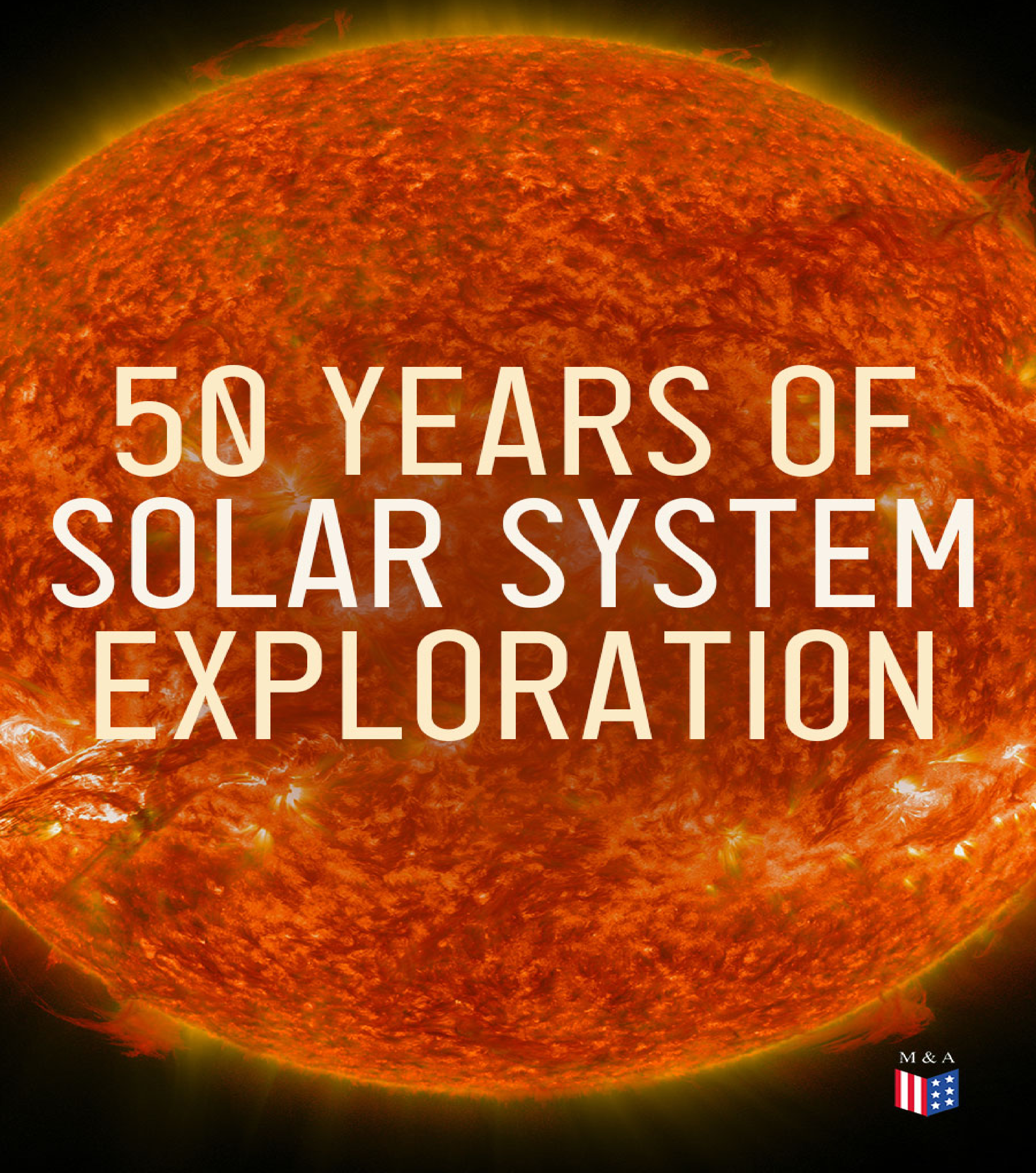
National Aeronautics and Space Administration



50 YEARS OF SOLAR SYSTEM EXPLORATION

M & A

National Aeronautics and Space Administration

50 Years of Solar System Exploration

Historical Perspectives

Contact: info@madisonadamspress.com

EAN 4066338125910

Table of Contents

Introduction:

NASA's Solar System Exploration Paradigm: The First 50 Years and a Look at the Next 50

(James L. Green and Kristen J. Erickson)

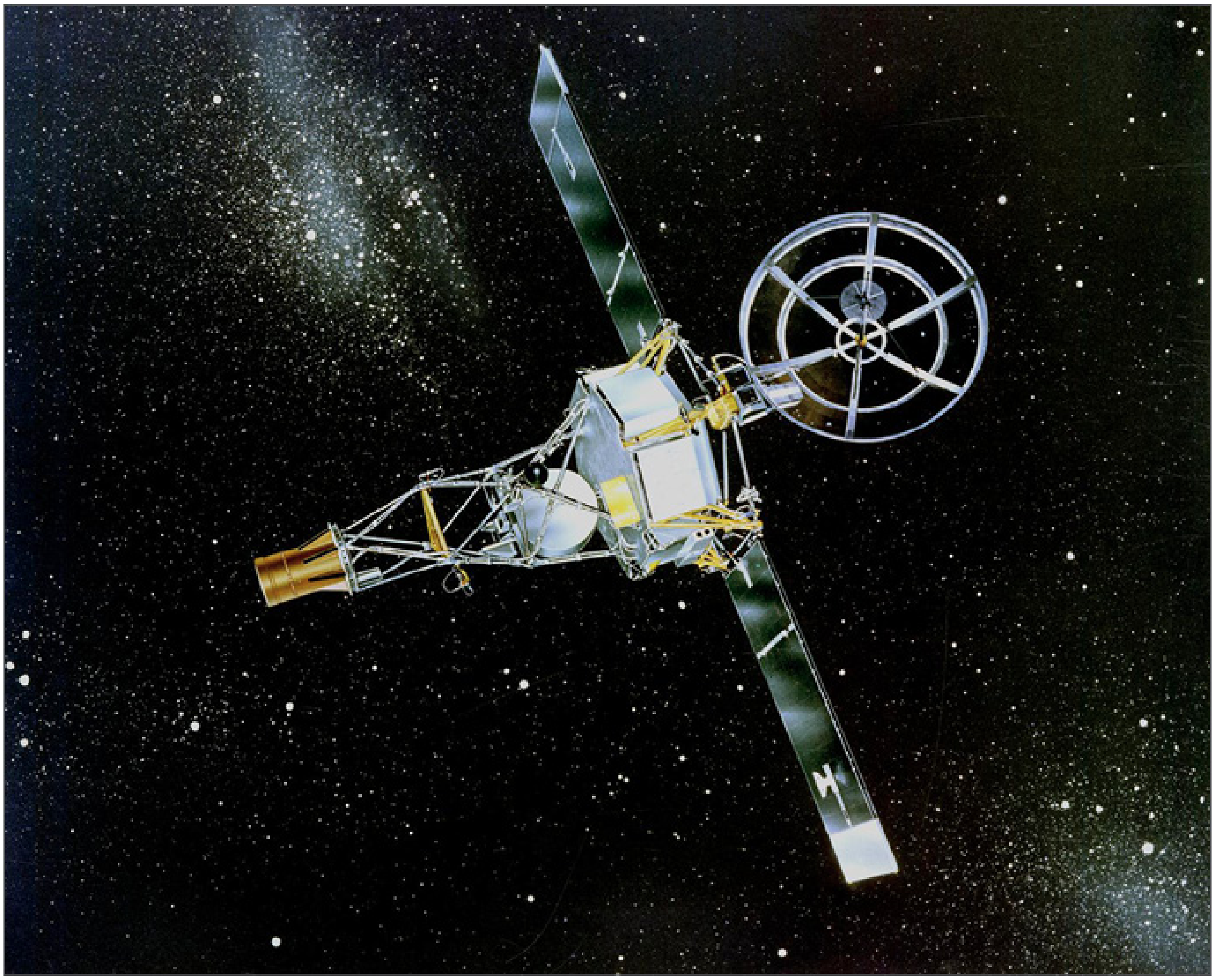
Table of Contents

After many failures to get to the Moon and to the planets beyond, Mariner 2 successfully flew by Venus in December 1962. This historic mission began a spectacular era of solar system exploration for NASA and many other space agencies. With the tremendously successful flyby of the Pluto system by the New Horizons spacecraft in July 2015, humankind completed its initial survey of our solar system, and the United States became the only nation to reach every planet from Mercury to the dwarf planet Pluto with a space probe.

Solar system exploration has always been and continues to be a grand human adventure that seeks to discover the nature and origin of our celestial neighbors and to explore whether life exists or could have existed beyond Earth. Before Mariner 2, everything we knew about our solar system came from ground-based telescope observations and from analysis of meteorites. This limited perspective could not begin to reveal the diversity and the true nature of our solar system. In this brief introduction, we address how NASA and other space agencies have approached a comprehensive series of missions for the last half century of solar system exploration.

The Solar System Exploration Paradigm

It is our spacecraft missions that provide the opportunity to get up close and personal with many bodies in the solar system. Mariner 2 was just the first robotic space probe to conduct a successful planetary encounter, the first step in a long journey. The scientific instruments on board were two radiometers (microwave and infrared), a micrometeorite sensor, a solar-plasma sensor, a charged-particle sensor, and a magnetometer. These instruments measured the temperature distribution on the surface of Venus, made basic measurements of Venus's atmosphere, discovered the solar wind, and determined that Venus, unlike Earth, has no intrinsic magnetic field.[1] This powerful set of observations fueled our fascination with our cosmic neighborhood and our desire to learn more.



Artist’s concept of the Mariner 2 spacecraft. *(NASA/JPL: PIA04594)*

Since Mariner 2, in exploring any particular object, solar system exploration has followed a general paradigm of “flyby, orbit, land, rove, and return samples.” A complete campaign may not be performed for each object in the solar system, since not all of our scientific questions can be studied at all objects, and there are difficult technological challenges and financial hurdles to overcome for some types of missions and certain destinations. Moreover, a healthy program of solar system exploration requires a balance between detailed investigations of a particular target and broader reconnaissance of a variety of similar targets. This approach is summarized in Figure 1 for the inner solar system and Figure 2 for the outer solar system, showing progress made in exploration of the major types of solar system bodies. Figures 1 and 2 also show NASA (black, roman text) and international (blue, italic text) space missions, with new mission concepts that have been put forward by the science community as our next steps (red, bold text).

By following the above paradigm in our exploration of the solar system, we have forged a path of significant progress in our knowledge and understanding and a recipe for future exploration as well. For the past 50 years, our primary goals have focused on advancing scientific knowledge of the origin and evolution of the solar system, the potential for life elsewhere, and the hazards and resources present as humans explore space. The quest to understand our origins is universal. How did we get here? Are we alone? What does our future hold? Modern science, especially space science, provides extraordinary opportunities to pursue these questions.

For the last several decades, NASA has sought guidance from the National Research Council (NRC) of the National Academy of Sciences on priorities in solar system exploration. The last two NRC “decadal surveys” of solar system exploration—*New Frontiers in the Solar System: An Integrated Exploration Strategy* (2003) and *Visions and Voyages for Planetary Science in the Decade 2013–2022* (2011)—show the wide diversity in potential targets. The next scientific leap in understanding these targets requires landers, rovers, atmospheric probes, or sample-return missions. The NRC’s latest mission recommendations in its last planetary decadal survey are shown in Figure 1 and Figure 2 in bold text. The next planetary science and astrobiology decadal survey 2023–2032, got under way in 2020 and will further refine priorities.

STEPS IN PLANETARY SCIENCE EXPLORATION

	Mercury	Venus	Earth's Moon
FLYBY 1	Mariner 10 MESSENGER	Mariner 2, 4, 10 *Venera 11, 12, 13, 15* Galileo Cassini MESSENGER *Akatsuki*	*Luna 1, 3* Pioneer 4 *Zond 3, 5, 6, 7, 8* Apollo 13 *Hiten*
ORBIT 2	MESSENGER *BepiColombo**	*Venera 9, 10, 15, 16* Pioneer Venus 1 Magellan *Venus Express* *Akatsuki** Venus Climate (FS)	*Luna 10, 11, 12, 14, 19, 22* Lunar Orbiter 1, 2, 3, 4, 5 Apollo 8, 10, 11, 12, 14, 15, 16, 17 *Hiten* Clementine Lunar Prospector *SMART-1* *SELENE (Kaguya + Okina & Ouna)*
LANDER 3		*Venera 7, 8, 9, 10, 11, 12, 13, 14* Pioneer Venus 2 *Vega 1, 2* Venus In-situ (NF)	Ranger 7, 8, 9 *Luna 2, 9, 13* Surveyor 1, 3, 4, 5 LCROSS *Chang'e 3* Geophysical Network (NF)
ROVER 4			Apollo 11, 12, 14 (legs) Apollo 15, 16, 17 (wheels) *Lunakhod 1, 2 (Luna 17, 21)* *Yutu*
SAMPLE RETURN 5			Apollo 11, 12, 14, 15, 16, 17 *Luna 16, 20, 24* South Pole Aitken Basin Sample Return (NF)

INNER SOLAR SYSTEM

DISTANCE FROM THE SUN

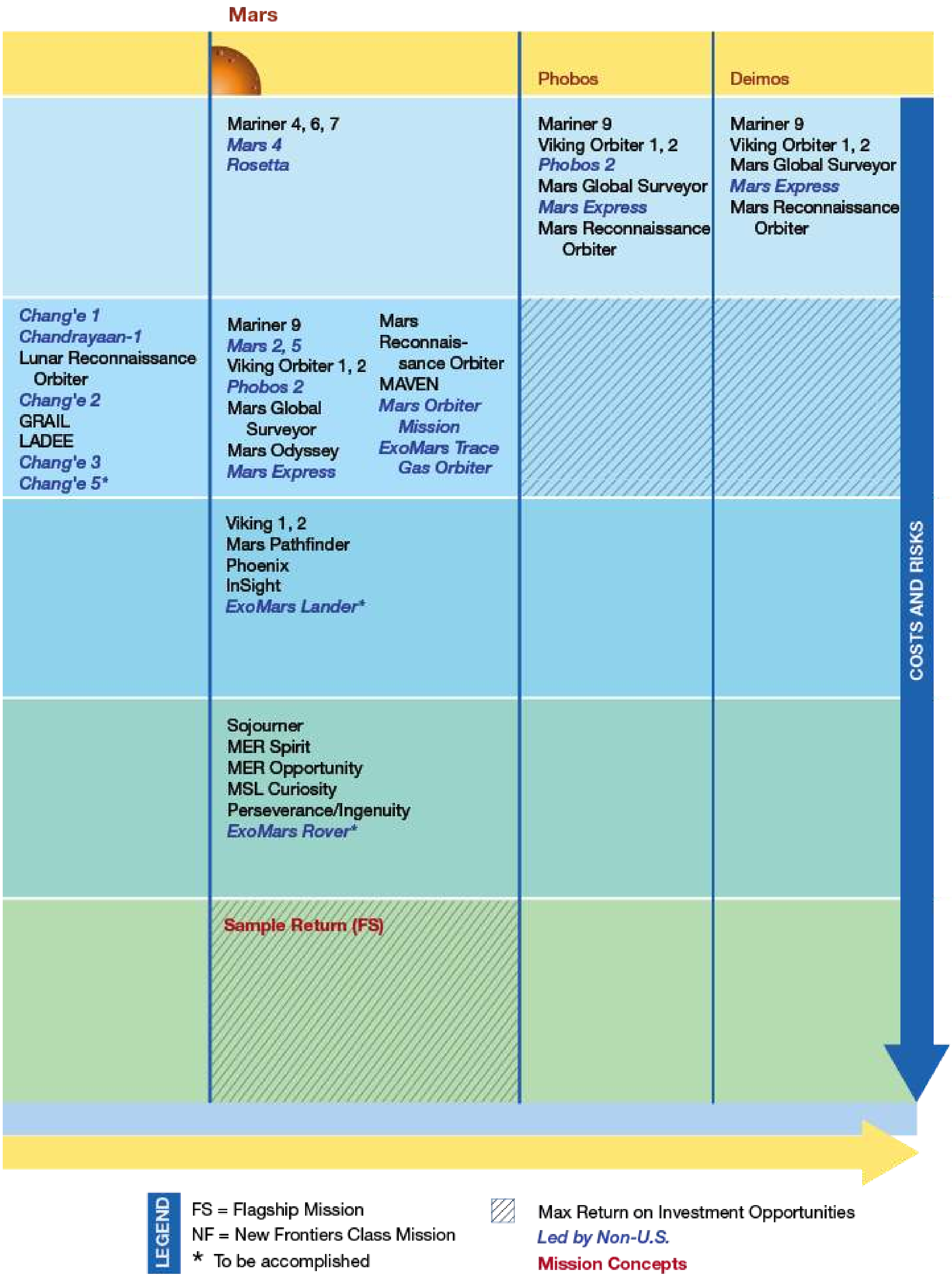
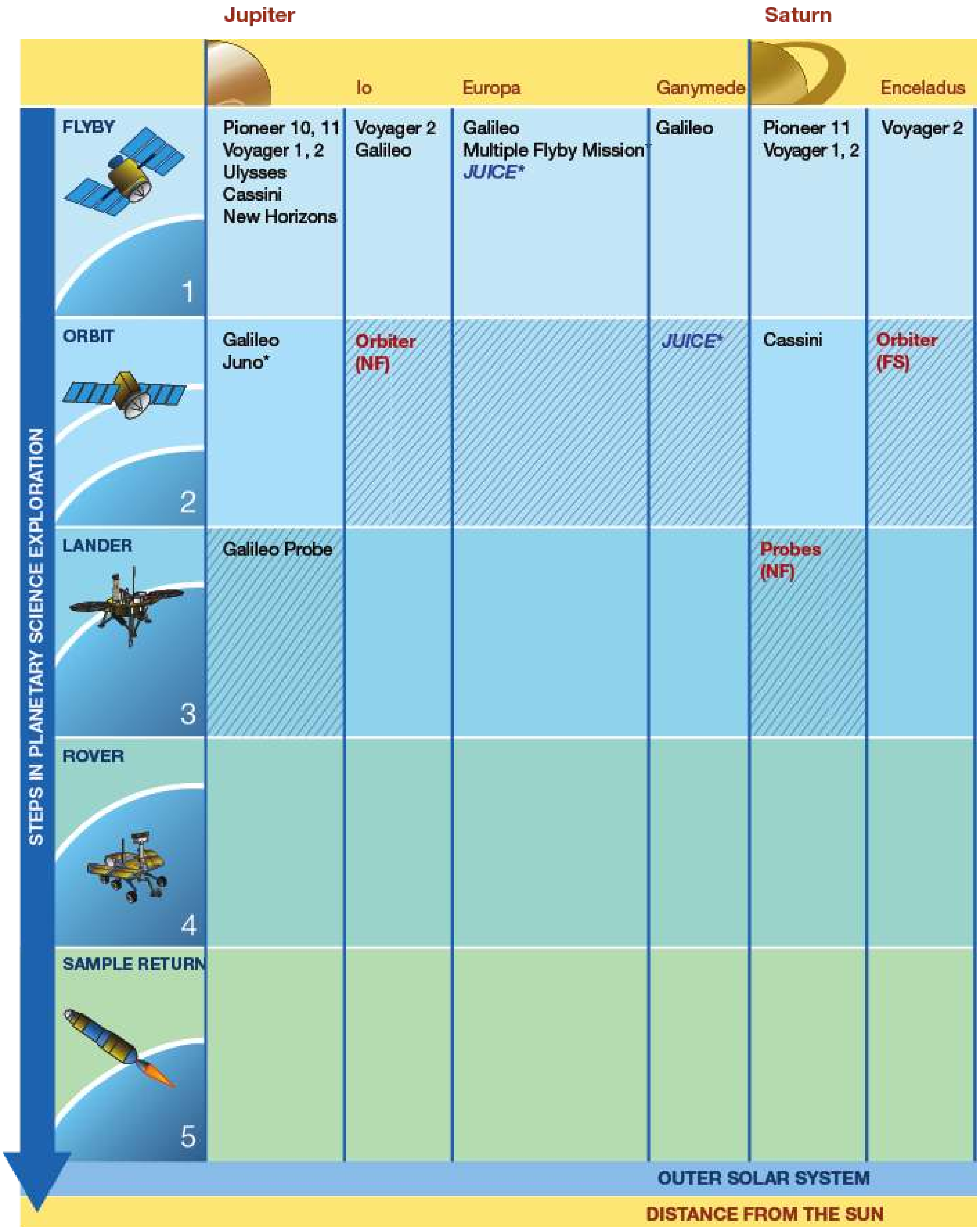


Figure 1. Summary of missions by inner solar system planetary body and steps

in planetary exploration: flyby to orbit to lander to rover to returning samples



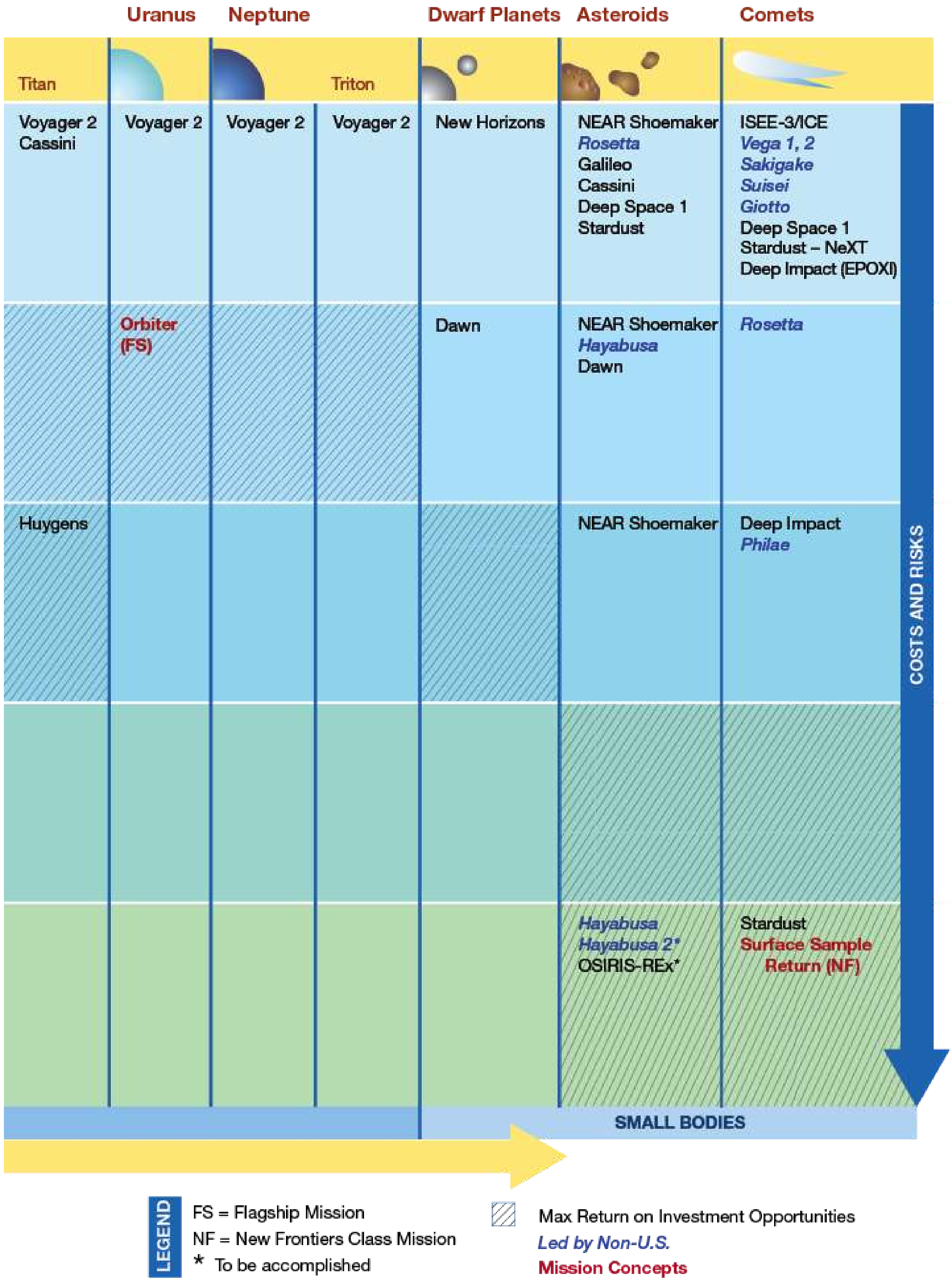


Figure 2. Summary of missions by outer solar system planetary body and steps

in planetary exploration: flyby to orbit to lander to rover to returning samples

To track spacecraft beyond low-Earth orbit (LEO), NASA developed the Deep Space Network (DSN), which has constantly been upgraded to continue to provide outstanding data tracking, telemetry, and navigation services. Today, all space agencies support large radio-frequency dishes that are coordinated through international agreements between the agencies to meet planetary mission needs. This has worked remarkably well and has naturally forged a set of tracking and navigation standards to the benefit of all.

Flyby Missions

Flyby missions are designed to obtain the most basic information on their target bodies. Early flyby missions also enabled space agencies to learn to fly between planets. This early trek into the solar system was accomplished with flybys to each planet in our local neighborhood as shown in Figure 1. U.S. Mariner and Soviet Venera missions surveyed and inventoried the inner planets Mercury, Venus, and Mars. In this section, we will discuss a few of these examples. The early flyby missions were all about leading the way in how to venture out into the solar system.

The first two Venera spacecraft were designed as flyby missions, but after they failed, the Soviet space program began targeting Veneras directly into the planet Venus, using the planet’s extensive atmosphere to slow them down during entry. The Venera 5 and 6 atmospheric probes lasted long enough to provide significant data. Venera 7, designed to survive all the way to the surface, landed and transmitted for about 20 minutes before its battery died.

Space agencies also paid particular attention to Earth’s Moon, with Soviet Luna and Zond spacecraft and one early U.S. Pioneer mission. Luna 1 was the first spacecraft to reach the vicinity of Earth’s Moon. Although intended to be an impactor, it missed due to an incorrectly timed upper-stage burn during its launch, and it became the first spacecraft to end up orbiting the Sun. Following the first two Zond mission failures, the Soviet Zond 3 mission, after imaging the far side of the Moon, continued well beyond Earth orbit in order to test telemetry and spacecraft systems in deep space.

The principle of gravitational assist was exploited early to provide a method of increasing or reducing the speed of a spacecraft without the use of propellant. The Mariner 10 spacecraft was the first to use gravitational assist to reach another planet by swinging by Venus on 5 February 1974. This maneuver placed it on a trajectory to fly by Mercury a total of three times, twice in 1974 and once in 1975. The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission used the same approach, executing two Venus and three Mercury flybys before entering into orbit around Mercury in March 2011.

As shown in Figure 3, the outer solar system had flybys with two Pioneer and two Voyager spacecraft. The Voyager flyby missions completely changed the way we view the outer solar system. The primary mission of Voyagers 1 and 2 was the exploration of the Jupiter and Saturn systems. After making a string of discoveries there, such as active volcanoes on Jupiter's moon Io and the intricacies of Saturn's rings, the Voyagers' mission was extended. Voyager 2 went on to explore Uranus and Neptune and is still the only spacecraft to have visited these outer ice giant planets.

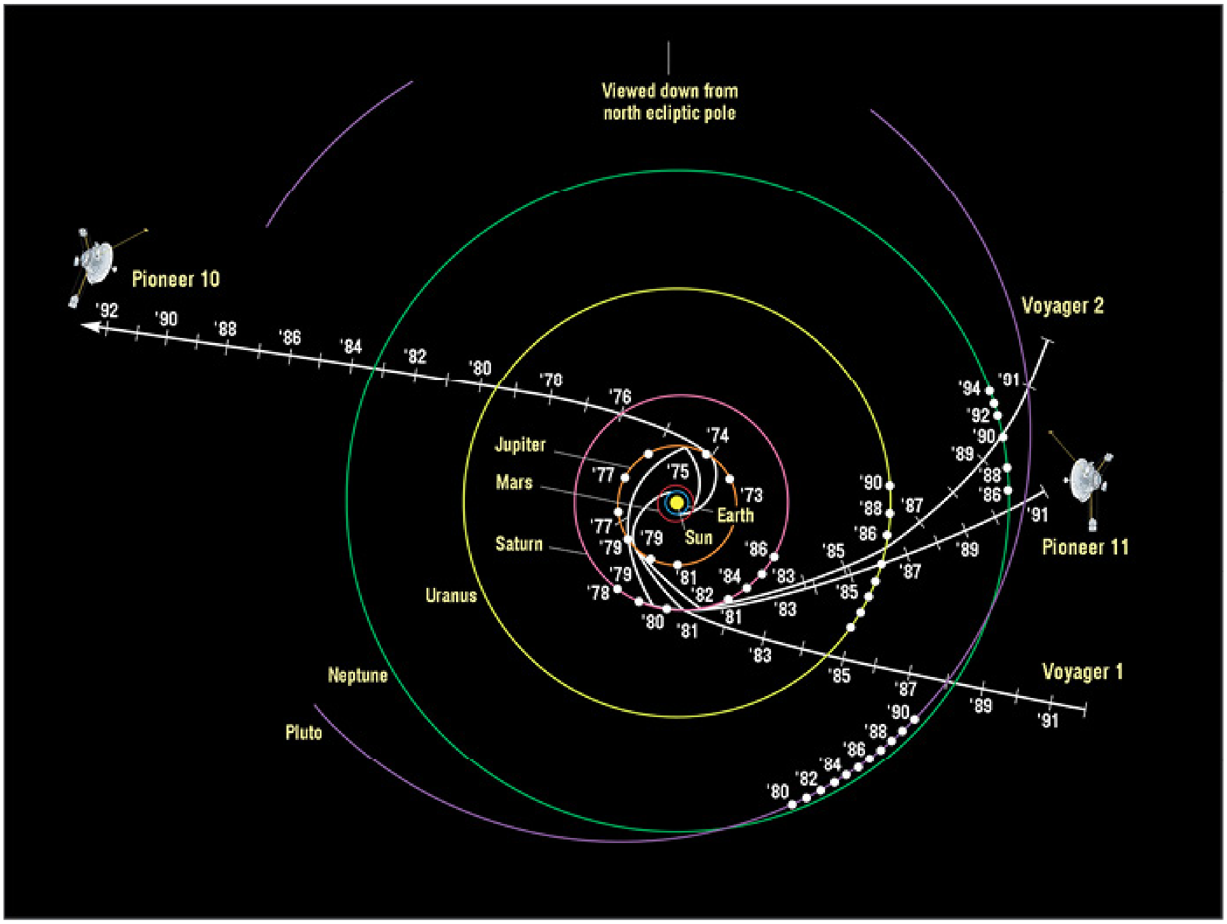
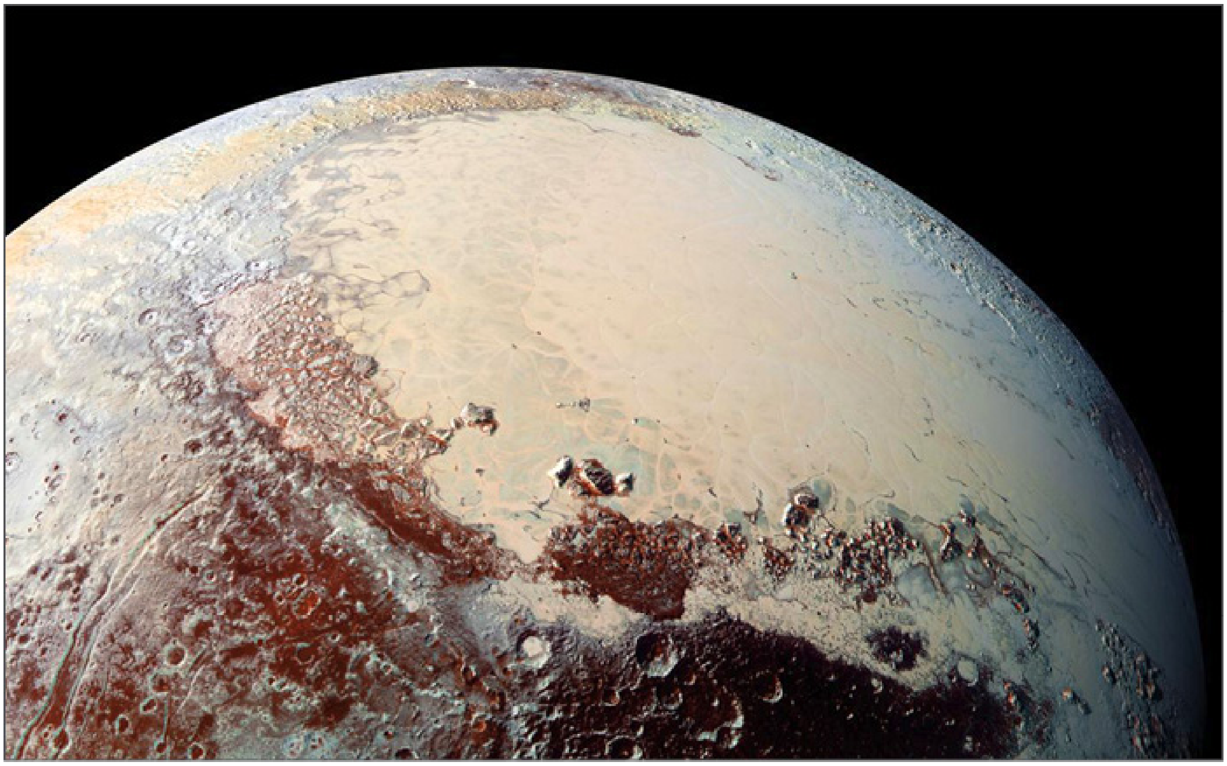


Figure 3. Pioneer and Voyager trajectories throughout the solar system. *(NASA: 72413 Main ACD97-0036-3)*

Voyagers 1 and 2 are currently into the fourth decade of their journey since their 1977 launches. In August 2012, data transmitted by Voyager 1 indicated that it had made a historic entry into interstellar space—the region between the stars, filled with the stellar winds of nearby stars. Scientists hope to learn more about this region when

Voyager 2 passes out of the heliosphere and begins measuring interstellar winds.

As part of NASA's New Frontiers program, the New Horizons mission made the first reconnaissance of the dwarf planet Pluto (at 39 AU from Earth) and is now venturing deeper into the distant, mysterious Kuiper Belt, a relic of early solar system formation. New Horizons was launched on 19 January 2006 from Cape Canaveral, Florida, directly into an Earth-and-solar-escape trajectory with an Earth-relative speed of about 16.26 kilometers per second. After a brief encounter with asteroid 132524 APL, New Horizons proceeded to Jupiter, making its closest approach on 28 February 2007. The Jupiter flyby provided a gravity assist that increased New Horizons' speed by 4 kilometers per second. The encounter was also used as a general test of New Horizons' scientific capabilities, as the spacecraft returned data about the planet's atmosphere, moons, and magnetosphere. Most of the spacecraft's post-Jupiter voyage was spent in hibernation mode to preserve on-board systems, except for brief annual checkups. On 15 January 2015, the New Horizons spacecraft successfully came out of hibernation and began its approach phase to the Pluto system, which resulted in the first flyby of the dwarf planet on 14 July 2015. With the completion of the New Horizons flyby of the Pluto system, NASA was the first and only space agency to have completed the initial exploration of the solar system.



High-resolution image captured by NASA’s New Horizons spacecraft of Pluto’s Sputnik Planum basin. *(NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute: PIA20007)*

Missions That Orbit

Beyond flybys, the next most sophisticated type of mission aimed to get a spacecraft into orbit around a solar system object. Data from flyby missions were essential to prioritizing which objects to orbit. High-resolution data from an orbiter mission are essential to planning for a future lander or rover mission.

After flyby missions, scientists wanted to learn much more about the basic properties of our planetary neighbors, such as structure, size, density, and atmospheric and surface composition. NASA’s Magellan and the European Space Agency’s (ESA)’s Venus Express spacecraft have orbited Venus. The world’s space agencies have sent armadas of spacecraft to orbit the Moon and Mars. We have had groundbreaking discoveries with various orbiting missions. To survey the outer planets following the Galileo orbiter to the Jupiter system, Juno, launched in August 2011, arrived at Jupiter in early July 2016, while the Cassini spacecraft orbited Saturn until September 2017.

As our nearest neighbor, the Moon is a natural laboratory for investigating fundamental questions about the origin and evolution of Earth and the solar system. The Lunar Reconnaissance Orbiter (LRO), a robotic mission that has mapped the Moon’s surface at high resolution (~1 square meter), is still operating as of this writing. LRO observations have enabled numerous groundbreaking discoveries, creating a new picture of the Moon as a dynamic and complex body.

Planetary scientists have made significant and steady progress in understanding what Mars is like today and what it was like in its distant past. The exploration of Mars is currently being accomplished by an international array of missions from NASA, the European Space Agency and its partner countries, and the Indian Space Research Organization (ISRO). Orbiter missions operating at Mars as of this writing include Mars Odyssey, Mars Express, the Mars Reconnaissance Orbiter, the Mars Atmosphere and Volatile EvolutioN Mission (MAVEN), and the Mars Orbiter Mission.

Lander and Rover Missions

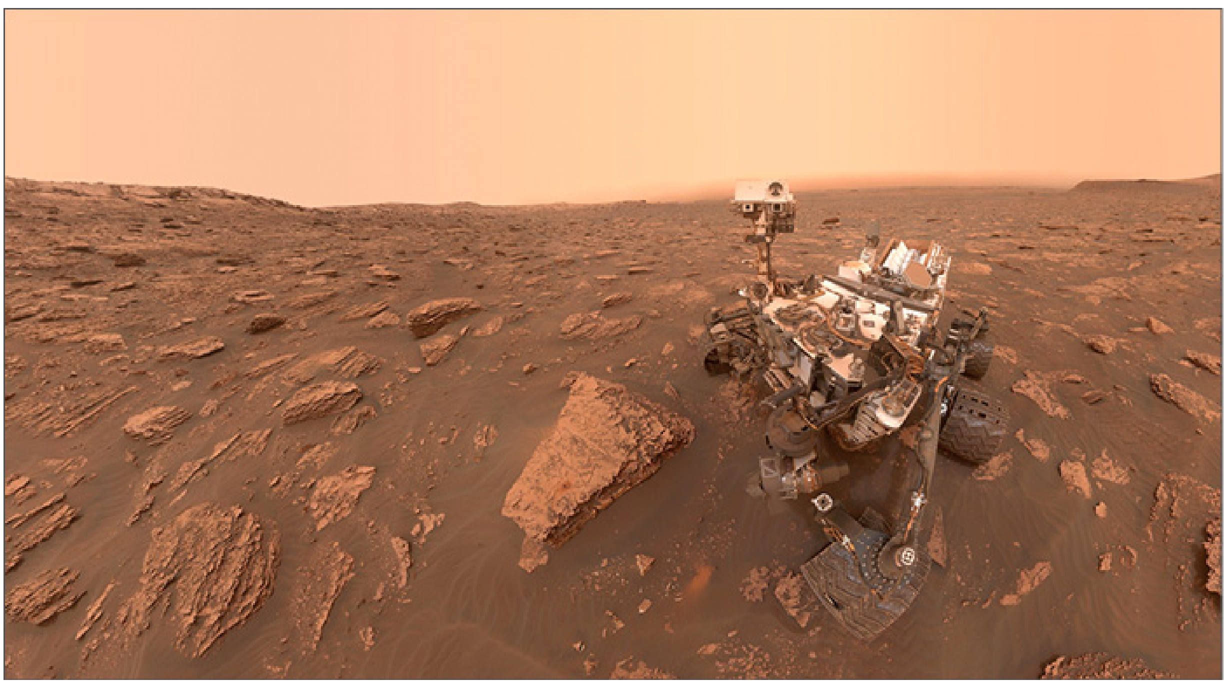
Lander and rover missions enable scientists to acquire “ground truth,” measurements so necessary to fully interpret data from orbital missions. The successful landings of the 1-metric-ton[2] Curiosity rover on Mars and the Rosetta mission’s Philae probe on comet 67P/Churyumov–Gerasimenko clearly show the ability of our space agencies to explore our solar system at a new level of intensity. Steps like these will allow humans to go beyond this planet and out into the solar system once again.

As of 6 August 2020, Curiosity had been on the surface for eight Earth years. From Curiosity data, we now know that Mars was more Earthlike in its distant past, with rivers, lakes, streams, a thick atmosphere, clouds and rain, and, perhaps, an extensive ocean. Although today Mars is rather arid, scientists now believe vast amounts of water are trapped under the surface of Mars and under the carbon dioxide snow of its polar caps. Water is the key that will enable human activity and long-term presence on Mars.

Sample Return

Sample return provides scientists with essential data to understand the geological history of a body. Up to the present, space agencies have collected samples from several solar system bodies, as well as samples of the solar wind. The Apollo program in the late 1960s and early 1970s brought back over 850 pounds of Moon rocks, soils, and regolith. These materials are still being analyzed and yielding significant scientific results. It is also important to note that many of the meteorites that have fallen on Earth can now be identified with specific solar system bodies such as the Moon, Mars, and Vesta. The comet 81P/Wild (Wild 2) and the asteroid 25143 Itokawa were visited by robotic spacecraft from NASA and the Japan Aerospace Exploration Agency (JAXA), respectively. Both missions returned samples to Earth.

The Mars 2020 rover mission was based on the design of the highly successful Mars Science Laboratory rover, Curiosity. This new rover, named Perseverance, landed on Mars on 18 February 2021 in Jezero Crater. Perseverance carries more sophisticated hardware and new instruments to conduct geological assessments of the rover's landing site, determine the potential habitability of the environment, and directly search for signs of ancient Martian life by contact instruments and by coring and storing rock samples for later return to Earth.



A self-portrait of NASA's Curiosity rover taken at the rover's location in Gale Crater on Sol 2082 (15 June 2018). *(NASA/JPL-Caltech/MSSS: PIA 22486)*

Hitching a ride on Perseverance was another kind of powered craft, the Mars Helicopter Ingenuity. After arriving on Mars and traveling on the belly of Perseverance to a suitable helipad location, Ingenuity demonstrated the first powered flight on another world on 19 April 2021, climbing approximately 10 feet (3 meters) above the ground before hovering and returning to the ground safely.

The Next 50 Years

Our robotic solar system explorers have gathered data to help us understand how the planets formed; what triggered different evolutionary paths among the planets; what processes are active; and how Earth formed, evolved, and became habitable. To search for evidence of life beyond Earth, we have used these data to map zones of habitability, study the chemistry of unfamiliar worlds, and reveal the processes that lead to conditions necessary for life.

This overview is not a comprehensive report on past missions. It touches on only a few examples in each of the categories that have defined our approach to solar system exploration for the last 50 years. We are now entering a new era of space exploration as we start to execute more complex missions that will land, rove, and return samples from top-priority targets in the solar system. In Figures 1 and 2, the crosshatched regions indicate the next big steps in the exploration of their target bodies, producing the maximum return based on knowledge acquired from the previous missions. In comparing Figures 1 and 2, it is clear that the inner solar system has been more thoroughly explored. This is understandable since outer solar system missions typically use radioisotope power systems and take many years to arrive at their target bodies.

New technologies will enable space agencies to develop and execute an astounding range of more complicated and challenging missions. We are at the leading edge of a journey of exploration that will yield a profound new understanding of the solar system as our home. NASA is building a Space Launch System (SLS) for human exploration, but its use is also being considered for some deep space robotic missions. The SLS will be more powerful than the Saturn V. If it is used for planetary missions to the outer solar system, direct trajectories rather than inner-solar-system gravity-assist maneuvers would be possible, cutting transit time, typically, by one-third. This launch approach alone would open the outer solar system to a significantly increased rate of missions and discoveries.

Robotic exploration not only yields knowledge of the solar system; it also will enable the expansion of humanity beyond low-Earth orbit. By studying and characterizing planetary environments beyond Earth and identifying possible resources, planetary scientists will enable safe and effective human missions into space. Scientific precursor missions to the Moon enabled the Apollo landings and have made significant progress toward enabling human missions to Mars within the next 50 years. A single-planet species may not long survive. It is our destiny to move off this planet and into the solar system. We are developing the capability to do it.

Acknowledgments

The authors would like to thank Stephen Edberg and Doris Daou for help with graphics and mission information.

[1] Scientific and Technical Information Division, *Mariner-Venus 1962 Final Project Report* (Washington, DC: NASA-SP-59, 1965).

[2] Mars Science Laboratory Landing press kit, National Aeronautics and Space Administration, July 2012, p. 6, *http://www.jpl.nasa.gov/news/press_kits/MSLLanding.pdf* (accessed 8 January 2020).

PART I.
Overview

Table of Contents

In his introduction to this volume, NASA Chief Scientist Jim Green has described NASA's long-standing paradigm for solar system exploration—flyby, orbit, land and rove, and return samples—and reviewed, from a scientific perspective, the multinational array of robotic missions that have been launched to probe the solar system. In this chapter, historian Peter Westwick provides a wide-reaching and thought-provoking overview of the first 50 years of solar system exploration from a different perspective. He raises important questions along the way, some of which other contributors to this volume address, and some of which remain open, for other historians to answer.

Westwick asks, for example, who are the people who have made solar system exploration possible? The history of human spaceflight tells the stories of the astronauts, cosmonauts, and leading engineers (e.g., Wernher von Braun, Sergei Korolev) who made it possible—not so much for robotic solar system exploration. "After 50 years, we still need a social history of space exploration," he observes.

"Who are the explorers," he asks, "the people, institutions, and nations" that have engaged in exploration? And what exactly *is* "exploration?" he asks. "What does 'exploring' involve?" These questions are especially relevant today, as the line between space exploration and space exploitation is beginning to blur, with proposals for asteroid mining and planetary colonization. Advocacy for human exploration has tended to be driven by profit, he notes. “The profit motive, however, as far as I have seen,” he writes, “was largely absent from planetary exploration, which is interesting for a major American enterprise.”

Westwick entertains a question that other space historians like to think about: why explore space? Scientists, engineers, and others engaged in exploring space tend to answer the “why” question with stories about “spinoff” benefits, jobs on the ground, national prestige, and educational value. All of these benefits can be supplied by other sorts of scientific and technological enterprises, however. So, the question remains open: why?

Westwick’s thoughtful perspective on the first half century of solar system exploration provides an excellent entry to the rest of this volume.

Chapter 1

Exploring the Solar System: Who Has Done It, How, and Why?

(Peter J. Westwick)

Table of Contents

Some 50 years ago, NASA's Mariner 2 spacecraft skimmed 20,000 miles over Venus. This first excursion to another planet landed Jet Propulsion Laboratory (JPL) Director William Pickering on the cover of *Time* magazine and as grand marshal of the Rose Parade. In August 2012, many were captivated by Curiosity's landing on Mars. That's the Curiosity spacecraft, not the human spirit of inquiry, although that was certainly present, too. JPL engineers spiced things up by devising a landing sequence with a preposterous, Rube Goldberg flavor. They knew better than anyone what was riding on the landing: a $2 billion rover, for starters, but also, perhaps, the national appetite for solar system exploration itself. Curiosity's success may have ensured that the United States, at least, will continue to explore the solar system, so that the history considered in this volume will continue.

Mariner and Curiosity bookend the first 50 years of solar system exploration. In between, robotic explorers have met triumphant success and epic failure; they have seen ring spokes and blueberries and have dealt with Great Galactic Ghouls and faces on Mars. These 50 years have taught us remarkable new things about the solar system. They have also taught us a great deal about ourselves. We now can look outward to our solar system and contemplate all we have learned about it. We also can drop our gaze back to Earth and consider what deep-space exploration tells us about our own human history over the last 50 years.

Who Has Done It?

The first question is, who are the explorers—not the robots, but the people, institutions, and nations who built them? Let's start with the people. After 50 years, we still need a social history of space exploration.[1] Who are these people, and what do they do all day? How have they changed over 50 years, and how has the work changed? What are their backgrounds? How do they balance work and personal life? What do they do when they are not working, and how does that affect their work?

We know a bit about the types of people involved—for starters, mostly men. Engineering and systems management was an overwhelmingly male preserve for the first half of this period. Women in the space program have been studied in relation to the astronaut corps, but much remains to be done for solar system exploration.[2] The number of women present in JPL's mission control for Curiosity was a marked contrast to all the men running Mariner, and how that happened is an interesting story. Still, though, the engineers on Curiosity are mostly male.

They are also mostly white. NASA has not had a sterling record of minority representation,[3] especially at higher levels, although that has changed recently. One might also think about socioeconomic classes. When we think of the people involved in solar system exploration, we mostly think about white-collar engineers and managers and neglect the many other people involved in the enterprise: machinists, security guards, secretaries—some of whom share the excitement of space exploration, others of whom do not. One JPL janitor said the most exciting thing about the Viking landing was the large rat that ran across the room and jumped into a trash can.

Glenn Research Center Propulsion Systems Laboratory Control Room. *(NASA: C-1998-00279)*

Next, what institutions explore the planets? Looking just at the United States, we have universities, government labs, and industrial corporations, for starters. Each type of