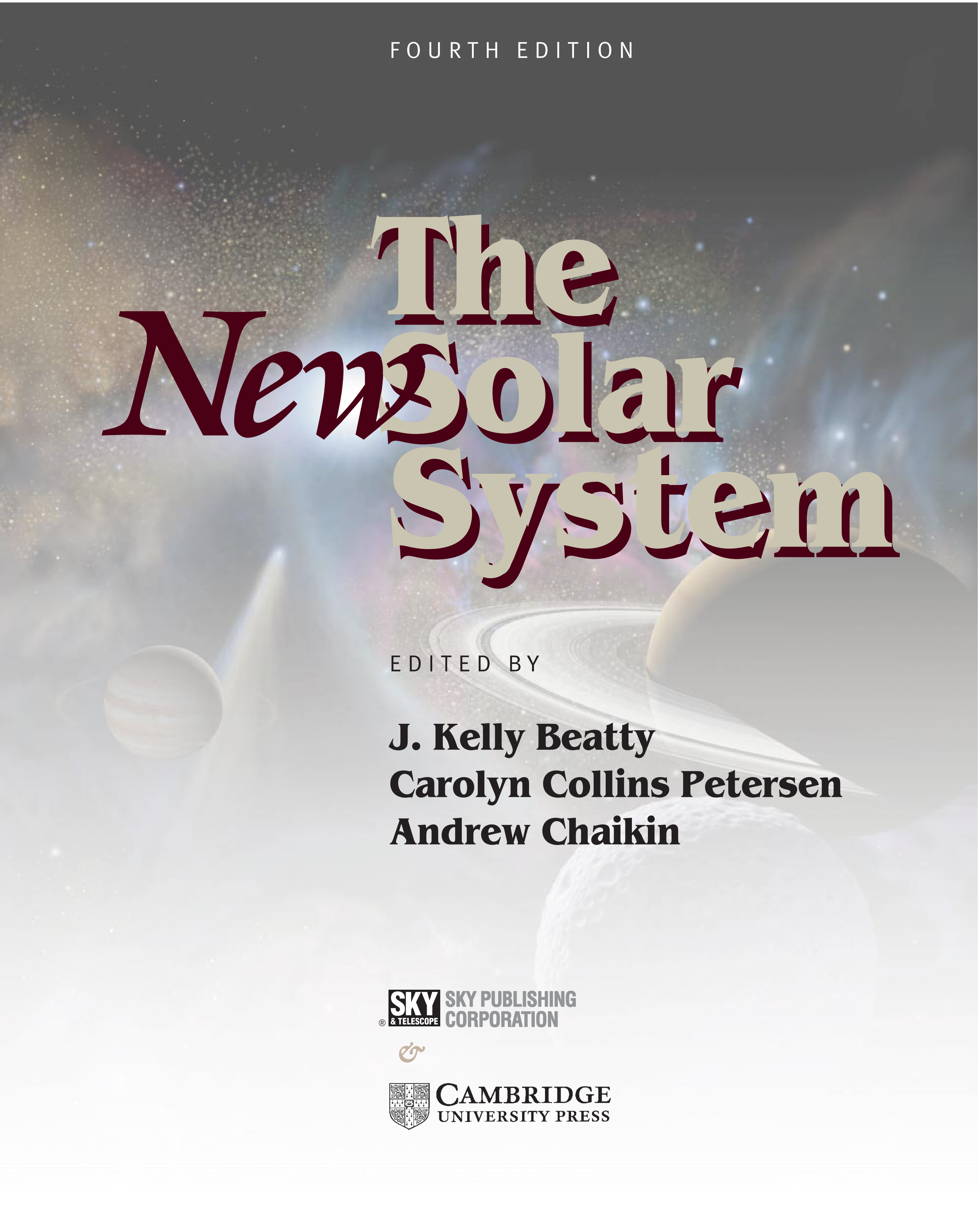
THE NEW SOLAR SYSTEM



FOURTH EDITION

The New Solar System

EDITED BY

J. Kelly Beatty
Carolyn Collins Petersen
Andrew Chaikin

SKY & TELESCOPE SKY PUBLISHING CORPORATION
&
CAMBRIDGE UNIVERSITY PRESS

PUBLISHED BY SKY PUBLISHING CORPORATION
49 Bay State Road, Cambridge, Massachusetts 02138

AND BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK http://www.cup.cam.ac.uk
40 West 20th Street, New York, NY 10011–4211, USA http://www.cup.org
10 Stamford Road, Oakleigh, Melbourne 3166, Australia

First published 1981
Second edition 1982
Third edition 1990
Fourth edition 1999

Printed in Canada

Typeface ITC Galliard 9/12pt *System* QuarkXPress® [DS]

Library of Congress cataloging in publication data

The new solar system / edited by J. Kelly Beatty, Carolyn Collins
Petersen, Andrew Chaikin. — 4th ed.
p. cm.
Includes bibliographical references and index.
ISBN: 0 933346 86 7 (alk. paper)
1. Solar system. I. Beatty, J. Kelly. II. Petersen, Carolyn Collins.
III. Chaikin, Andrew, 1956– .
QB501.N47 1999
523.2 — dc21 98-34472
CIP

A catalogue record for this book is available from the British Library

ISBN 0-933346-86-7 (Sky edition: softcover)
ISBN 0-521-64183-7 (Cambridge Univ. Press edition: hardcover)
ISBN 0-521-64587-5 (Cambridge Univ. Press edition: softcover)

Contents

Jupiter appeared as a slender crescent as Voyager 1 departed the Jovian system on 24 March 1979.

Preface

J. Kelly Beatty
Carolyn Collins Petersen
& Andrew Chaikin

THE STUDY OF our solar system is arguably the oldest branch of astronomy. Thousands of years before the invention of the telescope, human eyes looked into the night sky and perceived the steady, purposeful motion of certain "stars" among their neighbors. The wandering planets were seen as physical manifestations of prominent gods, whose Roman and Greek names remain with us to this day. Ancient astronomers became obsessed with deducing how and why the planets move as they do. Early telescopes, too crude to resolve dim galaxies, nonetheless revealed the Moon's stark craters, Jupiter's satellites, and the spectacle of Saturn's rings.

Given this legacy, it is hard to believe that 40 years ago — at the dawn of space exploration — planetary science was at its nadir. In the postwar 1940s and 1950s, world-class telescopes like the 5-m Hale reflector on Palomar Mountain were revealing the majesty of the distant universe. In those heady days, planetary research was considered second-rate science, and consequently very few professional astronomers observed Mars, Jupiter, or other planets on a regular basis. At many professional facilities, only a small fraction of the available observing time could be used for solar-system studies.

By stark contrast, the planets loomed large at the newly formed National Aeronautics and Space Administration, where mission planners had already set their sights on the Moon, Venus, and Mars. However, even though these worlds were within our technological reach, it soon became obvious that we had little concept of what spacecraft should do once they got there. Moreover, NASA managers were shocked to learn how few astronomers had any relevant experience in the planetary field.

Historian Joseph Tatarewicz describes the agency's predicament in his 1990 book *Space Technology and Planetary Astronomy:* "In order to develop lunar and planetary probes, calculate trajectories, and develop scientific instruments, NASA planners had hoped to enlist the expertise of a science that had spent literally thousands of years preoccupied with the planets. Yet on the very eve of planetary exploration astronomers showed little interest." Tatarewicz recalls that NASA officials even "stood before groups of astronomers and implored them to enter a field of study for which there were few inducements."

One of the few astronomers actively — and overtly — pursuing solar-system research at that time was Gerard P. Kuiper. Having already distinguished himself with research on double stars and stellar evolution, Kuiper had turned his considerable talent to the planets in the 1940s. Working with the limited tools of the era, utilizing his skills as an observer and his rigorous scientific judgment, Kuiper amassed a body of knowledge that formed the basis for modern planetary science.

In 1961, on the eve of the first interplanetary missions, Kuiper and Barbara Middlehurst published *Planets and Satellites,* the third installment in a four-volume series that surveyed the state of knowledge about the entire solar system. In its preface Kuiper argued that, even in the era of planetary exploration, telescopic observations from Earth would remain important. Today, even though our robotic emissaries have surveyed at close range every one of the known planets except Pluto, it is clear that he was right. Were it not for the ongoing scrutiny of the solar system by patient professional and amateur observers here on Earth, much of what you will read in these pages would still lie waiting to be discovered. We would know little about the potential danger posed by Earth-crossing asteroids and nothing about the planets of other stars, to cite but two examples.

When Gerard Kuiper died in 1973, he left a void not easily filled. No single person has yet matched his influence on and command of planetary science. In fairness, however, the present-day study of "a planet" can involve a host of scientific disciplines. Few scientists today possess a complete working knowledge of any one world, let alone the entire solar system. Over the years the ranks of traditional planetary astronomers have been fortified with geologists, physicists, chemists, mathematicians, fluid dynamicists, biologists, and others. We suspect Kuiper would be pleased to know that the study of our solar system now occupies the talents of roughly 1,500 researchers worldwide.

Given the tremendous growth of planetary science in both scope and detail, the task confronting this book's editors once again — to summarize the current state of what we know about the solar system — could only be accomplished by bringing together a wide variety of specialists. Each author endeavored not only to provide the most up-to-date information available, but also to identify the gaps in our understanding that beg further investigation. Their presentations, taken together, may not appear entirely self-consistent. Many topics are the subject of disagreement or even outright feuding. Others enjoy a consensus of theoretical opinion yet lack observational confirmation.

Since the third edition of *The New Solar System* was published in 1990, there have been so many new developments in planetary science that most chapters had to be entirely recast and several new ones added. Indeed, this fourth edition is nearly twice the length of the first. Advances in solar astronomy have transformed our understanding of the Sun. Robotic eyes have provided glimpses of several asteroids — one of which proved to have its own satellite. We have seen objects in the distant Kuiper belt, thus certifying that the Sun's dominion extends far beyond Pluto's orbit. And the final chapter provides a census of the rapidly growing number of known worlds around other stars.

In assembling this book, we have attempted, as before, to bring the fruits of recent planetary exploration to the widest possible audience. This is neither a textbook nor a "coffee-table" volume — it lies somewhere in between. By the same token, we have encouraged our authors to avoid both sweeping generalizations and incomprehensible details. An abiding theme has been that our solar system is no longer a collection of individual bodies that can be addressed in isolation. It is instead an interrelated whole, whose parts must be studied comparatively. Above all, we strove to make this enjoyable reading for those with either casual or professional interest.

We have drawn upon the talents of many individuals. Artist Don Davis and illustrator Sue Lee have imbued these pages with their colorful vitality and uncompromising attention to detail. We thank Richard Tresch Fienberg and Leif Robinson of Sky Publishing, and Simon Mitton of Cambridge University Press for editorial direction. Our thanks also go to designer David Seabourne and CUP production manager Tony Tomlinson, and to Mary Agner, Vanessa Thomas, Tal Mentall, Cheryl Beatty, Lynn Sternbergh, and Paul Williams for editorial and design support. Myche McAuley and Susan LaVoie of NASA's Planetary Photojournal ensured that we had the best possible spacecraft images at our disposal. And finally we are deeply indebted to SPC production manager Sally MacGillivray and photo researcher Imelda Joson, whose tireless perseverance and dedication were truly inspirational.

This edition has been two years in the making, an interval during which, sadly, we mourned the deaths of Carl Sagan and Gene Shoemaker, singular members of the planetary-science community who had served us as contributors and honored us with their close friendship. Also lost were Clyde Tombaugh, the discoverer of Pluto, and Jürgen Rahe, who helped manage NASA's planetary programs for many years. We acknowledge their accomplishments and unflagging spirit in furthering our understanding of the solar system.

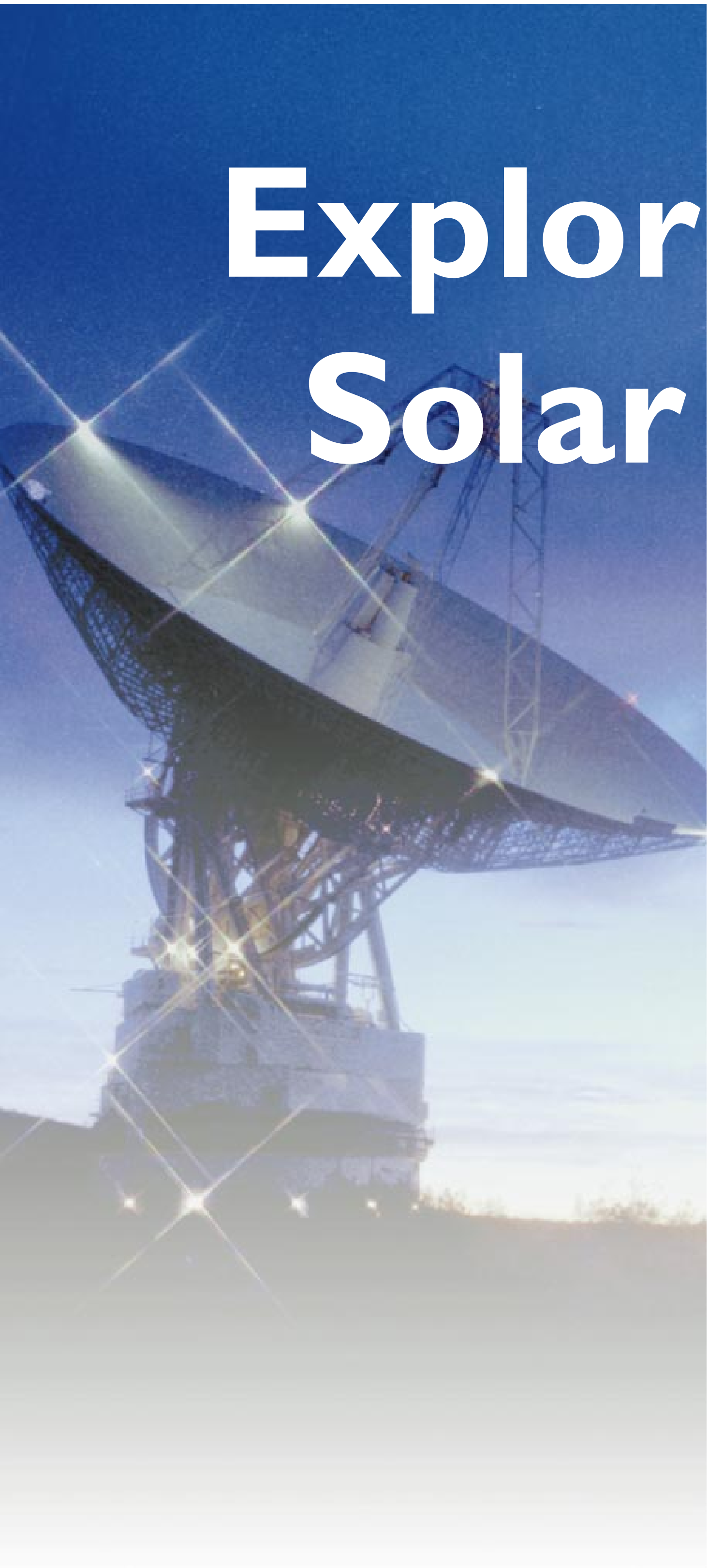
* * * *

The final chapter of *Planets and Satellites,* written by Kuiper, is entitled "The Limits of Completeness." There he took stock of the known worlds, equating "completeness" with knowing how *many* worlds orbited the Sun. Today we think of completeness in a much broader sense, and it remains unattainable. Consider, for example, Voyager 1's stunning image of a crescent Jupiter *(page vii),* which adorned the cover of this book's first two editions. Unobtainable from Earth, this view reminds us that our perspective — then, as now — is ever changing. As we write this, the Galileo, Mars Global Surveyor, and Lunar Prospector spacecraft continue their respective orbital vigils around Jupiter, Mars, and the Moon. Cassini and its Huygens probe are en route to Saturn, the NEAR spacecraft is closing in on asteroid 433 Eros, and Stardust is being readied for its sample-gathering dash through the periodic comet 81P/Wild 2. These missions, together with ongoing observations by the Hubble Space Telescope and by ground-based telescopes around the world, virtually guarantee that a fifth edition of *The New Solar System* will soon be a welcome necessity.

1

Exploring the Solar System

David Morrison



NASA's 70-m-diameter Goldstone tracking antenna near Barstow, California.

THE EXPLORATION OF our solar system has stimulated one of the most important scientific revolutions of the last third of the 20th century, comparable in significance to deciphering the genetic code of life. Planetary exploration has been carried out by the astronauts who traveled to the Moon, by robotic spacecraft that extend our reach to other planets, and by thousands of scientists working in observatories and laboratories on Earth. This international effort has yielded an initial reconnaissance of our cosmic neighborhood — the planets and other objects that share our solar system with the Earth. It has transformed dozens of planets and satellites from mysterious dots of light into real worlds, each with its own unique environment and history.

Why do we explore? An urge to explore seems to be a fundamental human trait, a hallmark of the most successful human societies of the past millennium. Exploration is partly motivated by a desire to understand our environment and the way it works. For some, the satisfaction of exploration can be achieved from reading books or surfing the Internet or performing computer simulations. For many others, there is an added dimension of experience. In addition to purely intellectual knowledge, we want a more personal involvement. We want to travel to new places, either directly or vicariously. We feel an urge to cross that river, to climb that mountain, or to set foot on that new world.

Only a few fortunate individuals have had the opportunity to travel into space, and even fewer (12, to be exact) have left their footprints on another world. Modern communications, however, allowed more than a billion people to share via television the experience of astronauts walking on the Moon. More than 100 million "hits" were made in a single day on Mars Pathfinder's Internet site. In an era when most of the frontiers of Earth have been reached, millions of people have been engaged to some degree in exploring the wider frontiers of our planetary system.

Figure 1. **The Voyager spacecraft. In many ways, Voyager represents the "typical" planetary-science mission. Laden with a variety of instruments to study its targets in different wavelengths, it was sent to the outer planets on a flyby trajectory. Other missions combine landers, orbiters, and probes.**

The basic human urge to explore may have motivated our solar-system missions, but without other factors it is unlikely that the necessary political and funding priorities could have been achieved. Over most of its short history, space travel was a direct product of the Cold War between capitalism and communism. Although nationalistic and geopolitical motives generated the resources that made solar-system exploration possible, we are fortunate that scientists often provided the detailed leadership to focus that effort on specific space goals.

In the United States, the National Aeronautics and Space Administration (NASA) was established in 1958 as a civilian agency and given a charter that places highest priority on scientific exploration and the acquisition and dissemination of new knowledge. Although the organizational details have changed, NASA has always had a space-science office or division, usually led by administrators with strong scientific credentials. NASA's planetary mission centers — principally the Jet Propulsion Laboratory (JPL) with contributions from Ames Research Center, Goddard Space Flight Center, and Langley Research Center — developed strong, science-driven cultures to advocate and manage planetary explorations like the highly successful Voyager missions (*Figure 1*).

For scientific and programmatic guidance, NASA has turned throughout its history to various committees and councils of the National Academy of Science's National Research Council. In addition, the broad scientific community has played an essential role through a process of open competition and peer review to select the scientific teams and instruments for planetary spacecraft. This unique government-academic partnership ensured a dominant role for science in American planetary missions. When the European Space Agency (ESA) inaugurated its own planetary program, it followed a similar partnership model. Even deep-space missions of the former Soviet Union drew on American studies, thus establishing a consistent scientific foundation for a truly international effort. Partly as a matter of luck, Soviet planetary exploration focused on Venus, while the NASA effort stressed Mars and, later, the outer planets. The two programs together accomplished much more than either might have alone.

At the dawn of the Space Age, planetary studies occupied the backwaters of astronomy. Only a handful of scientists worldwide actively studied the physical or chemical properties of the planets and their satellites. Indeed, progress was so slow that textbooks written in the 1920s still adequately described our level of knowledge 30 years later. Around the time of Sputnik 1's launch in 1957, people still speculated about global oceans of water on Venus. Belief in plant life on Mars was widespread, as was the theory that volcanoes created most of the Moon's craters. Speculations aside, we did not know the surface composition of any solid planet or satellite in the solar system — except Earth.

Key Parameters for Planetary Exploration

Planet	*Distance from Earth (AU)*	*Greatest apparent magnitude*	*Largest diameter (arcseconds)*	*Mean solar constant (Earth=1)*	*One-way flight time (years)*
Mercury	0.594	+0.6	8.4	6.67	0.18
Venus	0.267	–4.1	62.5	1.19	0.29
Mars	0.563	+1.7	6.0	0.431	0.71
Jupiter	3.966	–2.9	49.7	0.037	2.73
Saturn	8.293	+0.1	20.0*	0.011	6.05
Uranus	18.85	+5.7	3.7	0.003	16.03
Neptune	29.12	+7.8	2.3	0.001	30.60
Pluto	29.07	+13.7	0.1	0.0006	45.46

Table 1. **The vast distance to any of Earth's planetary neighbors poses obstacles for both telescopic observation and visiting spacecraft. Distances, magnitudes, and apparent angular diameters reflect the values at inferior conjunction for Mercury and Venus, and at oppositions for the outer planets. (*Saturn's rings span 45.5 arcseconds at opposition.)**

A PLANETARY TOOLKIT

The most obvious limitation to knowing more about solar-system objects was — and still is — distance (*Table 1*). Our Sun illuminates its planetary realm like a single, bare light bulb in a huge meeting hall. The strength of sunlight decreases by the square of the distance from the Sun; likewise, the area subtended by planet or moon in our nighttime sky shrinks as the square of its separation from Earth. This double penalty makes the study of distant solar-system objects very difficult. For example, Pluto is presently about 30 AU from the Sun, so sunlight there is a mere 1/900 the intensity of what we enjoy here on Earth. Even though the diminutive planet is fully two-thirds the size of our Moon, it remains an unresolved, 14th-magnitude pinpoint of light in ground-based telescopes. If we could somehow bring Pluto inward to a point 1 AU from the Sun and view its fully illuminated disk from 1 AU away, it would outshine every star (except Sirius) in the nighttime sky. Astronomers would have then little difficulty mapping its major surface features or tracking its moon, Charon. In reality, when Pluto reaches aphelion in 2113, it will be 49 AU from the Sun and a very dim 17th magnitude — 25,000 times fainter than the limit of human vision.

Another hindrance to planetary astronomy is the presence of Earth's atmosphere. Its turbulent motions distort the clarity of our telescopic views, and its gases prevent much of the electromagnetic spectrum from reaching the ground (*Figure 2*). Light reflected from the planets and other solar-system objects is a Rosetta stone of information about their surfaces, atmospheres, and positions. Since human eyes are sensitive only to a very small part of this light, astronomers have developed detectors to study solar-system objects in as many wavelengths of light as possible.

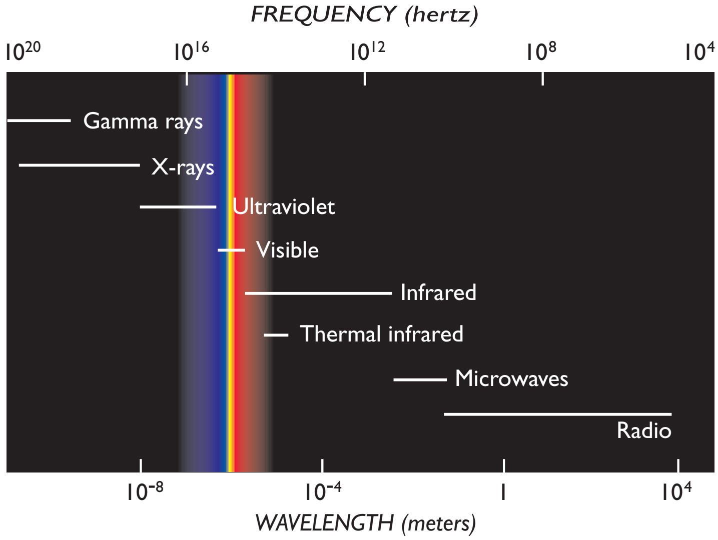


Figure 2. **Only the narrow, visible-light region of the electromagnetic spectrum reaches Earth's surface relatively unimpeded by our atmosphere. Thus, to extend our spectral knowledge, instruments on interplanetary spacecraft study their targets in nearly every wavelength regime.**

A primary tool of such remote sensing is *spectroscopy* – the science of separating light into its component wavelengths. Certain spectral regions have turned out to be quite useful for the detection and study of specific characteristics: ultraviolet wavelengths for atmospheres and magnetospheric ions, the near-infrared for understanding the mineralogical makeup of a solid surface, and radio (especially radar) for mapping gross surface properties. The spectra of atmospheric gases are generally diagnostic of composition and can even be used to infer the quantities of gas present. Solid surfaces are more problematic. Simple ices (those of water, methane, and carbon dioxide) can be identified easily, but the mineralogical interpretation of rocky surfaces is sometimes ambiguous even with good observational data.

There are other useful observational tools in the planetary scientist's "toolkit." *Photometry* characterizes the changes in the brightness of an object. For example, by monitoring variations in the light reflected from an asteroid over time (known as "obtaining a light curve"), we can learn how fast it spins, approximate its size and shape, and determine its color. *Polarimetry* takes advantage of another property of light: its polarization. When sunlight (or starlight) passes through an atmosphere, it is scattered and polarized by hazes and aerosols. Surfaces can polarize light as well, and polarimetry is particularly useful in the study of ring particles. *Astrometry,* usually thought of as a tool for tracking the precise positions of stars, is critically important in deducing the orbital characteristics of all solar-system bodies. Astrometric measurements of the exact positions of Pluto and Charon, for example, have given us reasonably precise estimates of their masses.

These remote-sensing techniques have extended our sensory range and given us views of solar-system objects that we could not otherwise obtain (*Figure 3*). The power of all these tech-

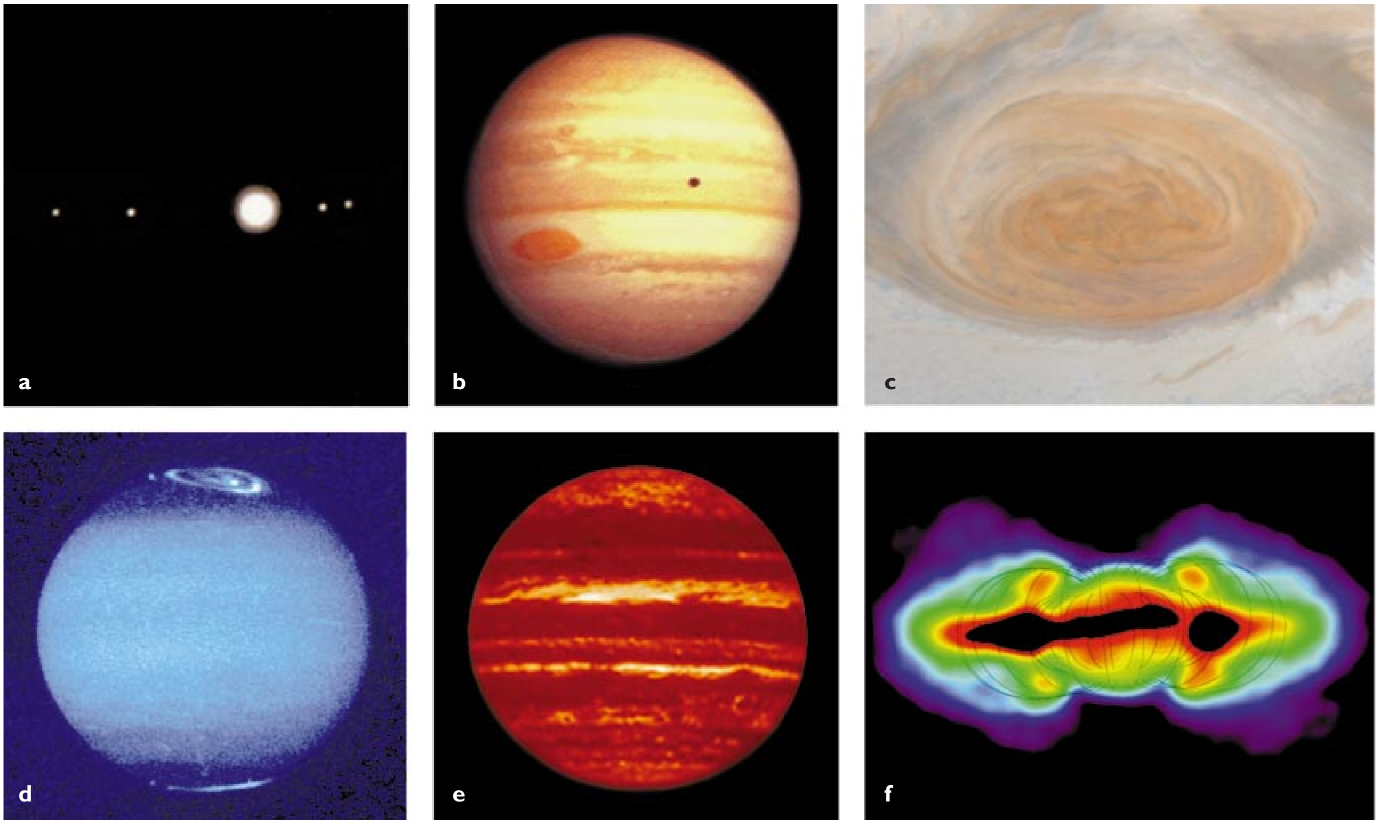


Figure 3. **These images of Jupiter demonstrate the importance of looking at an object using as many vantage points and wavelengths as possible. Seen through small telescopes, Jupiter and its four largest satellites *(a)* reveal few distinguishing characteristics. In 1973, Pioneer 10 transmitted the first crude images *(b)* from the giant's vicinity. Most recently *(c)*, the Galileo orbiter provided ongoing imagery of the constantly changing Jovian weather patterns, particularly the Great Red Spot. Astronomers back at Earth can study the planet at a wide range of wavelengths. The orbiting Hubble Space Telescope monitors the development of Jovian auroras in the ultraviolet *(d)*. From the ground, at 4.8 microns in the infrared *(e)*, holes in Jupiter's cloud structure are quite bright. Finally, a radio image *(f)* shows emission from charged particles cycling along field lines within the planet's magnetosphere.**

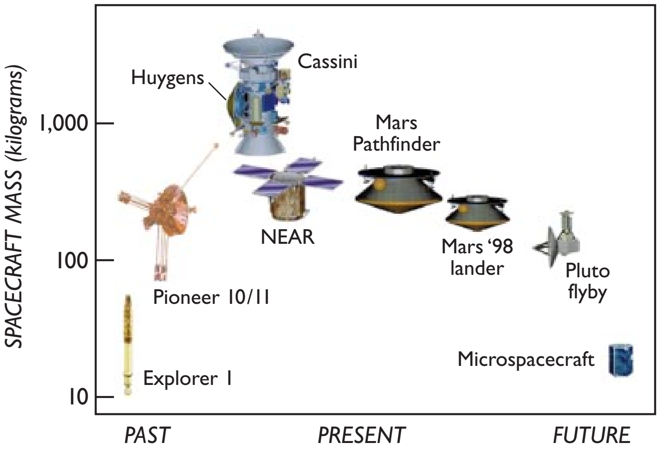


Figure 4. **The capabilities of interplanetary spacecraft have seen remarkable advances over the past four decades — even though their size has waxed and waned. Miniaturized electronic components now make possible entire spacecraft no larger than the cameras on early lunar and planetary probes.**

niques can be enhanced by placing detectors in orbit, thereby avoiding the degrading effects of Earth's atmosphere on resolution and spectral transmission. Moving these same sensors out to the planets themselves affords even better spatial and spectral resolution. Not surprisingly, therefore, interplanetary spacecraft have traditionally carried instruments covering a wide range of the electromagnetic spectrum.

THE EARLY YEARS: GETTING TO KNOW OUR NEIGHBORS

In the 1960s, when scientists first acquired the propulsive means to send instruments to the Moon and beyond, their immediate goal was a basic reconnaissance of the solar system. The first successful planetary mission, Mariner 2 (launched in 1962), had as its primary objective at Venus to determine the source of microwave emissions discovered by ground-based radio astronomers, and thus to answer the fundamental question of whether the planet's surface was hot (700° K) or temperate. Similarly, the first mission to carry a camera, Mariner 4 (launched in 1964), was designed to determine if the Martian surface was cratered and old or mountainous and geologically active, and also to measure the surface pressure of the atmosphere. These were truly basic questions, necessary to a first-order characterization of our nearest planetary neighbors.

In 1963, when the late Carl Sagan arrived at Harvard College Observatory as a young assistant professor, he gave a series of popular public lectures entitled "Planets are Places." At the time this was a radical idea, to think of the planets as other worlds to be compared with Earth. Scientists considering career paths in planetary science contemplated such questions as "What would it be like to stand on the surface of another planet? What does the ground look like? What is the temperature? What color is the sky?"

Planetary missions have changed a great deal since those early days. In response to budgetary changes and instrumentation advances, spacecraft have gotten first larger and then smaller (*Figure 4*). Some of the early planetary flights were focused on practical questions, serving as pathfinders for later scientific missions (*Table 2*). For example, the primary justification for the Surveyor lunar landers of the 1960s was to demonstrate that lunar dust had sufficient strength to bear the weight of the Apollo landers that would follow. The Pioneer 10 and 11 missions to Jupiter, the first spacecraft sent to the outer solar system, were built to determine whether a spacecraft could pass through the asteroid belt without being destroyed by collisions with small particles, and to assess the survivability of electronics in the intense radiation environment of the inner Jovian magnetosphere. Without Pioneer, the later Voyager missions to the outer solar system would not have been possible.

The initial characterization of the planets was not all achieved by spacecraft. In the United States, NASA and the National Science Foundation provided funds to build new telescopes and equip laboratories, which created the foundation for a new multidisciplinary field: planetary science. It was earthbound radio astronomers who discovered the high surface temperature of Venus and the magnetosphere of Jupiter; radar astronomers who established the rotation periods of Venus and Mercury and determined the distances between the planets with high accuracy; infrared and visible-light observers who measured the internal

Table 2. **Over the past four decades, spacecraft launched by the former Soviet Union (italic type) and United States have amassed an impressive list of milestones as space explorations have extended ever farther from Earth.**

Milestones in Solar-System Exploration

Spacecraft	***Launch***	***Encounter***	***Object***	***Accomplishment***
Explorer 1	1 Feb 1958	Feb 1958	Earth	detection of charged-particle belts
Luna 2	12 Sep 1959	15 Sep 1959	Moon	impact with surface
Luna 3	4 Oct 1959	7 Oct 1959	Moon	photograph of far side
Mariner 2	27 Aug 1962	14 Dec 1962	Venus	flyby
Ranger 7	28 Jul 1964	31 Jul 1964	Moon	photographs at close range
Mariner 4	28 Nov 1964	14 Jul 1965	Mars	flyby
Luna 9	31 Jan 1966	3 Feb 1966	Moon	photographs from surface
Venera 3	16 Nov 1965	1 Mar 1966	Venus	impact with surface
Luna 10	31 Mar 1966	3 Apr 1966	Moon	orbiter
Surveyor 1	30 May 1966	2 Jun 1966	Moon	controlled soft landing
Lunar Orbiter 1	10 Aug 1966	14 Aug 1966	Moon	photographic orbiter
Zond 5	15 Sep 1968	18 Sep 1968	Moon	round trip with life forms
Apollo 8	21 Dec 1968	24 Dec 1968	Moon	human crew (no landing)
Apollo 11	16 Jul 1969	20 Jul 1969	Moon	humans explore surface; samples returned to Earth
Luna 16	12 Sep 1970	20 Sep 1970	Moon	automated sample return
Luna 17	10 Nov 1970	17 Nov 1970	Moon	surface rover
Venera 7	17 Aug 1970	15 Dec 1970	Venus	soft landing
Mariner 9	30 May 1971	13 Nov 1971	Mars	long-life orbiter
Mars 3	28 May 1971	2 Dec 1971	Mars	soft landing
Pioneer 10	3 Mar 1972	3 Dec 1973	Jupiter	flyby
Mariner 10	3 Nov 1973	29 Mar 1974	Mercury	flyby (also on 21 Sep 1974 and 16 Mar 1975)
Venera 9	8 Jun 1975	22 Oct 1975	Venus	photographs from surface
Viking 1	20 Aug 1975	20 Jul 1976	Mars	photographs from surface; search for life forms
Pioneer Venus 1	20 May 1978	4 Dec 1978	Venus	long-life orbiter
Voyager 1	5 Sep 1977	5 Mar 1979	Jupiter	flyby
Pioneer 11	6 Apr 1973	1 Sep 1979	Saturn	flyby
Voyager 1		13 Nov 1980	Saturn	flyby
Vega 1	15 Dec 1984	11 Jun 1985	Venus	atmospheric balloon
ICE (ISEE 3)	12 Aug 1978	11 Sep 1985	comet	flyby through plasma tail of 21P/Giacobini-Zinner
Voyager 2	20 Aug 1977	24 Jan 1986	Uranus	flyby
Vega 1		6 Mar 1986	comet	photographs of 1P/Halley's nucleus
Voyager 2		25 Aug 1989	Neptune	flyby
Galileo	18 Oct 1989	29 Oct 1991	Gaspra	flyby of S-type asteroid
Ulysses	6 Oct 1990	13 Sep 1994	Sun	polar flyover at –80° latitude (European-built spacecraft)
Galileo		7 Dec 1995	Jupiter	orbiter, atmospheric probe
NEAR	17 Feb 1996	27 Jun 1997	Mathilde	flyby of C-type asteroid
Mars Pathfinder	4 Dec 1996	4 Jul 1997	Mars	automated surface rover

heat sources of the giant planets and discovered the rings of Uranus; and laboratory chemists studying meteorites and lunar samples who established the chronology and fundamental geochemistry of the solar system.

The first planetary missions were focused on answering a few specific questions, such as measuring the surface temperature of Venus or the bearing strength of the lunar soil. Influential scientists argued at the time that this was the proper way to carry out such an investigation: begin with a hypothesis, pose one or more specific questions to test the hypothesis, and fly a mission to make the critical measurements. Very quickly, however, it became apparent that spacecraft could do far more than answer a few predetermined questions (sometimes called "focused science"). Traveling to other planets, and eventually orbiting them and landing on their surfaces, spacecraft had demonstrated a remarkable capacity for serendipitous discovery. All they had to do, in effect, was look around — and the result would be wonderful new discoveries. Besides, it was not cost-effective to send a spacecraft all the way to another world just to answer a few questions when so much more could be done with cameras and other broadly based investigations.

Figure 5. **Exploration of the solar system depends critically on the worldwide collection of tracking antennas known as the Deep Space Network. The largest DSN antennas, like this 70-m-wide dish located northwest of Barstow, California, can receive transmissions from distant spacecraft far weaker than one-billionth of a watt.**

While nearly every spacecraft carried a payload customized for its particular target, a few basic types of measurements predominated. Only when cameras were added could the new era of exploration really begin. Remote-sensing instruments included, in addition to cameras, spectrometers to analyze the light for compositional information, as well as ultraviolet and infrared systems to extend spectral sensitivity. These devices were, in effect, small telescopes mounted together on a common platform that could be pointed toward specific regions of the target with high precision. Spacecraft could acquire color images and true spectra to deduce surface compositions. (Recent missions carry sophisticated instruments that combine photography and spectroscopy in a single device.)

A second major class of instruments measured electromagnetic fields and charged particles — not only the intrinsic magnetic field of a planet, but also the complex interactions of the electrons and ions that are trapped in the planet's magnetosphere. A third class of instruments, carried later on descent probes, made direct measurements of atmospheric composition, temperature, and pressure.

The data from all these measurements were digitally encoded and transmitted to Earth. The new multipurpose instruments required radio bandwidth to transmit all this information. High data rate became the key to planetary exploration, so more efficient spacecraft transmitters were designed, and the giant receiving antennas of the NASA Deep Space Network were built (*Figure 5*). As a result, our interplanetary data rates increased from 8 bits per second (bps) from Mars in 1965 to more than 116,000 bps from Jupiter in 1979.

The most successful mission of this era of initial reconnaissance was Voyager. Launched in 1977, the two Voyager spacecraft took advantage of a rare (once-in-176-years) alignment of the outer planets to achieve a "Grand Tour" of the outer solar system, flying at close range past Jupiter, Saturn, Uranus, and Neptune, each with an extensive system of satellites and rings (*Figure 6*). Each Voyager carried a dozen scientific instruments, and at Jupiter these spacecraft transmitted a detailed television image every 90 seconds. Even from Neptune, nearly 4 billion km from Earth, Voyager 2 sent us several images per hour (or an equivalent amount of other data). The twin spacecraft discovered rings, moons, and magnetospheres where none had been thought to exist. They vastly improved our understanding of the atmospheric dynamics on all four giant planets and sent back detailed images of 16 major satellites — several of them as large as planets themselves.

With each successive encounter, the Voyagers necessitated a rewrite of the texts that chronicle the advances in planetary science (like this one). Nothing we can ever do will equal this concentrated record of discovery and exploration. As Carl Sagan often pointed out, only one generation has the privilege of accomplishing the first scientific characterization of the solar system, and a great deal of that characterization was accomplished by Voyagers 1 and 2 (*Figure 7*).

A PROGRESSION OF EXPLORATORY MISSIONS

Voyager was a flyby mission. Launched on powerful Titan-Centaur rockets and accelerated by the gravity of each planet they passed, both Voyager spacecraft achieved escape velocity with respect to the Sun. At the turn of the 21st century, nearly 8 billion km from the Sun, they continue to transmit data from far beyond the classical realm of the planets.

A flyby is a great way to get an overview of a planetary target, but the time available for detailed studies is strictly limited because the spacecraft usually speeds by at 10 to 20 km per second. Typically, the Voyager cameras surpassed the resolution of the best Earth-based telescopes only a week or two before a given flyby, thus providing a useful encounter period of about a month's duration. The spacecraft took at most a few days to pass completely through each planet's magnetosphere. Opportunities for close-up views of satellites were much shorter, usually limited to a few hours. The result would be a few dozen good photographs of each object, some in color (by taking successive exposures through different filters), with the best resolution limited to just a handful of images.

There is no opportunity with a flyby to look a second time at an interesting feature. Flybys are best at providing an overview that is the necessary starting point of planetary exploration. Their strength, of course, is that the spacecraft can then move on to another target, as Voyager so beautifully demonstrated. It is also much easier (and less expensive) to fly past a target than to assume an orbit around it or to land on its surface. Thus, virtually all the early planetary missions were flybys.

The next evolutionary step is to orbit the target planet. With an orbiter, the time available for study increases from a few hours or days to the lifetime of the spacecraft (usually set by the exhaustion of either its fuel or its budget). In the case of the giant planets, with their many satellites, orbiters like Galileo and

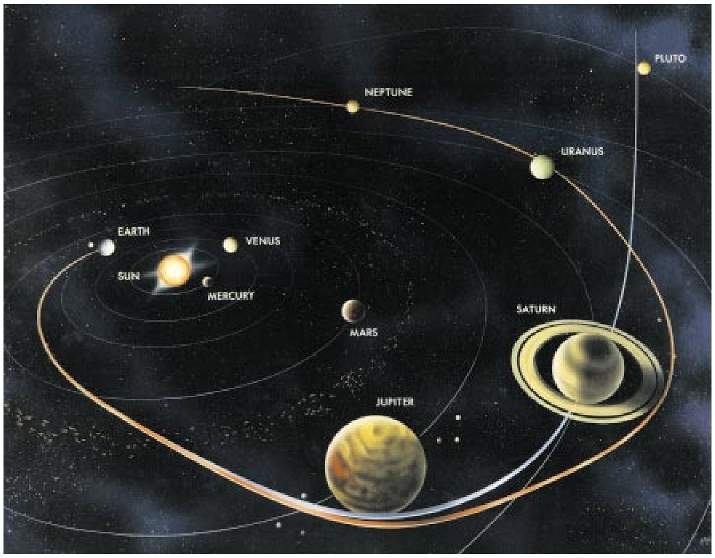


Figure 6 (right). **The long-lived Voyager spacecraft have completed virtually all of the ambitious "Grand Tour" of the outer solar system first envisioned by planetary scientists in the 1970s. The only world not visited was Pluto, which was cut out of the itinerary when the missions were downsized and launched later than expected.**

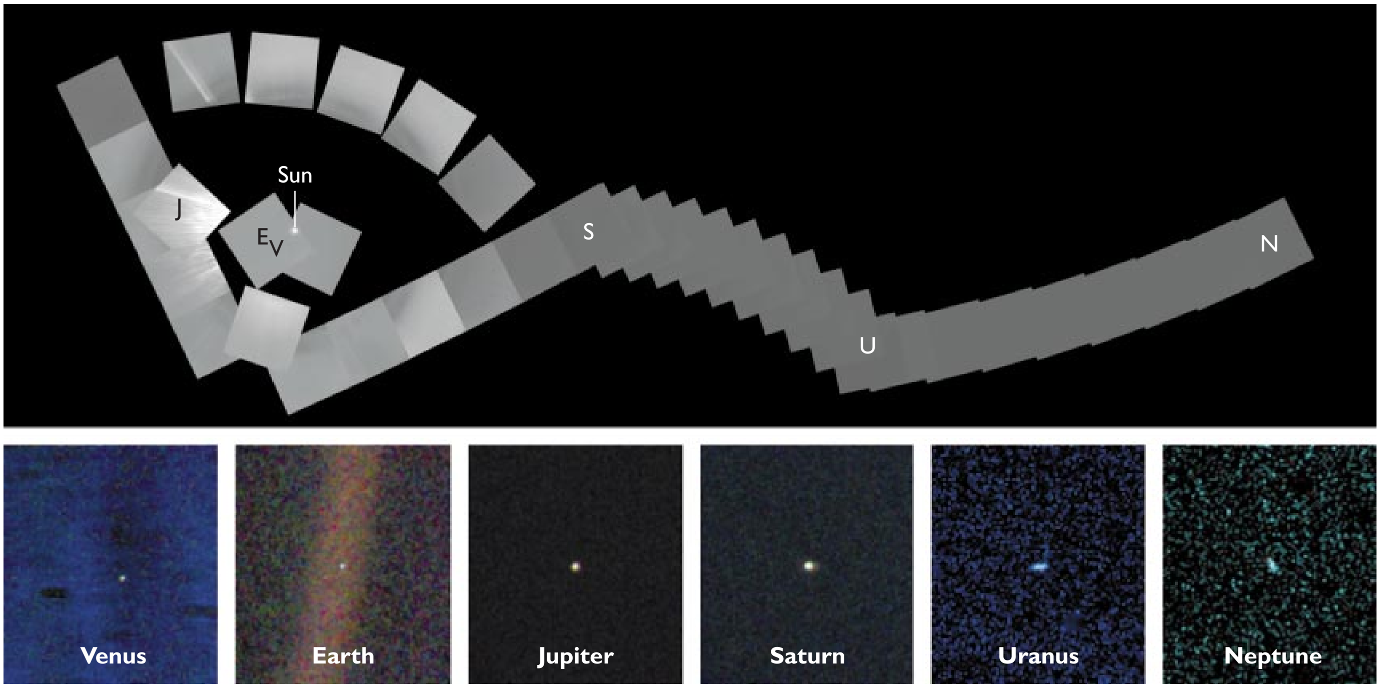


Figure 7. **History will record that our robotic emissaries had traveled to the edge of the planetary realm by the close of the 20th century. In February 1990 the cameras aboard Voyager 1 pointed back toward the Sun and took the first-ever "portrait" of our solar-system. At the time the spacecraft was 6 billion km from Earth and situated 32° above the ecliptic plane. The 39-frame mosaic of wide-angle images (upper panel) captures the Sun and six planets. Voyager's narrow-angle camera then recorded telephoto views of the individual planets. Mercury was too near the Sun to be resolved, Mars was hidden amid scattered sunlight, and Pluto was simply too dim to register.**

Cassini provide opportunities for multiple satellite flybys, allowing us to build up full coverage without orbiting each satellite individually.

Mariner 9 (launched in 1971) was the first successful planetary orbiter. The circumstances of its arrival at Mars illustrate the advantages of orbiting. At the time, Mars was shrouded in a global dust storm, making it impossible to photograph or measure the surface. If Mariner 9 had been a flyby craft, its mission would have been a failure. Instead, it simply waited in orbit for four months until the dust had settled, then began the planned mapping of the entire planet. Mariner 9 also demonstrated the power of a global examination. Three preceding Martian flybys, Mariners 4, 6, and 7, had made fascinating discoveries but, due to bad luck, had missed all of the younger geologic features. They spied none of Mars's great volcanoes, the rift valley Valles Marineris, or the evidence of ancient stream beds and water erosion. Indeed, there were suggestions made to terminate the exploration of the red planet after Mariners 6 and 7, on the grounds that Mars was a dead planet. Fortunately, by then Mariner 9 had already been built, and it changed our view of Mars forever.

Figure 8. **Jet Propulsion Laboratory director William Pickering, physicist James Van Allen, and rocket designer Wernher von Braun (left to right) hold a model of Explorer 1 and its integrated Sargeant rocket stage after the satellite's 1958 launch. Explorer 1 was the first American satellite and, by virtue of its discovery of the Van Allen radiation belts, the first planetary-science mission.**

The most productive planetary orbiter, measured by the volume of scientific data obtained, was Magellan. Venus, the nearest planet to Earth, is perpetually shrouded in clouds, its surface invisible to both optical telescopes and spacecraft cameras. Microwave radiation, however, can penetrate the atmosphere, and radar operating at microwave frequencies can be used to map the surface, as first demonstrated by large radar telescopes on Earth. In 1978, the Pioneer Venus orbiter constructed a crude radar map of Venus, followed in 1983 by two Soviet radar mappers, Veneras 15 and 16. The resolution of the Pioneer global map was 50 km, and the Veneras obtained radar images of much of the northern hemisphere at about 2 km resolution.

While enticing, the results of the Pioneer and Venera missions were unable to answer first-order questions about the geology of Venus, such as the age of its surface or the possible presence of plate tectonism. Thus Magellan was built to obtain a global map at 100-m resolution using radar imaging. Orbiting from 1989 to 1992, it returned more data than all previous planetary spacecraft combined, yielding a global map of Venus more detailed than our knowledge of many of the submarine portions of Earth. Planetary geologists are still making discoveries about Venus as they sift through its treasure-trove of radar images.

After we have orbited a planet, mapped its surface, measured its magnetic and gravity fields, and observed its weather from above, the next step is usually an atmospheric entry probe or surface lander. On Mars or Venus, it is possible to combine the probe and lander, measuring detailed atmospheric properties during descent and deploying the lander on the surface. At the opposite extreme, Jupiter has no surface, and in late 1995 the Galileo atmospheric probe just kept descending until it was vaporized by high temperatures.

Early interplanetary spacecraft were actually derivatives of those used to study Earth's upper atmosphere (*Figure 8*). The first successful probe of another planet was the Soviet Union's Venera 4, which in 1967 entered the atmosphere of Venus, deployed a descent parachute, and transmitted measurements of density and temperature. At the time, Soviet scientists announced that Venera 4 had dropped through the entire atmosphere and crash-landed on the surface. However, American scientists immediately questioned this claim, since it indicated a surface pressure on Venus about five times lower than had been implied by radar measurements combined with data from the Mariner 5 flyby. After some detective work, the Soviet team found that the probe had ceased transmitting when the atmospheric pressure exceeded its design limit. Not expecting so massive an atmosphere, Venera 4's designers had not provided for pressures higher than 15 bars. Subsequent Soviet probes were given stronger hulls, and Venera 7 successfully reached the surface of Venus in 1970.

Technologically, the solar system's most demanding probe target is Jupiter. Any free-falling object enters a planet's upper atmosphere at a speed nearly equal to the escape velocity, and giant Jupiter has the highest escape velocity of any planet. All of this velocity and kinetic energy had to be carefully dissipated if the Galileo probe were to decelerate safely. The spacecraft slowed from 47 km per second to subsonic velocities in only 110 seconds, enduring an abrupt deceleration that was 228 times the gravitational acceleration on Earth. Then it deployed a parachute and descended for nearly an hour, making measurements and transmitting data to Earth. At a pressure of 24 bars and a temperature of 425° K, transmissions ceased, and about 9 hours later the aluminum-titanium probe had sunk to a level in the atmosphere where the components melted and evaporated. The Galileo probe thus became a part of Jupiter's atmosphere.

The first successful robotic landers were Luna 9 and Surveyor 1, both of which landed on the Moon in 1966. As mentioned earlier, Venera 7 successfully transmitted data from the surface of Venus in 1970, followed by many successful Soviet missions to Venus. Soviet space engineers also achieved the first controlled landing on Mars with their Mars 4 in 1970, but after an apparently flawless entry sequence the spacecraft ceased transmitting data after just 20 seconds.

The U.S. spacecraft Vikings 1 and 2 made the first scientifically successful Mars landings in 1976. Built and flown at a cost of approximately $2 billion (in 1998 dollars), the Vikings were also the most expensive planetary spacecraft ever (excluding Apollo missions). They undertook a daunting challenge: to land safely on a surface that had never been imaged at the resolution of the landers themselves (so that we could not know of rocks or other hazards in the landing area) and to do so autonomously (since the communications travel time between the spacecraft and Earth precluded intervention during the landing sequence). In the end, both spacecraft accomplished flawless landings, becoming highly capable, nuclear-powered, 1-ton laboratories on the Martian surface. Both also greatly exceeded their nominal 90-day lifetimes. In fact, Viking 1's lander survived three frigid Martian winters and continued to transmit data until November 1982, when it was silenced by an engineer's programming error. Together with the two Voyager spacecraft, the Viking mission represented the high point of what has been called the Golden Age of planetary exploration.

One thing the Viking landers lacked was mobility. No one could look at their beautiful panoramas of the Martian surface without wanting to see what lay beyond the nearby hills. NASA considered a plan to launch a Martian rover in 1984, but it — and many other proposed missions — fell victim to budget cuts in the 1980s. The first rover did not arrive on the red planet until 1997, and while Sojourner worked well, its 100-m range did not allow excursions beyond the horizon of its accompanying lander (Mars Pathfinder).

Ultimately we wish to move beyond landing and roving, and to return samples of planetary surfaces for study in terrestrial laboratories. Only in a modern lab will such rocks give up the secrets of their origin and age, reveal the internal chemistry and geologic history of their parent planet, and perhaps even provide evidence of fossil life. Samples of many asteroids arrive at Earth in the form of meteorites, though in only a few cases can we confidently relate the meteorites to their parent asteroids. A handful of lunar and Martian rocks have also been found on Earth, ejected into space by hypervelocity impacts and eventually colliding with our planet. The most impressive sampling effort took place as part of the Apollo program, when more than a half ton of Moon rocks were carefully selected by astronauts and brought back with them. In 1970, a small amount of lunar material was also returned to Earth robotically by Luna 16, followed by two other Soviet sample-return missions. Today sample-return missions are a prime focus of NASA's Mars-exploration program. Also planned are the return of material from a comet (a mission called Stardust) and from a near-Earth asteroid (Japan's MUSES C).

The first Golden Age ended following the 1978 launches of the two Pioneer Venus craft. In 1981 the administration of President Ronald Reagan seriously considered terminating the NASA planetary program entirely. Budget director David Stockman announced that he expected the United States to be out of the planetary-exploration business by 1984, and he even proposed switching off the Voyagers after their Saturn encounters and closing down the Deep Space Network. This tragedy was averted, but budgets continued to be extremely tight following the loss of the Space Shuttle *Challenger* in 1986. More than 10 years elapsed between the Pioneer Venus launches and those of Magellan and Galileo. By this time the Soviet Union was crumbling, and its planetary program soon fell victim to Russia's desperate financial troubles. The launch failure of the ambitious Mars '96 mission probably marked the end of an independent Russian planetary program. The more modest efforts of the European Space Agency and Japan, though successful, could not begin to fill the gaps left by the United States and Russia.

WHAT HAVE WE LEARNED?

By 1990, more than 30 successful planetary missions had been flown (excluding lunar missions), primarily by the United States and Soviet Union. Most of these were aimed at initial reconnaissance of the solar system, though a few (Viking, the later Venera missions, and Magellan) had moved beyond reconnaissance into extensive exploration.

To summarize the results of these missions, let us define initial reconnaissance as equivalent to obtaining images with more than 10,000 picture elements (pixels) on the surface, together with some characterization of the local environment including magnetic and gravity fields. An image of this size, equivalent to a square of 100 by 100 pixels, is comparable to those we see every day on television, in newspapers, and on most Internet sites. To place this imaging yardstick in perspective, note that only five objects in the solar system can be photographed at this resolution by the Hubble Space Telescope: Venus, Mars, Jupiter, Saturn, and Uranus. And of course the Hubble telescope cannot measure magnetic or gravity fields at all.

Using this definition, by 1998 we had achieved an initial reconnaissance of eight of the nine planets (all but Pluto), 16 large satellites, and six small bodies (three asteroids, the two moons of Mars, and Comet Halley). In the decade of the 1990s, long-term studies of the Sun by such spacecraft as the Japanese Yohkoh and the multinational Solar and Heliospheric Observatory have changed our understanding of solar physics. The contents of this book bear witness to the scientific productivity of all these space missions, together with observational, laboratory, and theoretical research carried out in parallel with them.

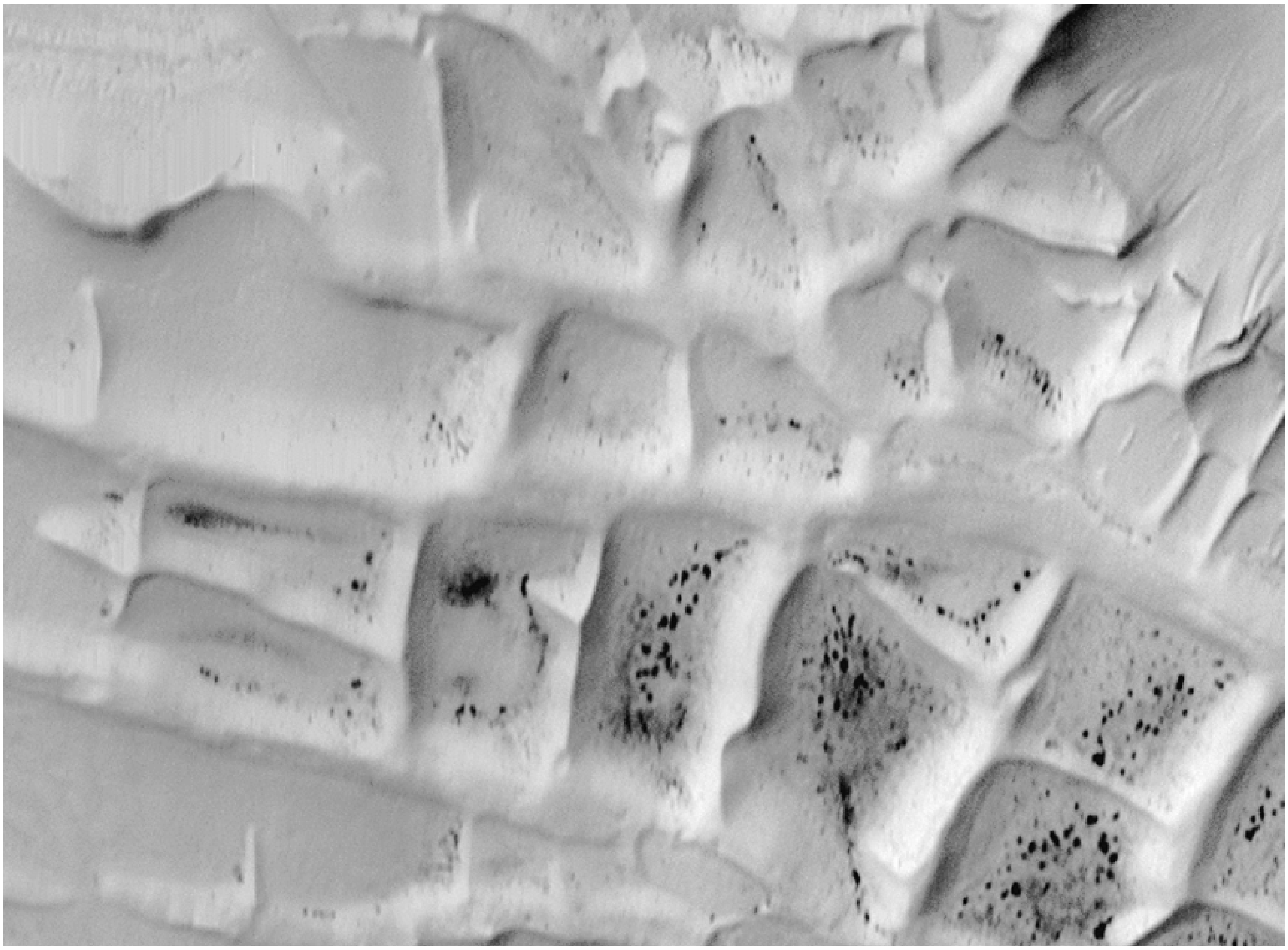


Figure 9. **This enigmatic complex of intersecting ridges was found in the Martian south-polar region early in the mapping mission of NASA's Mars Global Surveyor. Each ridge is about 1 km wide, and the smallest discernible details are no more than 25 m across.**

With high-resolution images it is possible to provide very basic characterization of a solar-system object, for example, to tell whether it is geologically active. Think of a typical "talking head" on the nightly television news: we can see all the main features but tend to miss most of the small wrinkles and blemishes. On small bodies such as asteroids it is possible to identify many individual craters with a 10,000-pixel image, since the largest craters are a fair fraction of the size of the object itself. But for a larger planet or the Galilean satellites of Jupiter, we must achieve a million-pixel image (1,000 by 1,000 elements) to resolve individual geologic features like impact craters, volcanoes, or lava flows. A million-pixel image is exemplified by the photographs we see printed in this book or on a high-resolution computer monitor. This is the sort of resolution obtained by Mariner 9 on Mars or by Voyager and Galileo in the Jovian system. With such images it is possible to distinguish different geologic units and to place these in a temporal sequence.

Until recently, a resolution of a kilometer or two was considered adequate for most geologic interpretations. However, the much higher-resolution images of the Jovian satellites obtained by Galileo and of the Martian surface by Mars Global Surveyor challenge this conclusion (*Figure 9*). The new photos, acquired with 5- to 50-m resolution, really look as if they were of different planets than those seen by the Voyagers and Vikings. They suggest geologic histories that could never have been guessed from the earlier data. As we analyze these higher-resolution images, we may have to rethink our ideas of what constitutes a general reconnaissance of a planetary surface.

Nonetheless, over the years a few common themes have emerged that cut across the planetary system. One of these is the ubiquity of impact cratering, testifying to a common intense bombardment of the inner planets in the first 500 million years of solar-system history as well as a continuing bombardment since. Every solid planet or satellite bears the scars of such impacts. It appears that the continuing flux of colliding objects is roughly the same for each of the inner planets (which are hit by both asteroids and comets) and a few times lower in the outer solar system (where comets are the only source of projectiles). Even a quick look at a spacecraft image reveals, from the number of visible craters, whether the object is geologically young or old (and hence geologically active or not). Thus the Moon, a world that has experienced little internal activity over the past 3 billion years, is heavily cratered. In contrast, Earth and Venus, both of which have typical surface ages of a few hundred million years, are rather sparsely cratered. At higher resolution, it is possible to count the numbers of craters of different sizes and their state of degradation, revealing the planet's general timetable of geologic evolution and allowing comparison of one object with another.

Volcanism provides another common element. Nearly every solid object more than a few hundred kilometers in diameter shows some evidence of internal melting and surface eruptions. For rocky planets and satellites, volcanism creates structures that are closely analogous to Earth's: shield volcanoes, calderas, rift zones, cascading flows, and even lava tubes. Surprisingly, many cold icy satellites also show evidence of fluidized eruptions, termed cryovolcanism. However, the "lava" in these cases could not have been molten silicate rock. More likely, at such low temperatures the working fluid is an exotic mixture of water and ammonia, icy slush, or simply warm ice.

Surface volcanism is an expression of the release of heat from the interior of a planet or satellite. This energy can remain from primordial times, a vestige of the object's accumulation of high-speed debris in the early solar system. It might also reflect the continuing decay of radioactive elements in the interior, or the dynamic heating created when a satellite interacts tidally with its parent planet. The greatest energy sources lie within the giant planets, three of which release interior heat in quantities comparable to the energy they absorb from the Sun. Among the giant planets only Uranus lacks such a heat source, for reasons that are not understood.

A consequence of this internal heating is that all of the larger solar-system objects are differentiated; that is, their interiors have sorted themselves into layers of different density, with the heavier metals at the center and the least-dense materials in the crust. Among the larger objects, only Callisto, the outer Galilean satellite of Jupiter, appears to have avoided a thorough differentiation.

One of the main reasons for making comparative studies of the solar system's members is to reveal the process by which the system itself formed and evolved. The general scheme has smaller, more oxidized, and metal-rich planets close to the Sun and larger, chemically reduced planets with their retinues of ice-rich satellites farther out. This arrangement is interpreted as the imprint of processes that were occurring within the disk of gas and dust from which the planets formed.

Beyond such broad generalizations, the compositions of the individual objects tell us a great deal about the details. In particular, the elemental and isotopic compositions of planetary atmospheres tell us how volatile materials were redistributed after the formation of planetary cores. Presumably the impacts of volatile-rich objects produced veneers of exotic materials, which today make up much of the atmosphere and hydrosphere of Earth and other terrestrial planets. These collisions also subtly modified the atmospheric composition of the outer planets. At this level of chemical detail, most of our data come from probes of the atmospheres of Venus, Mars, Jupiter, and, of course, Earth. Unique chemical data relevant to the formation and early history of the solar system are also obtained from laboratory analyses of meteorites and cosmic dust.

Finally, in any summary of the common aspects of the members of the solar system, the most general conclusion is that there are no valid generalizations, and that each world has experienced its own unique history. Time after time we have been surprised and thrilled as spacecraft revealed the unexpected. For example, scientists before Voyager had confidently predicted that the inner Galilean satellite Io would be heavily cratered and rather lunar in appearance, never anticipating its extraordinary level of volcanic activity. The little Uranian satellite Miranda was another complete surprise; we still do not understand the origin of its bizarre landforms. And we thought of asteroids as solid rock until the Near Earth Asteroid Rendezvous (NEAR) spacecraft showed that 253 Mathilde contains as much void space as rock in its interior. Veteran planetary scientist Laurence Soderblom once remarked that there are no dull satellites — once you look at them closely. Presumably we could generalize this sentiment to all the members of the planetary system.

STRATEGIES FOR FUTURE EXPLORATION

As we approach the 21st century, there is a resurgence of public and governmental interest in planetary exploration. However, the current level of financial support for NASA dictates that planetary missions be smaller and more efficient than their pre-

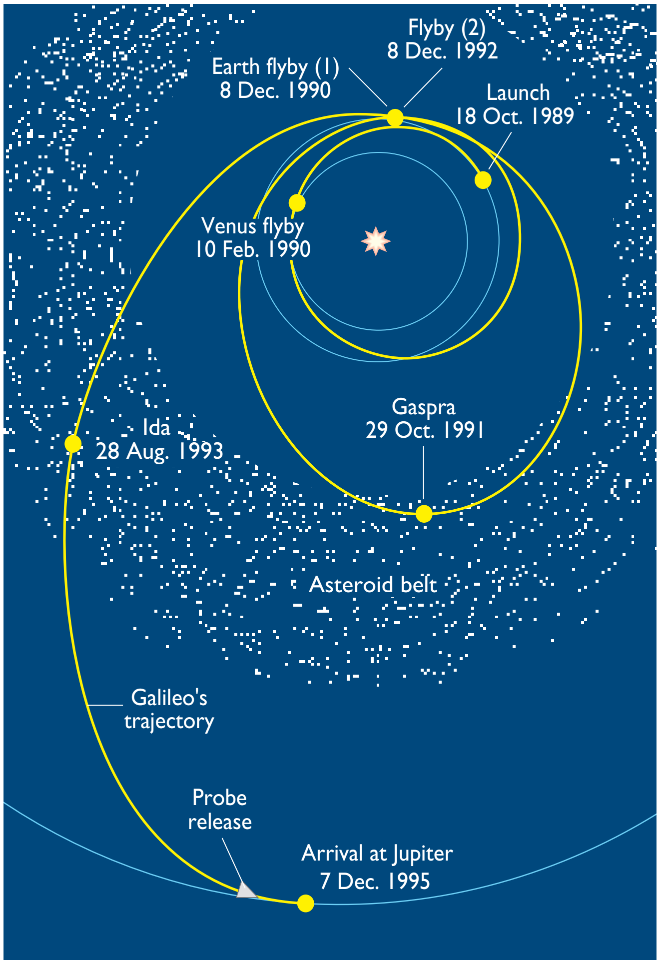


Figure 10. **The Galileo orbiter-probe spacecraft was so massive that no existing rocket had the power to launch it directly to Jupiter, its primary target. Instead, the spacecraft was placed on a looping trajectory that took it past Venus once and Earth twice — gaining enough velocity in the process to reach Jupiter. While the roundabout route took six years (versus just 21 months for the direct flights of Pioneers 10 and 11), it also afforded the opportunity for two flybys of asteroids along the way.**

decessors were. The Russians, Japanese, and Europeans are under similar pressure to reduce mission cost and complexity. Beginning in the early 1990s, NASA administrator Daniel Goldin demanded a new level of performance under the mantra “smaller, faster, cheaper.” Cassini, with its mass of more than 3 tons and a cost in excess of $3 billion, for now stands as the last of the large missions in the tradition of Lunar Surveyor, Viking, Voyager, and Galileo (*Figure 10*). Largely because of Goldin’s bold initiatives, the launch rate for NASA planetary missions has risen from two per decade in the 1980s to better than two per year in the late 1990s.

The reduction in cost and size of missions has been accompanied by changes in the way NASA missions are planned and executed. Individual “new starts,” laboriously planned and marketed with delays of up to a decade between planning and launch, are being replaced with generic classes such as Mars missions or outer-planet missions, within which resources and priorities can be more easily allocated. In the case of Mars, NASA has committed to launching both an orbiter and a lander at each orbital opportunity (which occur about every 26 months) through the year 2010, under the general program name of Mars Surveyor.

Even more flexible are the Discovery missions, an ongoing series of low-cost initiatives selected from a competition held annually. The first Discovery mission, Mars Pathfinder, was launched in 1996 and landed on Mars in August 1997. Pathfinder operated for three months and included a small rover (Sojourner). Next came the NEAR mission, also launched in 1996, which flew past the main-belt asteroid 253 Mathilde in 1997 en route to reaching the near-Earth asteroid 433 Eros in 1999. Lunar Prospector, the lowest-cost mission of all at $63 million (including launch vehicle and operations), was launched in 1998 to map the lunar surface composition and gravity field. Next in the Discovery queue are Stardust, which is to return a sample from Comet Wild 2; Genesis, to sample the solar wind for clues to how our solar system formed; and Contour, a multiple-comet flyby mission.

The most important emerging themes in planetary exploration are the origin of the solar system and the search for evidence of life, past or present. Most of the Discovery missions to date address questions about our origins, which are often best answered by studying small primitive bodies such as comets and asteroids. Interest in extraterrestrial biology is even newer. Twenty years after the Vikings found a sterile Mars, discoveries in terrestrial biology are reinvigorating the field of exobiology and have created a broader umbrella discipline within NASA called astrobiology. Astrobiology is the scientific study of the origin, evolution, distribution, and future of life in the universe. To understand life’s origin, we need to place terrestrial life in its cosmic context.

The search for evidence of past life is at the heart of the Mars Surveyor program. Although it is a frozen world today, Mars was not always so inhospitable. Large tracts of the surface were once washed by floods and drained by extensive river systems. Ancient lakes and hot springs have left their imprint as well. Significantly, Mars was its most Earthlike at the same time, between 3 and 4 billion years ago, that life first arose on our own planet. For the biological sciences, no discovery could be more exciting than the opportunity to study life forms having an independent, extraterrestrial origin. Surveyor’s first priority is the search for evidence of fossil Martian life, but the possibility of extant life cannot be excluded. Over the next decade we will also identify the most promising landing sites on Mars, select biologically interesting rocks, and return those rocks to Earth.

The solar-system exploration program hopes to address many questions dealing with possible past or present life on Mars. Did conditions ever exist there that were conducive to the introduction of biology? Did Martian life, in fact, develop independently of that on Earth? Alternatively, did the exchange of impact-related debris between the two developing worlds seed one with microbes from the other? If life once existed on Mars, does it persist today in some protected environments? Could we detect and recognize it as such? If it has not survived, what went wrong? And what dangers might a surviving Martian ecosystem pose to the biological diversity on Earth?

Looking beyond Mars, we can examine the biological prospects for Europa. To many scientists, Galileo’s images offer compelling evidence for a global ocean beneath the icy crust of this moon. But this is at best an indirect inference. The extension of Galileo’s mission to allow more comprehensive studies of Europa is a first response to this interest. The next logical step would be to dispatch an orbiter equipped with radar to probe the Europan ice from afar. For Europa to now have a liquid-water mantle, substantial amounts of heat must be coming from the moon’s interior. One can easily imagine the Europan equivalent of hydrothermal vents. On our planet, there is a thriving biota associated with these vents, independent of photosynthesis. By analogy, Europa could support similar lifeforms.

The search to understand our solar system’s origins naturally raises questions about its distant fringes, where conditions may still resemble those in the solar nebula from which the planets formed. Such scientific curiosity, as well as a desire to complete the spacecraft tour of the major planets, is the motivation behind a mission to Pluto and perhaps other large icy objects in the Kuiper belt. NASA’s Pluto Express, proposed for launch around 2004, is designed to reach the planet before its increasing distance from the Sun causes its tenuous atmosphere to collapse as frost onto the icy surface.

We face exciting opportunities in solar-system exploration. For NASA, lower-cost robotic missions provide the means for an expanded program, with special emphasis on Mars. The flexibility inherent in the competitively selected Discovery missions lets us respond rapidly to new conditions and scientific opportunities. Pluto Express will show us the last unexplored planet. Finally, a renewed interest in life’s origins may set the stage for the kind of public and political support that could eventually propel humans — not just machines — to the surfaces of other worlds.