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Ronald Greeley
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CHAPTER 1

Introduction

The early part of the twenty-first century saw the completion of the reconnaissance of the Solar System by spacecraft. With the launch of the *New Horizons* spacecraft to Pluto in early 2006 and its expected arrival in 2015, spacecraft will have been sent to every planet, major moon, and representative asteroid and comet in our Solar System. With the return of data taken by spacecraft of these objects, the study of planetary surfaces passed mostly from the astronomer to the geologist and led to the establishment of the field of **planetary geology**.[1] The term geology is used in the broadest sense to include the study of the solid parts of planetary objects and includes aspects of geophysics, geochemistry, and cartography. Much of our knowledge of the geologic evolution of planetary surfaces is derived from remote sensing, *in situ* surface measurements, geophysical data, and the analysis of landforms, or their geomorphology, the primary subject of this book.

In this chapter, an overview of Solar System objects is given, the objectives of Solar System exploration are outlined, and the strategy for exploration by spacecraft is discussed. In the following chapters, the approach used in understanding the geomorphology of planets is presented, including the types and attributes of various data sets. The principal geologic processes operating on planets are then introduced, and the geology and geomorphology of each planetary system is described in subsequent chapters. The book ends with a discussion of future missions and trends in Solar System exploration.

1.1 Solar System overview

Our Solar System consists of a fascinating array of objects, including the Sun, planets and their satellites, comets and asteroids, and tiny bits of dust. Most of the mass of the Solar System is found within the Sun, a rather ordinary star that generates energy through nuclear fusion with the conversion of hydrogen to helium. Coupled with astrophysical models, analyses of meteorites suggest that the Solar System began to form at about 4.6 Ga (Ga is the abbreviation for giga or 10^9 *annum*, or years).

Planets are relatively large objects that are in orbit around the Sun. As we learned at a very young age, the planets are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. And then there is Pluto! The year 2006 saw an interesting controversy emerge when the International Astronomical Union (the scientific group responsible for formal naming of objects in the heavens) declared that Pluto was no longer a "planet" and demoted it to a new class of objects called "dwarf planets." This issue will be discussed later.

All of the planets originally formed through the accretion of dust and smaller objects, making **protoplanets**. As the protoplanets grew in size, still more dust and accreted materials were swept up, a process that continues even today. For example, it is estimated that more than 10,000 tons of materials are added to Earth each day. Although this addition is impressive, it is insignificant in comparison with the orders-of-magnitude larger rates of accretion in the early stages of planetary formation. In the first 0.5 Ga, so much material was amassed that the heat generated by impacts probably melted the planets completely, leading to their **differentiation**, in which the heavier elements, such as iron, sank to their interiors to form planetary cores while the lighter elements floated toward the surface.

1.1.1 The terrestrial planets

Mercury, Venus, Earth, and Mars are called the **terrestrial planets** because they share similar attributes to Earth (which in Latin is *terra*). As shown in **Fig. 1.1**, these planets are small in comparison with the other planets

[1] Terms when first used are in bold and defined. These terms are given in the index, where the page number in bold indicates where the term is defined.

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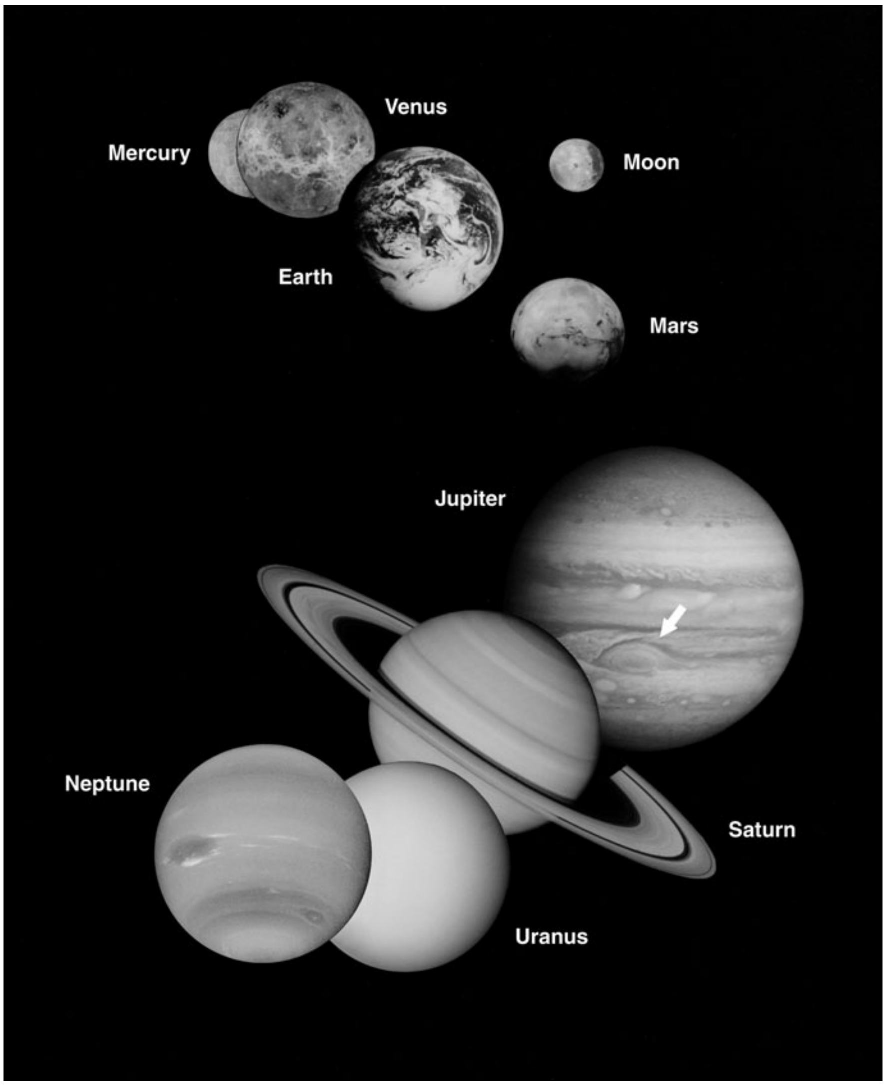

Figure 1.1. A family portrait of the planets imaged by spacecraft. The inner planets (Mercury, Venus, Earth and Moon, and Mars) are shown to scale with each other and are enlarged relative to the giant planets (Jupiter, Saturn, Uranus, and Neptune), which are shown to scale with each other. Earth is somewhat smaller than the Giant Red Spot (indicated by the arrow) of Jupiter (NASA PIA01341).

and are found closest to the Sun, leading to their alternative description as the **inner planets**. They are composed primarily of rocky material and have solid surfaces. In planetary geology, Earth's Moon is typically included with the terrestrial planets because of its large size and similar characteristics.

As the terrestrial planets began to cool and form crusts, elements combined and crystallized into rocks and minerals. For the most part, these elements are silicon, oxygen, iron, magnesium, sodium, calcium, potassium, and aluminum in various combinations that collectively make up the **silicate minerals**. The most important silicate minerals fall into two groups. Light-colored silicate minerals are common in continental rocks on Earth and include quartz, orthoclase feldspar, plagioclase feldspar, and muscovite mica. Dark-colored silicate minerals are common on Earth's sea floor and are rich in iron and magnesium; they include olivine, pyroxene, hornblende, and biotite mica. Silicate minerals are the basic building blocks of most rocks in the crusts of Earth and the Moon, and they are thought to make up most of the rocks on Mercury, Venus, and Mars.

Venus, Earth, and Mars all have significant atmospheres composed of gasses that are gravitationally bound to the planets (**Table 1.1**). Mercury and the Moon are too small to retain anything but the most tenuous atmospheres, measurable only by very sensitive instruments. Although some gasses were accumulated by all of the terrestrial protoplanets during their initial formation, these **primary atmospheres** were lost to space. **Secondary atmospheres** were later released as gasses escaped from the interior and interacted with the surface. Earth's atmosphere may be termed a **tertiary atmosphere** because it has been greatly modified by biologic processes.

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Table 1.1. **Basic data for planets**

Name	Orbit semi-major axis (10^6 km)	(AU)[a]	Revolution period (yr)	Diameter (km)	Rotation (days)	Mass (10^{24} kg)	Density (g/cm^3)	Escape velocity (km/s)	Surface	Atmosphere
Mercury	57.9	0.39	0.24	4,879	58.65	0.33	5.4	4.3	Silicates	Trace Na
Venus	108	0.72	0.62	12,104	243.0 (R[b])	4.87	5.2	10	Basalt, granite?	90 bar: 97% CO_2
Earth	150	1.00	1.00	12,756	1.00	5.97	5.5	11	Basalt, granite, water	1 bar: 78% N_2, 21% O_2
Mars	228	1.52	1.88	6,794	1.03	0.64	3.9	5.0	Basalt, clays, ice	0.07 bar: 95% CO_2
Jupiter	778	5.20	11.86	142,984	0.41	1,899	1.3	60	None	H_2, He, CH_4, NH_3, etc.
Saturn	1427	9.54	29.46	120,536	0.44	569	0.7	35	None	H_2, He, CH_4, NH_3, etc.
Uranus	2871	19.19	84.02	51,118	0.72 (R[b])	86.8	1.3	21	None (?)	H_2, He, CH_4, NH_3, etc.
Neptune	4498	30.07	164.79	49,528	0.67	102	1.8	24	None (?)	H_2, He, CH_4, NH_3, etc.
Pluto	5906	39.48	247.9	2,302	6.39 (R)	0.013	2	1.3	CH_4, ice	Trace CH_4

[a] 1 AU (astronomical unit) = Earth–Sun distance, or ~149.6×10^6 km.
[b] R = retrograde.

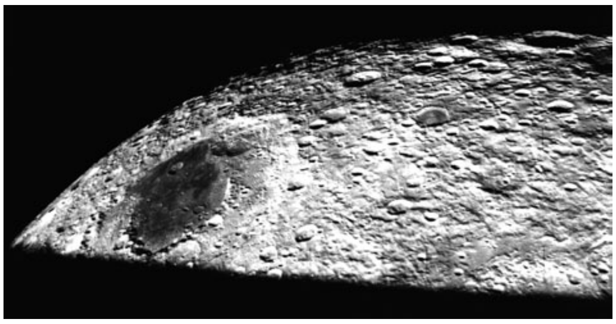

Figure 1.2. The heavily cratered surface of the Moon, shown in this view obtained by the *Apollo 13* astronauts, represents the final stages of planetary accretion in the first 0.5 Ga of the Solar System. The dark, smooth area is Mare Moscoviense on the lunar far side (NASA 70–H–700).

The presence of large impact craters on the terrestrial planets (**Fig. 1.2**) shows that their crusts had cooled and solidified in the first 0.5 Ga of Solar System history before all of the miscellaneous debris had been swept up.

1.1.2 The giant planets

Jupiter, Saturn, Uranus, and Neptune are referred to as **giant planets**. Relative to the terrestrial planets, these planets are enormous and contain most of the mass in the Solar System outside the Sun. Jupiter and Saturn are composed mostly of hydrogen and helium, while Uranus and Neptune are composed mostly of water, ices, and other volatile materials. Collectively, the giant planets and Pluto are called the **outer planets**, referring to their location in the Solar System.

The early history of the giant planets is similar to that of the terrestrial planets. The giant planets also formed by the accretion of smaller bodies, with each forming a nucleus large enough to capture the lighter elements that had escaped from the inner Solar System to the outer frigid parts of the Solar System. As this process continued, the giant planets grew to their large sizes, with heavier elements sinking to their interior. Most models of the giant planets suggest that each contains a rock-like core, some of which are larger than Mars.

Each of the giant planets resembles the Sun in composition, but not even the largest, Jupiter, was destined to grow to a size sufficient to initiate nuclear fusion. However, giant planets do resemble the Sun in one important way – each grew and evolved to have a family of smaller bodies in orbit about them so that each resembles the Solar System in miniature.

Although the giant planets have no "geology" because they lack solid surfaces, their satellites are of great interest for planetary geomorphology (**Table 1.2**). Collectively,

Table 1.2. **Basic data for selected satellites**

Planet	Satellite name	Discovery	Period (days)	Diameter (km)	Mass (10^{20} kg)	Density (g/cm^3)	Surface material
Earth	Moon	–	27.32	3,476	735	3.3	Silicates
Mars	Phobos	Hall (1877)	0.32	27	1×10^{-4}	2.2	Carbonaceous
	Deimos	Hall (1877)	1.26	13	2×10^{-5}	1.7	Carbonaceous
Jupiter	Io	Galileo (1610)	1.77	3,660	893	3.6	Sulfur, SO_2
	Europa	Galileo (1610)	3.55	3,130	480	3.0	Ice
	Ganymede	Galileo (1610)	7.15	5,268	1,482	1.9	Dirty ice
	Callisto	Galileo (1610)	16.69	4,806	1,076	1.8	Dirty ice
Saturn	Mimas	Herschel (1789)	0.94	396	0.376	1.2	Ice
	Enceladus	Herschel (1789)	1.37	504	0.74	1.10	Pure ice
	Tethys	Cassini (1684)	1.89	1,048	6.27	1.0	Ice
	Dione	Cassini (1684)	2.74	1,120	11	1.4	Ice
	Rhea	Cassini (1672)	4.52	1,528	23	1.3	Ice
	Titan	Huygens (1655)	15.95	5,150	1,346	1.9	Methane ice
	Hyperion	Bond, Lassell (1848)	21.3	360	8×10^{-3}?	?	Dirty ice
	Iapetus	Cassini (1671)	79.3	1,436	16	1.1	Ice/carbonaceous
	Phoebe	Pickering (1898)	550 (R[a])	220	0.004	?	Carbonaceous?
Uranus	Miranda	Kuiper (1948)	1.41	474	0.7	1.3	Dirty ice
	Ariel	Lassell (1851)	2.52	1,159	14	1.6	Dirty ice
	Umbriel	Lassell (1851)	4.14	1,170	12	1.4	Dirty ice
	Titania	Herschel (1787)	8.71	1,578	35	1.6	Dirty ice
	Oberon	Herschel (1787)	13.5	1,522	30	1.5	Dirty ice
Neptune	Triton	Lassell (1846)	5.88 (R[a])	2,704	214	2.0	Methane ice
Pluto	Charon	Christy (1978)	6.39	1,186	16.2	?	Ice

[a] R = retrograde.

these moons represent a myriad of objects of different sizes, compositions, and geologic histories. They are classified as **regular satellites** (orbiting in the same direction as the parent planet's spin direction) or **irregular satellites** (orbiting in the opposite direction) that are probably captured objects. Jupiter's moons Ganymede and Callisto are about the size of the planet Mercury. At least three moons, Jupiter's satellite Io, Saturn's Enceladus, and Neptune's Triton, are currently volcanically active – in fact, Io is the most geologically active object in the Solar System (**Fig. 1.3**). Other outer planet satellites appear to have remained relatively unaltered since their initial formation. Many of the geologic processes that operate on terrestrial planets are also seen on outer planet satellites; however, because of their different compositions (mostly ices, plus some silicates) and extremely cold environments, the outer planet satellites also display features representing processes unique to the outer Solar System.

1.1.3 Small bodies, Pluto, and "dwarf planets"

Asteroids, comets, and the smaller moons of the outer planets are often called **small bodies**, even though the largest asteroids are hundreds of kilometers in diameter. Comets consist of primordial material left over from the early stages of Solar System formation. Most comets are found in the **Oort cloud** and the **Kuiper belt**, both beyond the orbit of Pluto. The Oort cloud forms a spherical zone some 3×10^{12} km from the Sun and is the apparent source of long-period comets (those that take more than 200 years to complete an orbit around the Sun), while the Kuiper belt is a disk-shaped region extending from Neptune's orbit to ~8×10^{9} km from the Sun and is the source for short-period comets (those that orbit the Sun in less than 200 years). Just to make things a little more complex, objects that are in orbit in this belt are referred to as **Kuiper belt objects**, or KBOs. Some of the outer planet satellites, such as Neptune's Triton, could have been captured from the Kuiper belt.

Often described as "dirty snowballs," comets are composed of dust grains and carbonaceous (carbon-rich) materials embedded in a matrix of water-ice (**Fig. 1.4**). Study of cometary material collected from Comet Wild 2 by NASA's *Stardust* mission (Brownlee *et al*., 2006) and returned to Earth suggests that at least some comets are composed of grains that were heated in the inner Solar

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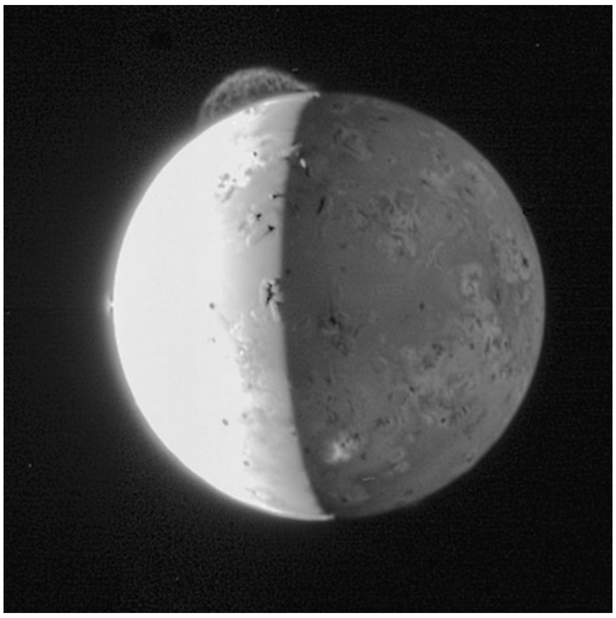

Figure 1.3. One of the moons of Jupiter, Io, is the most volcanically active object in the Solar System. This image was taken by the *New Horizons* spacecraft in 2007 during its flyby of the Jupiter system on the way to Pluto. The huge umbrella-shaped plume at the top of the image is pyroclastic material rising 290 km from the active volcano Tvashtar. Also visible (left side) is a smaller (60 km high) plume erupted from the volcano, Prometheus (NASA PIA09248).

System, were driven outward from the Sun, and then coalesced to form some comets. This led to the reference to some comets as "icy dirt balls," a concept that was supported in 2005 when the *Deep Impact* spacecraft launched a roughly half-ton metal ball into Tempel 1, a comet measuring 7.6 km by 4.9 km. The impact explosion released a plume of icy dust, suggesting the properties of freshly fallen, fluffy snow with dust. Images taken by *Deep Impact* and those taken by the NASA *NExT* spacecraft in 2011 after the impact show that Tempel 1's surface has smooth terrains and areas that have been eroded.

Most asteroids are found in the zone between the orbits of Mars and Jupiter, known as the **main asteroid belt**. However, asteroids are also found in orbits of larger planets and are called **Trojan asteroids**, while those in orbits that come close to the Earth are called **near-Earth objects**, or NEOs. Asteroids can be further classified in terms of their spectral properties and comparisons with meteorites, many of which were derived from asteroids. Historically, asteroids were thought to be either remnants of a former planet that broke apart or objects that never accreted to form a planet early in Solar System history. As with many ideas in planetary science, this was an over-simplification. It is now fairly clear that some asteroids (and the corresponding meteorites) represent fragments of a larger body that had been differentiated. Thus, "metallic" objects are thought to represent the core of a planet, while those having signatures of the mineral olivine would represent a planetary mantle, and "stony" objects would represent the crust. Other asteroids have the signatures of carbon-rich materials and are considered to represent "unprocessed," or primitive, planetary material. In this regard, many planetologists suggest that some of these types of asteroids are actually the rocky material left over from comets that have lost most or all of their volatile materials.

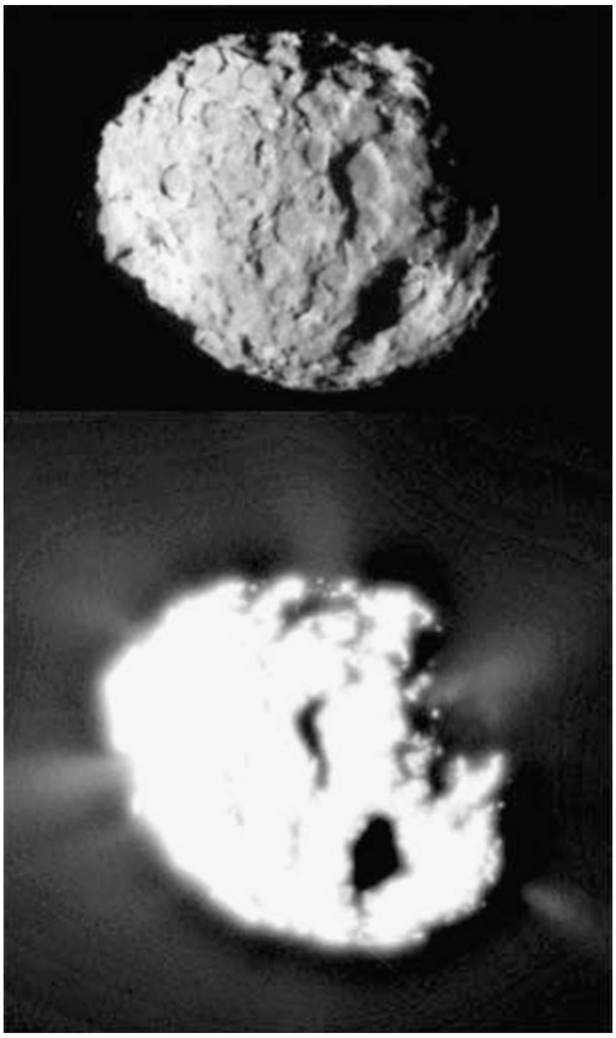

Figure 1.4. This view of the 5 km in diameter Comet Wild 2 was taken by the *Stardust* spacecraft in January 2004 (NASA *Stardust* Project).

Numerous missions have flown past, orbited, and even landed on asteroids, with one mission returning samples to Earth. The first images of asteroids up-close were taken in

Figure 1.5. The first close-up view of an asteroid was obtained by the *Galileo* spacecraft in October 1991, shown in this view of asteroid Gaspra, which is of dimensions 19 km by 12 km by 11 km. Gaspra's irregular shape suggests that it might be a piece of a larger object that fragmented from one or more collisions. More than 600 impact craters ranging in size from 100 to 500 m are visible on Gaspra's surface (NASA JPL P-40449).

1991 and 1993 by NASA's *Galileo* spacecraft in the main asteroid belt (**Fig. 1.5**) and included the discovery that asteroids could even have their own small moons. In 2003, Japan launched the *Hayabusa* spacecraft, which rendezvoused with the NEO Itokawa (**Fig. 1.6**) in 2005; the spacecraft touched down on the asteroid and collected samples that were returned to Earth in 2010 for analyses.

Pluto was discovered telescopically in 1930 and for 76 years was classified as a planet. But it does not fit neatly into either the terrestrial planet or the giant planet classification; it is relatively small and has an orbit that is substantially inclined to the general ecliptic plane and at times is inside the orbit of Neptune. In the past few decades, many more large objects have been discovered in orbit around the Sun, including Eris, which is slightly larger than Pluto. It is estimated that, as a minimum, some several dozen large objects reside within the zone of Pluto's orbit, and many hundreds could well be found in the Kuiper belt. These factors led the International Astronomical Union to "demote" Pluto as a main planet in 2006 and to define a new category, the so-called "dwarf planets," currently consisting of Pluto, Ceres (formerly classified as an asteroid), Haumea, Makemake, and Eris, some of which have one or more moons. None of these objects has been visited by spacecraft, but the

Figure 1.6. An image of the asteroid Itokawa, taken by the JAXA *Hayabusa* spacecraft, which touched down on the surface, collected samples, and returned them to Earth in the fall of 2010. This asteroid measures 535 m by 294 m by 209 m and appears to be a "rubble-pile" of boulders, the biggest of which is about 50 m across. More than 1,500 small grains were collected, and initial analyses show the presence of silicate minerals, such as olivine.

Dawn spacecraft will visit Ceres in 2014, and the *New Horizons* spacecraft is slated to fly past Pluto in 2015.

1.2 Objectives of Solar System exploration

October 1957 saw the launch of the Soviet orbiter *Sputnik* around Earth and the beginning of the "Space Age." About the size of a basketball, *Sputnik* did little more than send a "beep–beep" radio signal, but it was the starting gun for the space race. The United States responded with President Kennedy's decision to send men to the Moon before the end of the 1960s and the formation of the National Aeronautics and Space Administration, or NASA, in October 1958. Although the decision was motivated by politics and military considerations (an orbiting spacecraft has the ability to deliver warheads to any place on Earth), the National Academy of Sciences was asked to define the scientific goals for Solar System exploration. After careful consideration by a group of distinguished scientists, the principal goals were defined as determining: (1) the origin and evolution of the Solar System, (2) the origin and evolution of life, and (3) the processes that shape humankind's terrestrial environment. Although these goals have evolved over the years, the basic concepts remain the foundation for Solar System exploration.

1.2.1 Planetary geology objectives

Geologic sciences figure prominently in the goals for Solar System exploration. Basic geologic questions include the following. (a) What is the present state of the planet? (b) What was the past state of the planet? (c) How do the present and past states compare with those of other objects in the Solar System?

The question dealing with the present state seeks to determine the composition, distribution, and ages of rocks on the surface, identify active geologic processes, and characterize the interior.

Determining the past state of a planet, including Earth, is a fundamental aspect of geology and involves determining its geologic history. For example, is the present state representative of previous conditions on the planet, or has there been a change or evolution in the surface or interior? Answering these questions is typically accomplished through geologic mapping, coupled with the derivation of a stratigraphic framework and geologic time scale.

Comparative planetology addresses the third aspect in the geologic study of planets. Once the present and past states have been assessed, the results are then compared among all of the planets to determine their differences and similarities. This comparision enables a more complete understanding of geologic processes in general and of the evolution of all solid-surface objects in the Solar System.

1.2.2 Astrobiology

Are we alone? That fundamental question has been posed in various forms throughout humankind's history and constitutes one of the key motivations in the exploration of space. The term **astrobiology** was coined to encompass all aspects of the search for present and past life, including research on the conditions for the origin of life and study of the environments conducive for biological processes. The NASA Astrobiology Institute (NAI), which was formed in 1998 and is headquartered at the NASA-Ames Research Center in California, consists of an international consortium of universities and institutions conducting a wide variety of research projects in astrobiology. The NAI organizes annual spring meetings to review the latest results in astrobiology (http://nai.nasa.gov); these meetings are well attended and open to the public.

The *Viking* mission to Mars in the mid 1970s was the first project to search for life beyond Earth. Experiments for the two *Viking* landers (**Fig. 1.7**) were developed to search specifically for life-forms and to assess possible biological processes. The results from these experiments were negative, and the general search for life was out of vogue for some 20 years. However, during this period, careful considerations were given as to how astrobiology questions should be addressed. For example, when targeting specific planetary objects for astrobiology exploration, at least three factors should be considered: the presence of water (preferably in the liquid state), a source of sufficient energy to support biological processes, and the availability of organic chemistry and other elements essential for life processes (primarily carbon, nitrogen, hydrogen, oxygen, phosphorus, and sulfur). With current data, the search narrows to Mars, Jupiter's moon Europa, and possibly Saturn's moons Enceladus and Titan. If the search is expanded to include potential *past* environments, objects such as Jupiter's moon Ganymede might be included.

In 1996 a meteorite (designated ALH84001) found in Antarctica was thought to have been ejected from Mars and was suggested to show evidence for biology. Although much of this evidence has been rejected, interest in astrobiology increased substantially, especially as related to the exploration of Mars. The current search strategy focuses on identifying the present and past environments conducive for biology and is a "win–win" approach. Obviously, if life or the signs of life (e.g., fossils) are found, the result would be truly profound (**Fig. 1.8**). However, a negative result is equally intriguing; if present or past environments are found that are amenable for life, but life is not found, then one must ask why not, and what is it about Earth that would make our planet unique for life if indeed we are truly "alone?"

As the field of astrobiology has moved forward, life has been found to be much more pervasive on Earth than had previously been suspected. In recent years life-forms have been found in extreme conditions of temperature, pressure, pH, and other environmental parameters, showing that biology can occur in a much greater range of settings than previously suspected, thus widening the search for life throughout the Solar System.

1.3 Strategy for Solar System exploration

Determining the present and past states of planets and comparative planetology requires observations and measurements from orbit, placement of instruments on planetary surfaces, and the return of samples to Earth. Thus, the general exploration of the Solar System by spacecraft follows a strategy involving a series of missions of increasing capabilities. However, even before spacecraft are launched, Earth-based telescopic observations are made to determine the fundamental characteristics of

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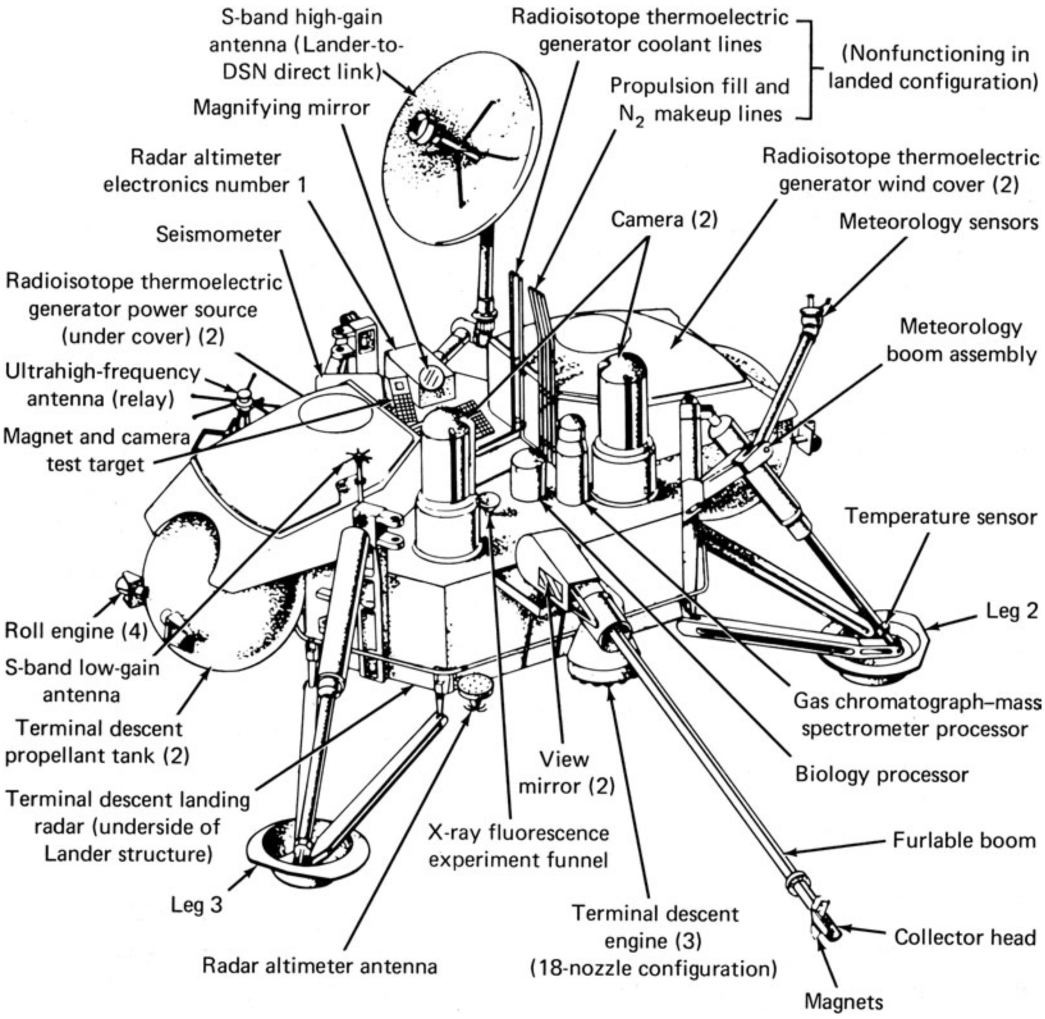

Figure 1.7. The first successful landing on Mars was the *Viking 1* lander, shown in this diagram with its principal components.

planetary objects, such as their size and density, and the presence or absence of atmospheres.

The first exploratory missions are usually “flybys,” in which spacecraft zoom past planetary objects and, over a period of only hours or a few days, collect data. Although limited, these data provide the first glimpses of the object up-close and are far better than those obtained from Earth-based telescopes. For example, in 1979 and the 1980s the spectacular *Voyager 1* and *2* spacecraft (**Fig. 1.9**) revealed the complexities of the moons of Jupiter, Saturn, Uranus, and Neptune during brief flybys of those planetary systems.

Next in exploration comes the use of orbiting spacecraft. Remaining in orbit for days, months, or even years, orbiters provide the opportunity for more complete mapping and observations of potential seasonal changes. Spacecraft in polar or near-polar orbits can obtain remote sensing data for the entire planet, enabling assessments of the surface complexity, collection of geophysical data, and measurements of topography. Thus, one of the primary advantages of orbiters is the collection of global data.

Once a planet has been surveyed from orbit, the missions that follow can include landed spacecraft. Landers enable “ground-truthing” of the remote sensing data obtained from orbit. Such data include *in situ* measurements of surface chemistry and mineralogy, determinations of the physical properties of the surface enviroment, and geophysical measurements, including seismometry. Landed missions are significantly enhanced by surface mobility as afforded by robotic systems, such as the *Mars Exploration Rovers* (**Fig. 1.10**). The advantage of

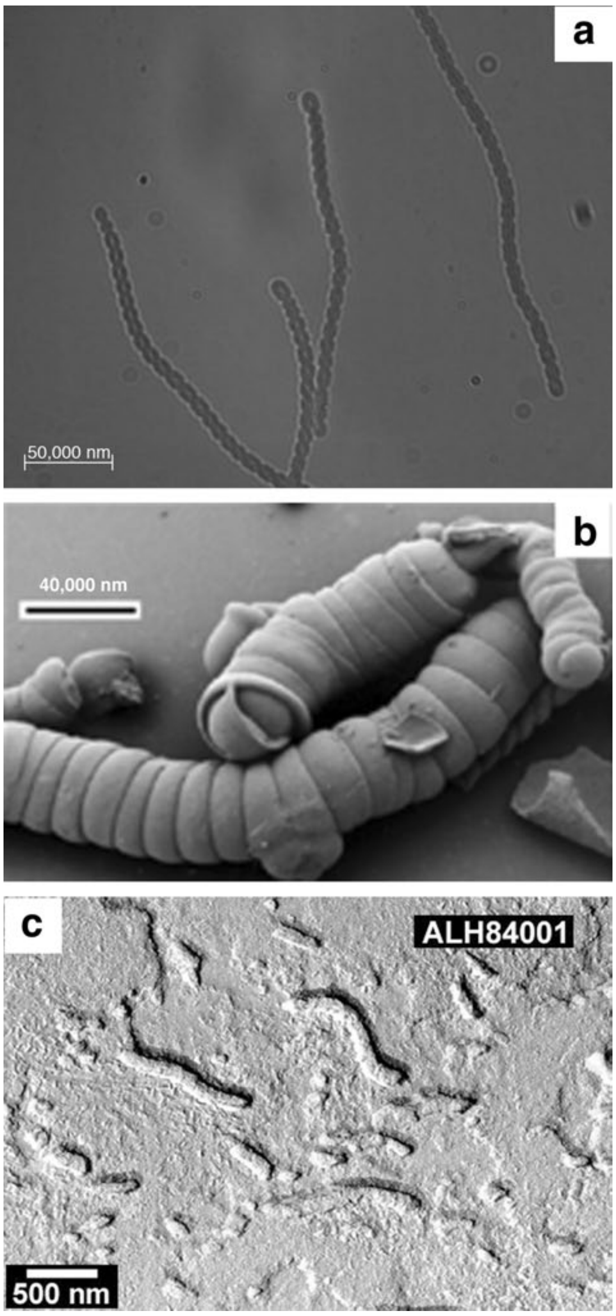

Figure 1.8. What are the signs of life that might be sought in the search for present or past life beyond Earth? From our "Earth bias," we might think that we know what fossils look like. But even on Earth, some cases are not so clear: (a) living cyanobacteria (courtesy of Jennifer Glass, Arizona State University), (b) synthetic non-biological filaments containing silica and the mineral witherite (from Garcia-Ruiz, J. M., Hyde, S. T., Carnerup, A. M. *et al.* (2003), Self-assembled silica–carbonate structures and detection of ancient microfossils, *Science*, **302**, 1,194–1,197. Reprinted with permission from the AAAS), and (c) an image of martian meteorite ALH84001 (courtesy of NASA Astrobiology Institute).

landers and rovers is the ability to obtain data directly from planetary surfaces and near-surface materials, as from drill cores, which was first done robotically by the Soviets on the Moon. The disadvantage is the relatively limited number of sites that can be visited; can you imagine characterizing the complex geology of the Earth from only a handful of stations on the surface?

Samples returned from planetary objects represent the next stage in exploration. These enable sophisticated laboratory analyses of compositions, measurements of physical properties, and searches for signs of past or present life. Although significant advances in instruments that can be applied on robotic missions have been made in recent years, none can approach the accuracy and precision afforded by full laboratory facilities on Earth. Particularly critical for geology are the ages of rocks determined on returned samples using techniques based on the decay of radioactive materials (see **Section 2.4**). While some measurements can be made from robotic spacecraft, the complexities of obtaining and properly handling samples in order to make the measurements have not been solved satisfactorily for determining ages.

The ultimate in planetary science is human exploration. Humans have the ability to analyze and synthesize data quickly, make decisions on the spot, and respond to the results. No machine can match these attributes. But, of course, sending humans into space is both risky and costly. Currently, it is far more cost-effective to send robotic spacecraft throughout the Solar System. However, the time will come when humans will be required for the ultimate step in exploration.

Figure 1.11 shows the "score-board" for the different stages of Solar System exploration. Nearby objects, such as our Moon, have been explored extensively, while most of the outer Solar System has been viewed only by flyby missions. Despite this uneven coverage, we are now well poised to address many of the fundamental aspects of the origin and evolution of the major planetary objects.

1.4 Flight projects

Getting a NASA spacecraft "off the ground" is a long process that involves many constituencies, including NASA, Congress (which appropriates the money), the aerospace industry (which builds much of the hardware),

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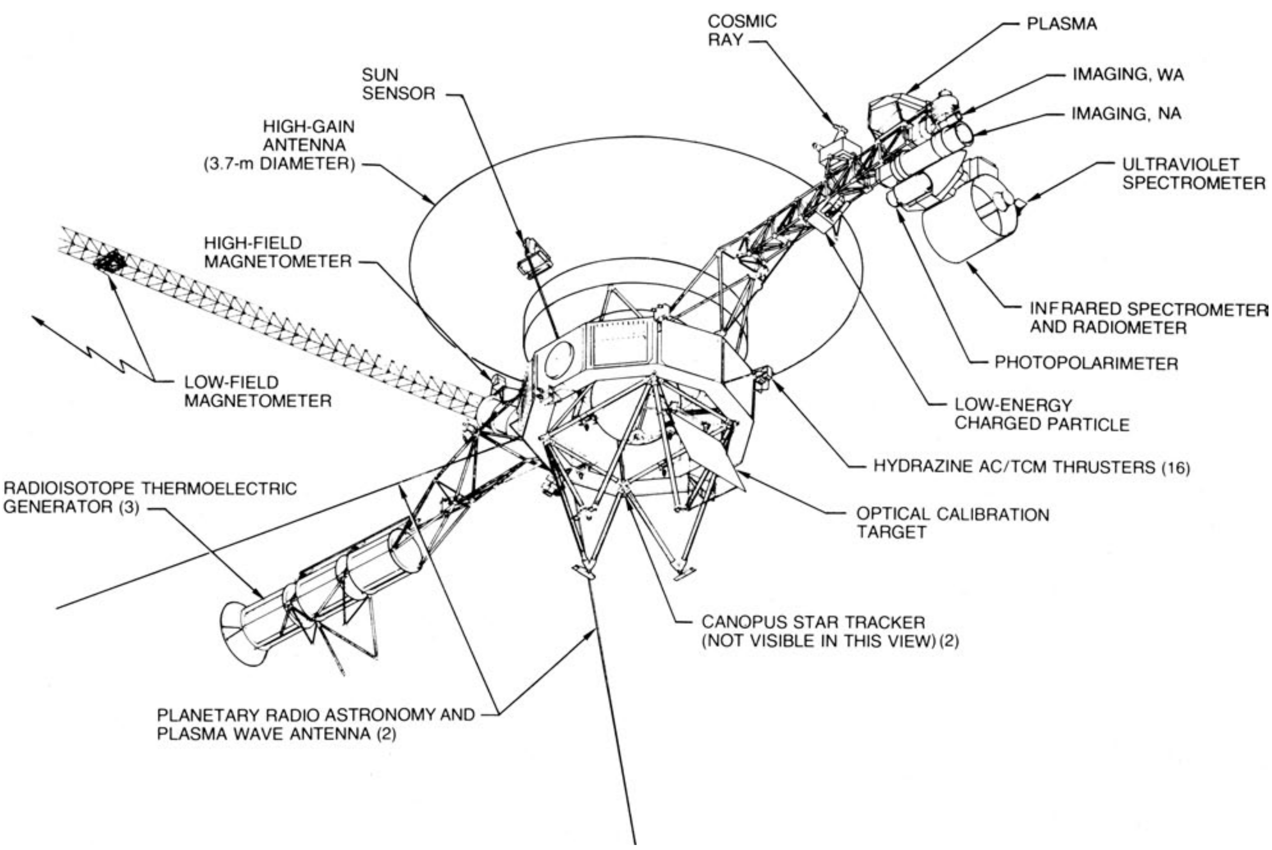

Figure 1.9. The *Voyager* project involved two spacecraft that explored the outer Solar System in 1979 and into the 1980s with flybys of Jupiter and Saturn (*Voyagers 1* and *2*) and Uranus and Neptune (*Voyager 2*), providing the first clear images of their major moons.

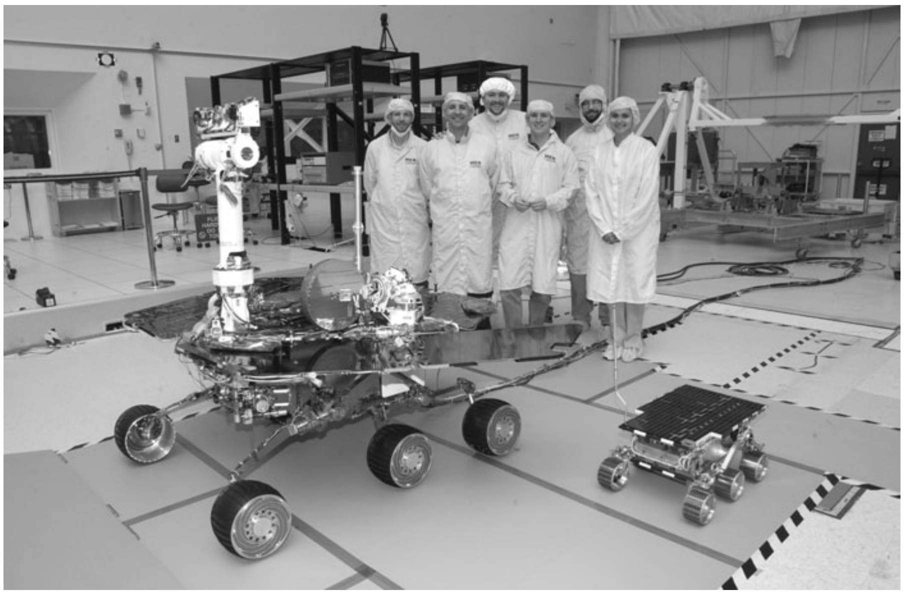

Figure 1.10. The Mars Exploration Rovers, *Spirit* and *Opportunity*, landed in early 2004. Shown here is *Spirit* before launch, compared with the flight-spare of the *Mars Pathfinder* rover on the right (NASA PIA04421).

