment of their technical feasibility and projected costs, the *Vision and Voyages* report identified seven candidate New Frontiers missions for the decade 2013-2022. Each of these is judged to be plausibly achievable within the recommended New Frontiers cost cap of approximately $1 billion (excluding the cost of the launch vehicle). In alphabetical order, they are as follows:

**Comet Surface Sample Return**—A mission to return a sample from the nucleus of a comet.

**Io Observer**—A spacecraft designed to study the intense volcanic activity on Jupiter's satellite, Io.

**Lunar Geophysical Network**—An array of landers designed to study the Moon's interior.

**Lunar South Pole-Aitken Basin Sample Return**—A mission to return samples from the oldest impact basin on the Moon.

**Saturn Probe**—A mission that would deploy a probe into Saturn's atmosphere.

**Trojan Tour and Rendezvous**—A mission designed to examine two or more of the small primitive bodies that share the orbit of Jupiter.

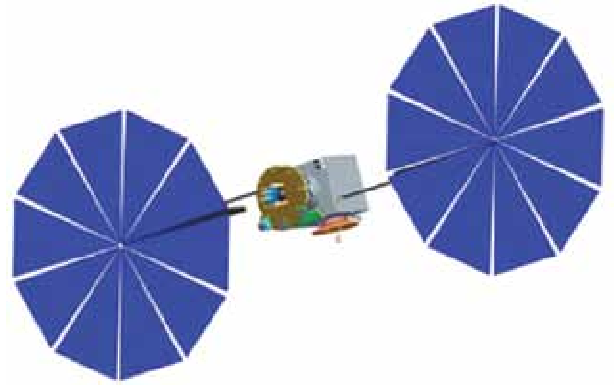
**Venus In Situ Explorer**—A lander designed to study the physics and chemistry of Venus's atmosphere and crust.

See pages 18-19 for additional details. To achieve an appropriate balance among small, medium, and large missions, *Vision and Voyages* recommended that NASA select two of these seven candidate New Frontiers missions during the decade 2013-2022. The first of these, referred to as New Frontiers 4, would likely be selected in the latter part of this decade. Work on New Frontiers 5 would likely not begin until the early 2020s.

*A radar image of most of one hemisphere of Venus based on data returned by NASA's Magellan spacecraft. The colors indicate altitude, with browns being high and blues low.*

## Comet Surface Sample Return

The objective of this mission is to acquire and return to Earth a macroscopic sample from the surface of a comet nucleus using a sampling technique that preserves organic material in the sample. The mission would also use additional instrumentation on the spacecraft to determine the geologic and geomorphologic context of the sampled region. Because of the increasingly blurred distinction between comets and the most primitive asteroids, many important objectives of an asteroid sample return mission could also be accomplished by this mission.

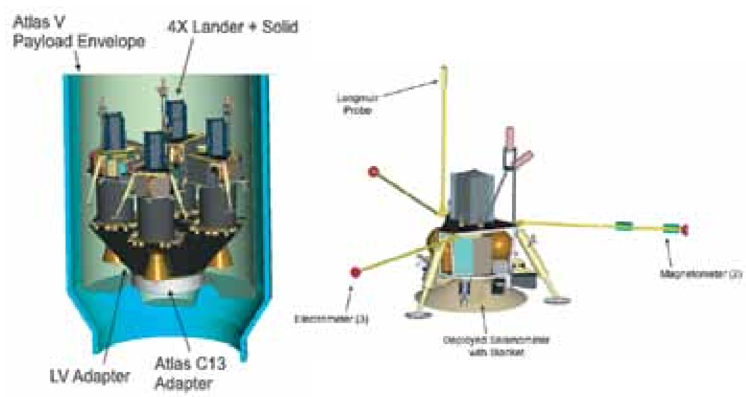


## Io Observer

The focus of this mission is to determine the internal structure of Io and to investigate the mechanisms that contribute to the satellite's intense volcanic activity. The spacecraft would go into a highly elliptical orbit around Jupiter and make multiple flybys of Io. Specific science objectives would include characterization of surface geology and heat flow, as well as determination of the composition of erupted materials and study of their interactions with the jovian magnetosphere.

## Lunar Geophysical Network

This mission consists of four identical landers distributed across the lunar surface, each carrying instruments for geophysical studies. The primary science objectives of this mission are to characterize the Moon's internal structure, seismic activity, global heat flow budget, bulk composition, and magnetic field. The mission's duration would be several years, allowing detailed study of the Moon's seismic activity and internal structure. Such data are critical to determining the initial composition of the Moon and the bulk composition of the Earth-Moon system, and to understanding the collision process thought to have created the Moon.

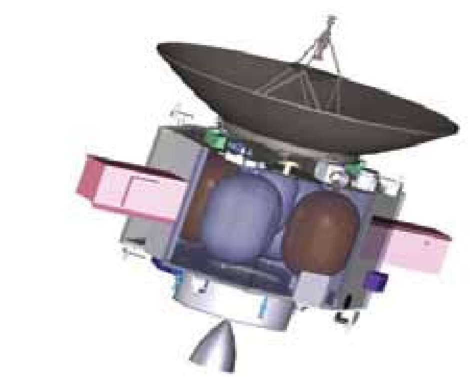



## Lunar South Pole-Aitken Basin Sample Return

The primary science objective of this mission is to return samples from this ancient and deeply excavated impact basin to Earth for characterization and study. Although recent lunar orbiters have provided much valuable remote-sensing data about the diversity of material and the geophysical context of this, the oldest and deepest impact feature on the Moon, achieving the highest-priority science objectives requires precision measurements of the basin's age and elemental composition. Such measurements can only be made in terrestrial laboratories. In addition to returning at least 1 kilogram of samples, this mission would also document the geologic context of the landing site with high-resolution and multispectral imaging.

## Saturn Probe

This mission is intended to determine the structure of Saturn's atmosphere as well as abundances of noble gases and isotopic ratios of hydrogen, carbon, nitrogen, and oxygen. The flight system consists of a carrier-relay spacecraft and a probe to be deployed into Saturn's atmosphere. The probe would make continuous in situ measurements of Saturn's atmosphere as it descends some 250 kilometers from its initial entry point and relays measurement data to the carrier spacecraft. Such a mission will complete the initial in-depth reconnaissance of the Saturn system begun by the Cassini spacecraft.

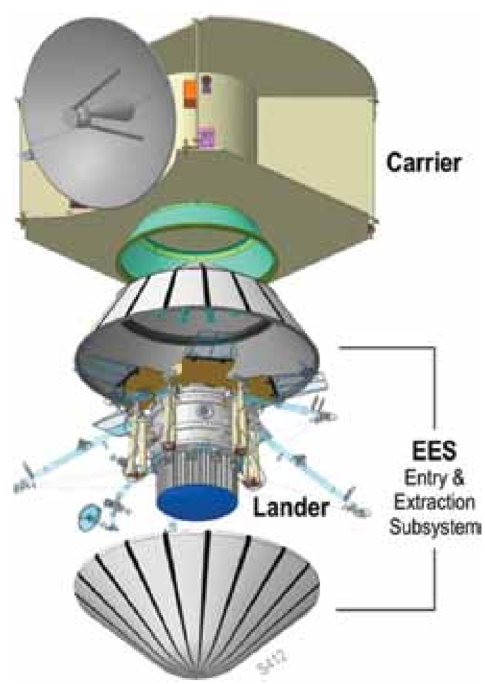


## Trojan Tour and Rendezvous

This mission is designed to examine two or more small primitive bodies sharing the orbit of Jupiter, including one or more flybys followed by an extended rendezvous with a single Trojan object. The primary science objectives for this mission include characterization of the bulk composition, interior structure, and near-surface volatiles. The Trojans, located as they are at the boundary between the inner and outer solar system, are one of the keys to understanding solar system formation.

## Venus In Situ Explorer

The primary science objectives of this mission are to examine the physics and chemistry of Venus's atmosphere and crust. This mission would attempt to characterize variables that cannot be measured from orbit, including the detailed composition of the lower atmosphere and the elemental and mineralogic composition of surface materials. The mission architecture consists of a lander that would acquire atmospheric measurements during descent and then carry out a brief period of remote sensing and in situ measurements on the planet's surface. The extreme conditions of temperature and pressure on Venus's surface limit the lander's lifetime to a couple of hours.



# BEGINNING THE MARS SAMPLE RETURN CAMPAIGN

Data returned to Earth from a highly successful series of Mars missions conducted over the past 15 years have revolutionized understanding of the Red Planet. Current ideas concerning the origin and evolution of the diverse martian environments viewed by spacecraft (as illustrated above) have reached a level of sophistication such that additional fundamental advances will come only from the analysis of samples collected on Mars and returned to Earth for study in terrestrial laboratories.

Although the idea of collecting martian samples and returning them to Earth is not new, a Mars sample return (MSR) mission has always been viewed as too complex, too expensive, and too risky. Fortunately, what was originally envisaged as a single spacecraft that would land on Mars, grab a scoop of martian soil, and then blast off for Earth has been superseded by a much more feasible three-mission MSR campaign. The first mission is a rover designed to collect samples and place them in a canister. The second mission will retrieve the rover's sample canister and place it in a small rocket that sends the canister into orbit about Mars. The third mission will maneuver up to the orbiting sample canister, capture it, and return it to Earth. The complexity, cost, and risk of MSR is thus spread out over multiple launch opportunities, rendering each mission less of a technical challenge.

NASA has made significant strides in developing the technologies and mission infrastructure needed support a multi-mission MSR campaign. In particular:

- Mars Pathfinder and the Mars Exploration Rovers (MERs) have demonstrated surface mobility, and the MERs have demonstrated much of the basic instrumentation needed to select high-priority samples.
- MER and Phoenix have provided valuable experience in sample handling and surface preparations; the Mars Science Laboratory (MSL) will do significantly more.
- The Sky Crane entry, descent, and landing system, so spectacularly demonstrated by MSL, can deploy all the surface assets needed for a sample return campaign.
- The technologies needed for the orbital rendezvous and capture of the sample canister have been demonstrated in Earth orbit.
- Sample return protocols and the design of Earth-entry vehicles have been validated by the Stardust and Genesis missions.
- The instruments on NASA orbiters such as Mars Odyssey and Mars Reconnaissance Orbiter and the European Space Agency's Mars Express can search the planet for safe, but scientifically interesting, landing sites and act as communications relays for the MRS missions.

For these reasons and more, the *Vision and Voyages* report ranked the first element of an MSR campaign—a rover called the Mars Astrobiology Explorer-Cacher (MAX-C)—as the highest-priority large mission for the decade 2013-2022. MAX-C is intermediate in size between the MERs and MSL. It is equipped with a suite of instruments sufficient to collect samples (probably in the form of pencil-lead-size rock cores), document them, and then package them for return to Earth. MAX-C would be deployed on Mars using a Sky Crane and then conduct an extended geologic traverse very much like that conducted by the MERs. The traverse, in itself, would significantly advance understanding of the geologic history and evolution of Mars, even before the cached samples are returned to Earth.

MAX-C was envisaged as being a part of a joint NASA-ESA program of Mars exploration. The plan was to deploy both MAX-C and an ESA rover called ExoMars at the same location on Mars using a single Sky Crane. However, landing a payload as massive and bulky as both MAX-C and ExoMars would require a major redesign of the Sky Crane system, with substantial associated cost growth.

While strongly supporting the NASA-ESA partnership, *Vision and Voyages* recommended that a significant reduction in the scope of the joint mission—for example, by avoiding modifications to the Sky Crane—was needed to keep its cost within realistic limits.

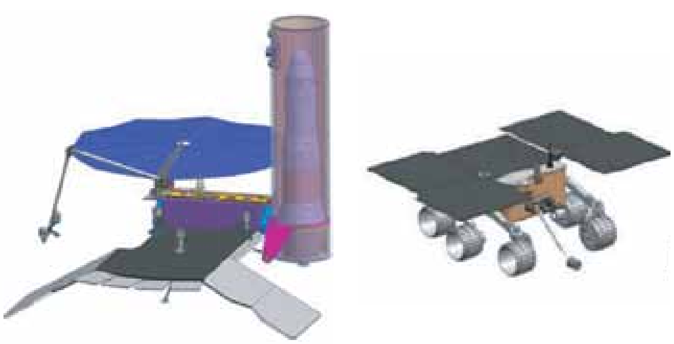
Following the publication of *Vision and Voyages* in 2010, budgetary pressures on both sides of the Atlantic forced NASA and ESA to reformulate their plans. Rather than landing two rovers on Mars in 2018, the agencies decided to combine forces and deliver a single rover.

Unfortunately, this is not the end of the story. Continuing budgetary pressures caused NASA to withdraw from its partnership with ESA in the early months of 2012. NASA currently has no plans for additional missions to Mars following the launch of the MAVEN orbiter in 2013 and the InSight lander in 2016. Meanwhile, ESA has established a new partnership with Russia and still plans to proceed with ExoMars.

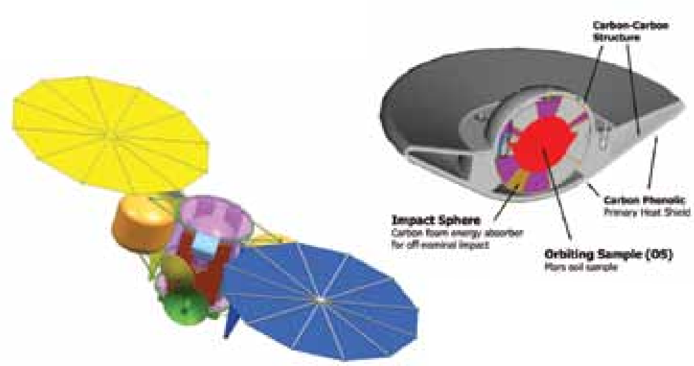
## Elements of the Mars Sample Return Campaign

The three missions that make up the Mars sample return (MSR) campaign. First, the Mars Astrobiology Explorer-Cacher collects martian samples and places them in a canister and deposits it on the surface for later retrieval. Second, a small rover deployed by the MSR Lander collects the canister and transfers it to the Mars Ascent Vehicle (MAV). The MAV then launch the canister into Mars orbit to await retrieval. Third, the MSR Orbiter rendezvous with and captures the canister. The MSR Orbiter then fires its rockets and sets course for its return voyage to Earth. *Note: Images not to scale.*

**Mars Astrobiology Explorer-Cacher**



**Mars Sample Return Lander, Mars Ascent Vehicle, and Fetch Rover**




**Mars Sample Return Orbiter and Earth Entry Vehicle**

# THE JUPITER EUROPA ORBITER

Europa, the third largest of Jupiter's Galilean satellites, almost certainly contains a vast subsurface ocean sandwiched between a rocky interior and a highly dynamic surface ice shell (pictured above). The ocean water remains unfrozen because of the continual tidal flexing of the satellite as it responds to the ever-changing gravitational forces exerted by Jupiter and the other Galilean satellites. As such, Europa offers one of the most promising habitable environments known in the solar system. Moreover, the larger Jupiter system in which Europa resides hosts an astonishing diversity of phenomena, illuminating many fundamental planetary processes. While Voyager and Galileo revealed much new information about Europa and the Jupiter system, the relatively primitive instrumentation carried by these spacecraft, and the low data volumes returned, have left many questions unanswered, and it is likely that major discoveries remain to be made.

The initiation of a Europa orbiter mission has been a priority of the planetary science community for the past decade, and multiple mission options have been studied. At the time the *Vision and Voyages* study was initiated, the favored option was the Europa Jupiter System Mission (EJSM). The concept was conceived as a partnership between NASA and the European Space Agency (ESA). EJSM would have had two components, to be launched separately: the Jupiter Europa Orbiter (JEO), which would be built and flown by NASA, and a Jupiter Ganymede Orbiter (JGO, also known as Laplace), which would be built and flown by ESA.

The NASA mission was designed to be launched in 2020 and enter the Jupiter system in 2026. The JEO mission featured a 30-month jovian system tour, which included four Io flybys, nine Callisto flybys, six Ganymede flybys, and six Europa flybys, along with some 2.5 years of observing Io's volcanic activity and Jupiter's atmosphere, magnetosphere, and rings.

After the jovian tour phase, JEO would enter orbit around Europa and spend the first month in a 200-kilometer circular orbit before descending to a 100-kilometer circular orbit for another 8 months. The spacecraft lifetime in the vicinity of Europa is limited because the satellite is immersed in the intense radiation belts surrounding Jupiter.

ESA's JGO mission would launch at about the same time as its NASA counterpart. Upon capture into orbit about Jupiter, JGO would accomplish numerous Callisto flybys before going into orbit around Ganymede. The presence of both JEO and JGO in the jovian system at the same time would have allowed for unprecedented synergistic observations.

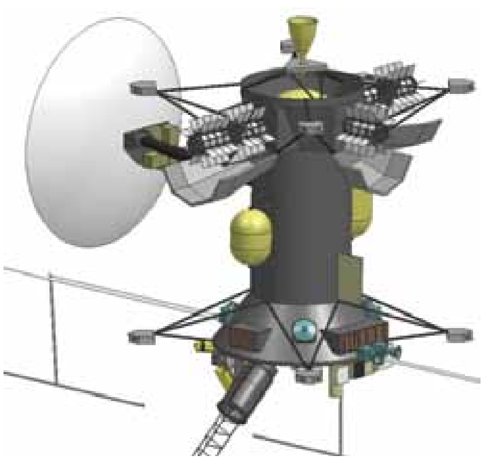
The principal goals of JEO are as follows, in the priority order shown:

1. **Characterize the extent of the ocean and its relation to the deeper interior.**
2. **Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of the surface-ice-ocean exchange.**
3. **Determine global surface compositions and chemistry, especially as related to habitability.**
4. **Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future in situ exploration.**
5. **Understand Europa's space environment and interaction with the magnetosphere.**
6. **Conduct studies of Jupiter's atmosphere, magnetosphere, other satellites, and rings.**

The authors of *Vision and Voyages* found the scientific case for JEO to be compelling. Substantial technology work has been done on JEO over the past decade, with the result that NASA is much more capable of accomplishing this mission than was the case when a Europa orbiter was first conceived in the late 1990s. The difficulty in achieving JEO is its projected cost of almost $5 billion. To initiate JEO as it was conceived would lead to the elimination of too many other important missions. Therefore, while the report recommended JEO as the second-highest-priority flagship mission, it could only be initiated following a reduction in the mission's scope and an increase in the NASA budget. While the former has occurred, the latter has not. In fact, severe reductions in 2012 to the budget of NASA's Planetary Science Division render problematic the initiation of any flagship mission to the outer solar system in the near- to mid-term future.

Budget cuts aside, the scientific priority of future studies of Europa and the other Galilean satellites remains high. In early 2012 ESA formally initiated the JGO mission, now called the Jupiter Icy Moons Explorer (JUICE). European scientists have augmented the design of their mission to include several flybys of Europa, thus recovering some of the science lost following the cancellation of JEO. Moreover, ESA has invited NASA to provide several of JUICE's instruments.

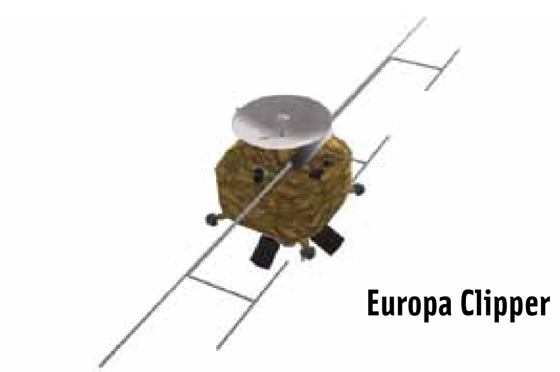
JUICE is currently scheduled to launch in 2022. It will enter orbit around Jupiter in 2030 and conduct a 2-year-long jovian tour before settling into orbit around Ganymede in 2032.



**Jupiter Europa Orbiter**

## Evolving Europa Orbiter Concepts

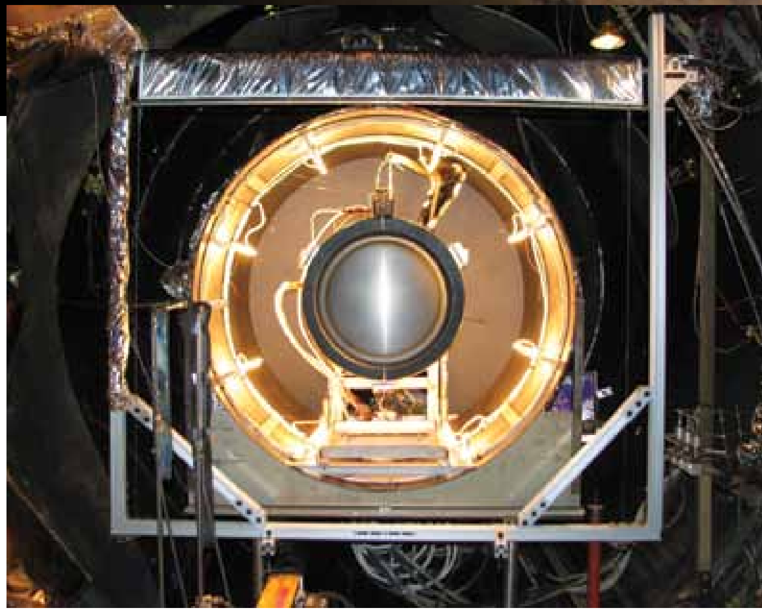
The Jupiter Europa Orbiter (*top left*) recommended by *Vision and Voyages* was designed to carry a large and complex suite of instruments. The resulting mission was highly capable but prohibitively expensive. Since the completion of *Vision and Voyages*, researchers have rescoped the mission as two smaller, less complex, and less expensive missions. The Europa Orbiter (*bottom right*) carries only those instruments that need to in orbit about Europa. The remaining instruments are placed on the Europa Clipper (*bottom left*), a Jupiter orbiter, which would perform multiple flybys of Europa. *Note: Images not to scale.*



**Europa Clipper**

**Europa Orbiter**

# TECHNOLOGY DEVELOPMENT



*The NASA Evolutionary Xenon Thruster which will use electrical power to propel future spacecraft with ionized xenon gas atoms.*

The future of planetary science depends on a well-conceived, robust, stable technology investment program. Early investment in key technologies reduces the cost risk of complex projects, allowing them to be initiated with less uncertainty regarding their eventual total costs. Investments must be strategic to enable future missions with the greatest potential for discovery. Although the need for a technology program seems obvious, investments in new planetary exploration technologies have been sharply curtailed. Furthermore, technology funding has been used to pay for flight project overruns in recent years, which is tantamount to eating the seed corn.

A substantial program of planetary exploration technology development should be reconstituted and carefully protected against all incursions that would deplete its resources. The technology program should be targeted toward the planetary missions that NASA intends to fly, and the missions should be selected competitively whenever possible. This reconstituted technology element should aggregate related, but currently uncoordinated, NASA technology activities that support planetary exploration. These activities should be reprioritized and rebalanced to ensure that they contribute to the twin goals of reducing the cost of planetary missions and improving their scientific capabilities and reliability.

A significant concern with the current planetary exploration technology program is the apparent lack of innovation at the front end of the development pipeline. Truly innovative, breakthrough technologies appear to stand little chance of success in the competition for development money because, by their very nature, they are directed toward far-future objectives rather than specific near-term missions. NASA should expand its program of regular future mission studies to identify as early as possible the technology drivers and common needs for likely future missions.

Particularly important technologies identified in *Vision and Voyages* include the following:

- **Advanced Stirling Radioisotope Generator**, a new high-efficiency nuclear power source for missions to locations were the use of solar power is not practical.
- **NASA Evolutionary Xenon Thruster**, a new-generation ion engine for interplanetary spacecraft currently being tested in the laboratory.
- **Advanced Material Bipropellant Rocket**, a high-performance, high-thrust chemical rocket engine for use by future deep-space missions.
- **UltraFlex Solar Array**, a lightweight solar power system using an innovative fanfold circular design, first used by NASA on its Phoenix Mars lander.
- **Aerocapture**, a technique by which a spacecraft can be placed into orbit about a planetary body by making a single precisely controlled flight through the body's atmosphere (as depicted in the artist's impression at top left).

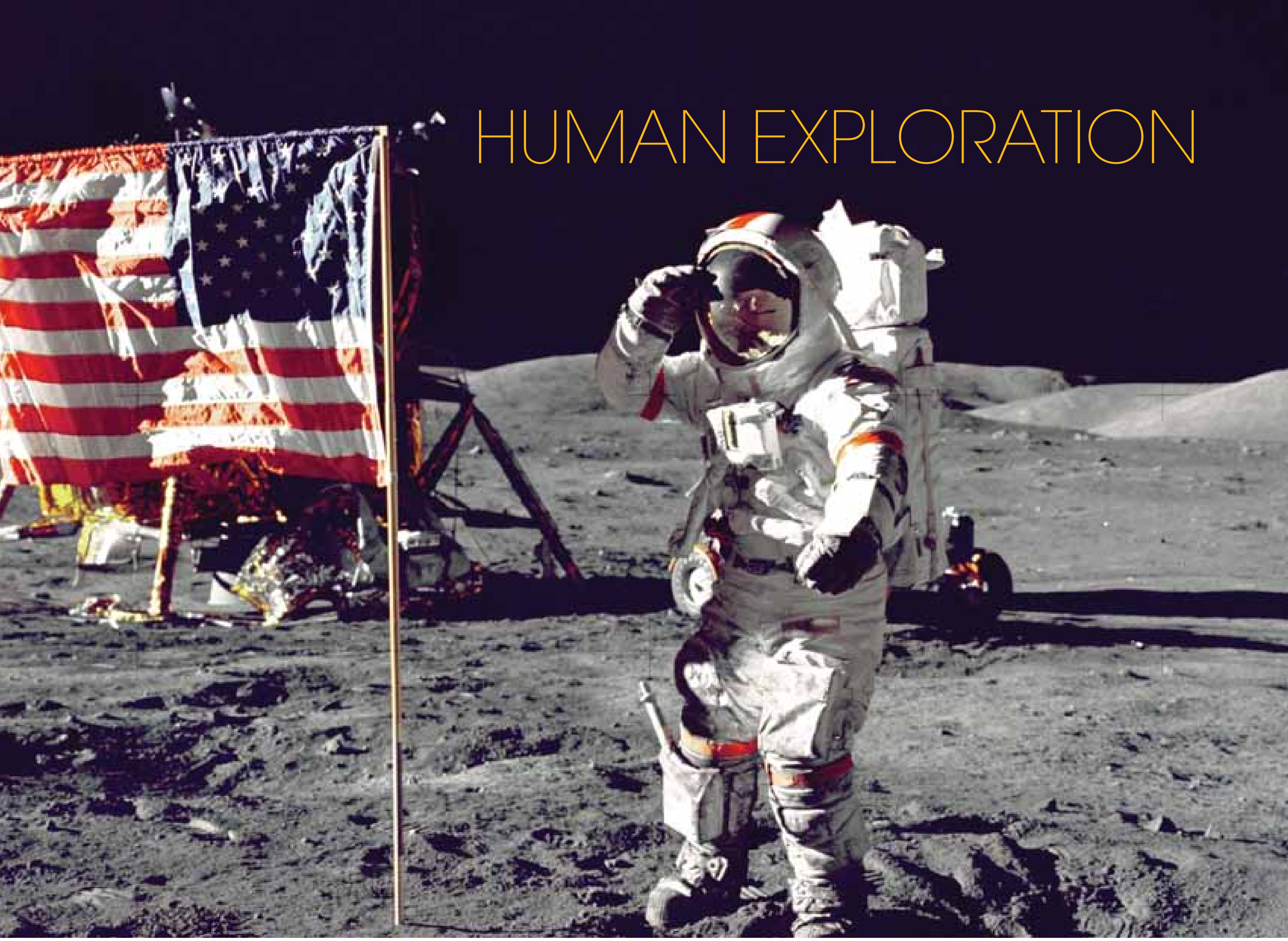
## THE ADVANCED STIRLING RADIOISOTOPE GENERATOR

No technology is more critical than high-efficiency power systems for application in those planetary environments where the use of solar power is not feasible, e.g., during the 2-week long lunar night and in the outer solar system. The Advanced Stirling Radioisotope Generator (ASRG) is a highly efficient nuclear power supply currently under development by the U.S. Department of Energy (DoE) and NASA. The ASRG, like the current generation of radioisotope power systems (RPS) used by Cassini, New Horizons, and the Mars Science Laboratory, converts heat from the decay of plutonium-238 into electrical power. But the ASRG is three- to four-times more efficient in its use of plutonium than current RPS. The down side is that unlike current RPS, the ASRG has moving parts; heat from the radioactive source drives a piston that moves a magnet back and forth through a coil of conducting wire, producing electricity. Suspending the piston in a helium gas bearing eliminates physical contact with the rest of the ASRG, preventing wear.

Plutonium-238 is a limited and expensive resource. DoE production of this rare isotope ceased in the late 1980s, and since then NASA has relied on a rapidly depleting U.S. stockpile, supplemented by supplies purchased from Russia. Although NASA and DoE have plans to resume domestic production of plutonium-238, the schedule for the availability of a new supply is still uncertain. Since more efficient use of the limited plutonium supply will help to ensure a robust and ongoing planetary science program, the highest priority for near-term technology investment identified in *Vision and Voyages* is the completion and flight validation of the ASRG.


*An engineer adjusts the test unit for the Advanced Stirling Radioisotope Generator.*

# HUMAN EXPLORATION



Although human space exploration is undertaken to serve a variety of national and international interests, science is not a primary motivation. But this does not mean that astronauts cannot address important space science goals. Even the most advanced robotic spacecraft have limited intellectual and physical capabilities. A sophisticated rover, such as the Mars Science Laboratory, can do only what it is told and is incapable of completely independent autonomous reasoning. By comparison, astronauts are intellectually flexible and adaptable to different situations, as demonstrated by the space shuttle missions to repair and service the Hubble Space Telescope. Humans develop and communicate ideas, not just data. Human adaptability and capability in an unstructured environment far surpass those of robots, and will for the foreseeable future. Conversely, the cost of human spaceflight is perhaps 10 to 100 times that of robotic missions, primarily because of the cost of keeping astronauts alive and well.

Throughout the Space Age there have been periods of tension and cooperation between the human spaceflight and the planetary science programs. The greatest degree of cooperation between the two occurred during the Apollo era, when scientists were involved in the selection of landing sites, the development of exploration goals, and the training of astronauts. Scientists also benefited heavily from the lunar samples and other data returned from the six Apollo Moon landings.

What then are the most appropriate roles for robots and astronauts? Although many, if not most, of the science goals recommended in *Vision and Voyages* are best and most economically conducted using robotic spacecraft, an important subset of planetary exploration goals can benefit from human spaceflight. These are missions to the surfaces of solid bodies whose surface conditions are not too hostile for humans. For the foreseeable future, humans can realistically explore the surfaces of only the Moon, Mars and its moons Phobos and Diemos, and some asteroids.

*(Left) Astronaut Gene Cernan on the Moon's surface during Apollo 17. The Apollo program was the last widespread cooperation between planetary scientists and the human spaceflight program, and the later Apollo missions provided a wealth of scientific data about the Moon.*

If the Apollo experience is an applicable guide, robotic missions to targets of interest will undoubtedly precede human landings. The measurement objectives for human exploration precursor missions will focus mainly on engineering practicalities and issues regarding health and safety, rather than science. Although there are a number of examples where the interests intersect, such as finding a resource like water, the motivation and ultimate data applications of the two sets of goals are typically quite different.

A positive example of synergy between the human exploration program and planetary science is the current Lunar Reconnaissance Orbiter (LRO) mission. This project was conceived as a precursor for the human exploration program but ultimately was executed in concert with the planetary science community. Indeed, with one exception, LRO's instruments were selected via the same open, competitive process used for science missions. Then, in 2010, after the end of the exploration phase of LRO's mission, responsibility for the spacecraft was turned over to NASA's Planetary Science Division. Some 23 scientists were added to the mission team to ensure that top-quality science is executed. By building on lessons learned from LRO, an effective approach to exploration-driven robotic precursor missions can be devised.

*In a clean room at NASA's Goddard Space Flight Center, the Lunar Reconnaissance Orbiter is assembled, integrated, and ready for testing prior to its launch on June 18, 2009.*

Despite the positive recent example of LRO, the concern remains that human spaceflight programs can cannibalize space science programs. NASA's planetary science program probably will include missions to destinations that are likely targets of human exploration. A relevant example is the asteroid sample return mission OSIRIS-REx, selected in 2011 as the next mission in NASA's New Frontiers program. It is vital to maintain the science focus of such missions and to avoid incorporating human exploration requirements after the mission has been selected and development has begun. If the data gathered by such missions have utility for human exploration activities, the analysis should be paid for by the human exploration program. Similarly, if the human exploration program proposes a precursor mission (such as LRO) and there is an opportunity for conducting science at the destination, the science programs must be very cautious about directly or indirectly imposing mission-defining requirements and should be willing to pay for any such requirements.

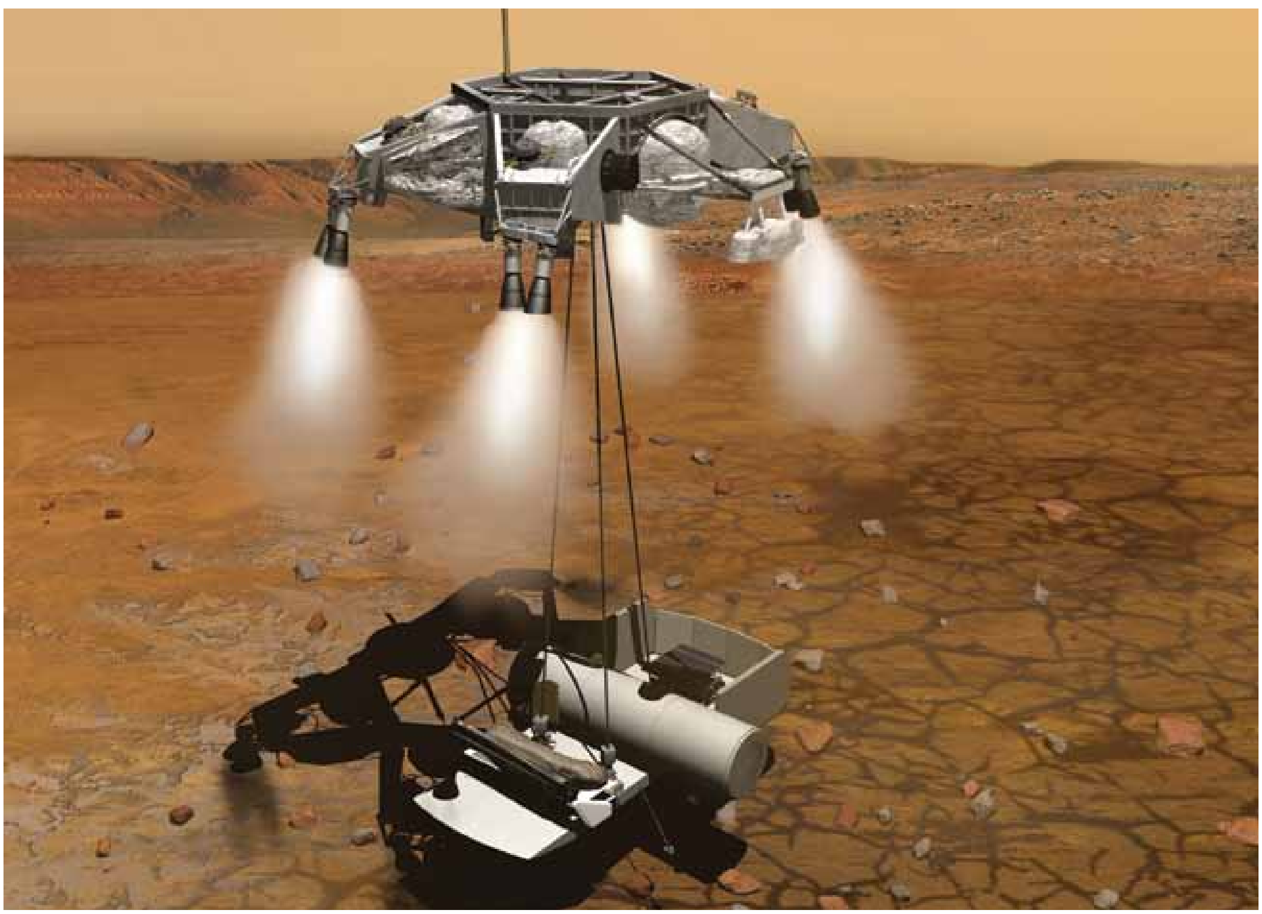
The need for caution does not rule out the possibility of carefully crafted collaborations, however. It may be possible, for example, to put science-focused instrumentation on precursor missions sponsored by NASA's human exploration program. Similarly, science missions to certain targets could carry instruments funded by the human exploration program. Also, missions designed to prepare for future human exploration can be "re-purposed" to address science questions once their primary mission has been completed, as was done for LRO.

Numerous studies have considered the scientific utility of human explorers or human-robotic exploration teams for exploring the solar system. Invariably, the target of greatest interest has been Mars. The scientific rationale cited has focused largely on answering questions relating to the search for past or present biological activity. On the basis of the importance of questions relating to life, the *Vision and Voyages* report concluded that for the more distant future, human explorers with robotic assistance may contribute more to the scientific exploration of Mars than they can for any other body in the solar system. Robotic missions to Mars, either purely for science or as precursors to a human landing, can lay the scientific groundwork for a human presence. Humans will then take exploration to the next steps by making sense of the complex martian environment, rapidly making on-the-spot decisions to choose the right spots for sampling, performing the best experiments, and then interpreting the results and following up opportunistically.

# CONCLUDING THOUGHTS

The panoply of planetary science missions launched into the solar system over the past decades has returned a tremendous amount of new knowledge. Still, many questions await answers: What processes transformed a clump of gas and dust into our solar system? How do physics and chemistry shape the evolution of planetary interiors, surfaces, and atmospheres? Does life exist beyond Earth? Drawing on the expertise of the entire planetary science community, *Vision and Voyages* presents a balanced portfolio of space missions, technology development, and terrestrial research that provides the potential to yield revolutionary new discoveries. Ambitious missions to Mars and Europa have the capability to answer profound questions, while the Discovery and New Frontiers programs enable a steady stream of new findings in this decade. The general public supplies the support for these endeavors, so it is fitting that the program outlined in *Vision and Voyages* will produce accessible science with broad appeal.

A vigorous program of planetary exploration is both a feasible and an appropriate goal for the nation. Many targets of investigation—from the hellish climate of Venus to threatening near-Earth objects—have dramatic implications for the future of our own planet. A global community of scientists and engineers stands ready to build and operate an inspiring slate of planetary missions. Unfortunately, the recent manifestations of an austere budgetary climate, including the cancellation of NASA's plans to initiate the first element of a Mars sample return campaign later this decade and to explore the jovian system in cooperation with the European Space Agency during the subsequent decade, threatens our ability to bring the objectives outlined in *Vision and Voyages* to reality. But, as President Theodore Roosevelt commented: "Far better is it to dare mighty things, to win glorious triumphs, even though checkered by failure than to rank with those poor spirits who neither enjoy nor suffer much, because they live in a gray twilight that knows not victory nor defeat." Thus, our challenge is to find the resources necessary to fulfill this vision and to embark upon these epic voyages.



*A Sky Crane deploys the Mars Sample Return Lander (see page 21) on the surface of the Red Planet sometime in the 2020s or 2030s. Is this just an artist's vision or preview of a voyage to come?*

## Image Credits and Sources

Page 1 NASA/JPL

Page 2 *Top*: NASA/JPL – Caltech. <http://solarsystem.nasa.gov/multimedia/gallery/OSS.jpg>. *Bottom*: NASA/JPL – Caltech. <http://explanet.info/images/Ch01/01GalileanSat00601.jpg>.

Page 3 *Top*: NASA/JPL/Space Science Institute <http://photojournal.jpl.nasa.gov/jpeg/PIA11133.jpg>. *Bottom*: NASA/JPL – Caltech/University of Maryland.

Page 4 Gemini Observatory/AURA/UC Berkeley/SSI/JPL-Caltech <http://photojournal.jpl.nasa.gov/jpeg/PIA13761.jpg>.

Page 5 *Top*: ESA/NASA/JPL-Caltech < http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=46816>. *Second*: NASA/JPL-Caltech. *Third*: NASA/JPL-Caltech/Space Science Institution. *Bottom*: NASA/JPL-Caltech <http://photojournal.jpl.nasa.gov/jpeg/PIA15258.jpg>.

Page 6 NASA/JPL-Caltech <http://nexsci.caltech.edu/workshop/2010/PIA11375.jpg>. Background image - NASA/JPL-Caltech.

Page 7 *Top*: NASA/JPL-Caltech. *Bottom*: NASA/GSFC/NSSDC <http://nssdc.gsfc.nasa.gov/image/planetary/venus/venera13-left.jpg>.

Page 8 *Top Left*: NASA/Regina Mitchell-Ryall and Tom Farrar <http://www.nasa.gov/multimedia/imagegallery/image_feature_2123.html>. *Bottom Right*: NASA.

Page 9 Top: NASA/JHUAPL/SwRI. Bottom: NASA/MSFC/David Higginbotham <http://www.nasa.gov/centers/marshall/images/content/480832main_1001527_4256x2832.jpg>.

Page 10 NASA <http://kepler.nasa.gov/images/goldstone-full.jpg>.

Page 11 NASA/JPL-Caltech/University of Arizona <http://phoenix.lpl.arizona.edu/images/gallery/lg_4865.jpg>.

Page 12 *Top Right*: Courtesy of Silvio Lorenzetti, Swiss Federal Institute of Technology, Zurich. *Bottom Left*: Howard Lester/LSST Corporation.

Page 13 Gemini Observatory <http://www.gemini.edu/gallery/v/gn/exterior/20100128_gn_ext_fe_tl_no_lasers_0484.jpg.html>.

Page 14 Background: NASA/JPL-Caltech.

Page 16 NASA/JPL/USGS.

Page 18 *Top*: NASA Mission Study (transmitted from Lindley N. Johnson, NASA SMD/Planetary Science Division). *Second*: NASA Mission Study (transmitted from Curt Niebur, NASA SMD/Planetary Science Division). *Third*: NASA Mission Study (transmitted from George J. Tahu, NASA Planetary Science Division). *Bottom*: NASA.

Page 19 *Top*: NASA Mission Study (transmitted from Leonard Dudzinski, NASA SMD/Planetary Science Division. *Middle:* NASA. *Bottom*: Larry Esposito, University of Colorado, Boulder.

Page 20 NASA/JPL-Caltech/Cornell/Arizona State University <http://photojournal.jpl.nasa.gov/jpeg/PIA15282.jpg>.

Page 21 NASA Mission Study (transmitted from Lisa May, NASA Planetary Science Division).

Page 22 NASA/JPL/University of Arizona <http://photojournal.jpl.nasa.gov/catalog/?IDNumber=PIA01296>.

Page 23 *Top Left*: NASA Mission Study (transmitted from Curt Niebur, NASA SMD/Planetary Science Division). *Bottom Left*: NASA/JPL. *Bottom Right*: NASA/JPL.

Page 24 *Top*: NASA/MSFC. <http://www.nasa.gov/centers/marshall/images/content/155634main_LOW_LD_MARS_STARS_SUN_HIRES_3333x1667.jpg>. *Bottom*: NASA.

Page 25 NASA <http://solarsystem.nasa.gov/images/asrg2.jpg>.

Page 26 NASA.

Page 27 NASA/Debbie McCallum <http://www.nasa.gov/images/content/348720main_LROspacecraft_full_LG.jpg>.

Page 28 NASA/JPL-Caltech <http://photojournal.jpl.nasa.gov/catalog/?IDNumber=PIA14264>.