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Harry Y. McSween, Jr , Jeffrey E. Moersch , Devon M. Burr , William M. Dunne , Joshua P. Emery , Linda C. Kah , Molly C. McCanta
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Exploring the Solar System

We present a brief overview of the planets, moons, dwarf planets, asteroids, and comets – intended as a primer for those with limited or no familiarity with planetary science. The terrestrial planets (Earth, Mars, Venus, and Mercury) are rocky bodies having mean densities that indicate metal cores; the giant planets are composed mostly of hydrogen and helium and can be divided into gas giants (Jupiter and Saturn) and ice giants (Uranus and Neptune), based on their physical states. Small bodies, composed of rock and ices, are either differentiated or not, depending on their thermal histories. Each section of this chapter is generally organized in the historical order in which the objects have been explored by spacecraft. We will return to these bodies repeatedly in the book, focusing on understanding their geologic characteristics and materials, and the processes that produced them.

1.1 Planetary Exploration and Explorers

Planetary books traditionally begin with the Grand Tour – an obligatory traverse of the planets, in lockstep from innermost to outermost. However, that route is not how the planets have been explored. So, instead of introducing the planets in order of distance from the Sun, we will discuss planets (and moons and small bodies) in the order in which they have been meaningfully investigated by spacecraft missions. This book is all about planetary geologic processes, which are revealed through exploration.

The explorers have been national space agencies, the only institutions with the financial wherewithal to undertake these challenges. These agencies are best known by their acronyms: NASA (USA's National Aeronautics and Space Administration), ESA (European Space Agency), ROSCOSMOS (Russian State Corporation for Space Activities), JAXA (Japan Aerospace Exploration Agency), CNSA (China National Space Administration), ISRO (Indian Space Research Organization), and a few others. It is conceivable that private industry may conduct some future planetary exploration efforts, but that is not yet reality.

Spacecraft have flown rapidly by planets and small bodies, orbited them, and landed (or crashed; the euphemistic term is "lithobraking") on them, and in a few cases deposited astronauts or unmanned rovers to explore their surfaces. An assortment of flyby and orbital spacecraft is shown in Figure 1.1, and a family portrait of Mars rovers is shown in Figure 1.2. Exploration by spacecraft is complex, and large multidisciplinary (often international) teams of scientists and engineers have to work together seamlessly. Mission operations can last for decades, sometimes requiring several generations of investigators. This can be heady stuff for geoscientists used to working in isolation and on projects of limited duration.

But sometimes it is disheartening; the history of planetary exploration is littered with as many spacecraft failures as successes. Moreover, many early missions counted as successes returned little or no scientific data or were technology demonstrations. In this chapter, we focus on missions that provided the most useful data for geoscience.

1.2 Poking Around the Neighborhood: The Terrestrial Planets

The so-called **terrestrial planets** are Mercury, Venus, Earth, and Mars (Figure 1.3). Although the Moon is not really a planet, we will include it in this list. These bodies are composed of silicate rock and metal, and have solid surfaces.

All the terrestrial planets (as well as other planets) orbit within a common plane, called the **ecliptic**. This planar orientation is likely inherited from the **protoplanetary**

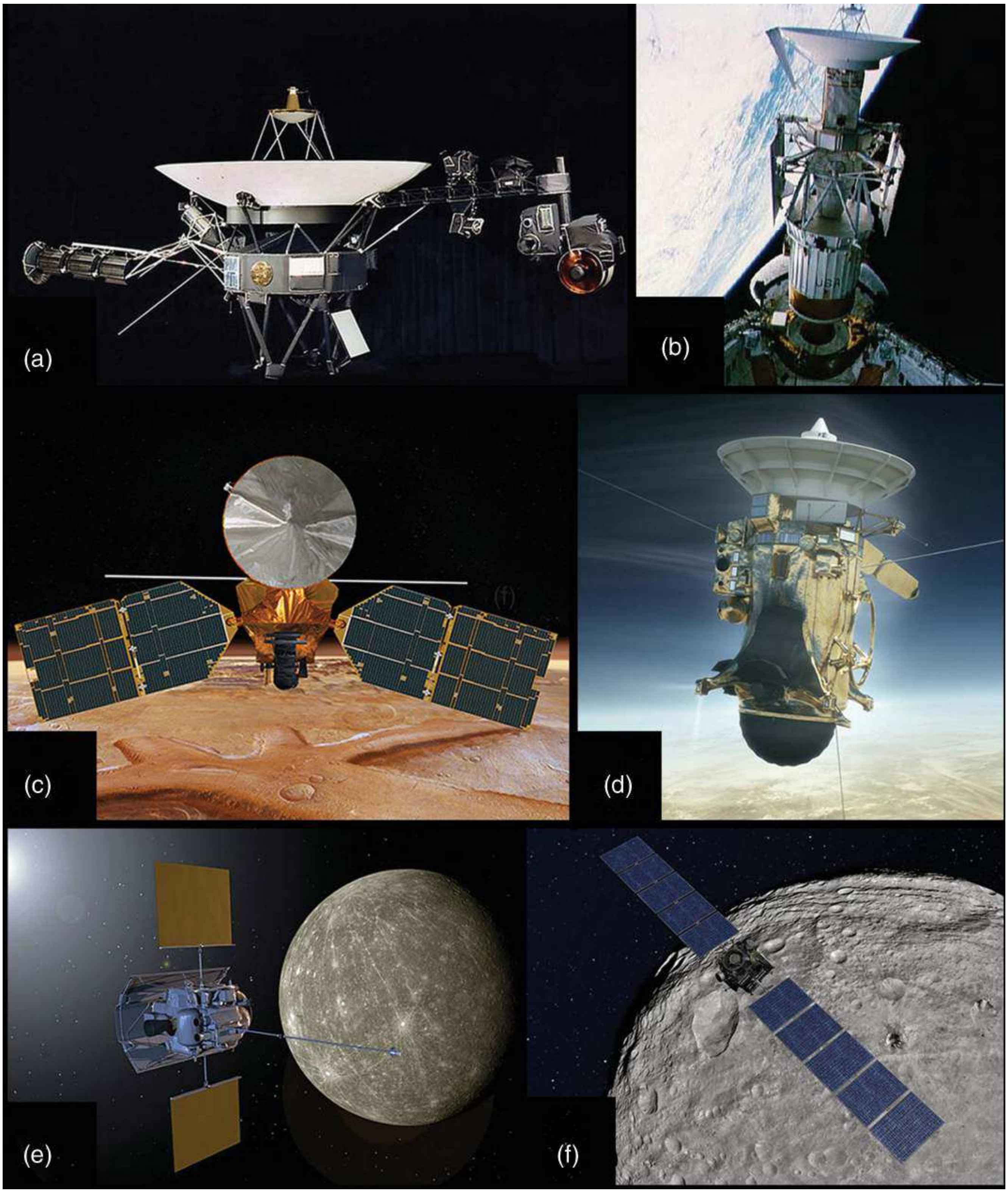

Figure 1.1 A few examples of spacecraft that have flown by or orbited planets and small bodies. (a) *Voyagers*, which conducted the first exploration of planets of the outer Solar System. (b) *Magellan*, being launched from the bay of a space shuttle, toward Venus. (c) *Mars Reconnaissance Orbiter*, mapping the red planet. (d) *Cassini*, a nuclear-powered probe that explored the Saturn system. (e) *MESSENGER*, which recently completed its exploration of Mercury. (f) *Dawn*, with solar panels needed to explore asteroids at great solar distance. NASA images.

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BOX 1.1 HOW DO WE GET THERE?

One of the great challenges of exploration by spacecraft is accommodating the combined needs of engineering and science (both can be expressed in terms of mass) versus available power (which is required for both propulsion and operations). The greatest contribution to mass is usually the propellants used to launch the spacecraft and allow it to escape the gravitational grasp of the Earth. Launch vehicles and their fuel are also commonly the most costly parts of a spacecraft mission.

The escape velocity from the Earth's surface is ~11.2 km/s, normally achieved using several rocket stages. Once the spacecraft has left our planet, we stop using the conventional velocity notation. The reason, of course, is that spacecraft do not travel to their targets in straight lines, but instead are placed into elliptical orbits around the Sun so that they spiral outward over time. The spacecraft's velocity is constantly changing, depending on where it is in its orbit, so it is more convenient to speak of ΔV (literally "change in velocity," pronounced "delta V"), a measure of the impulse needed to perform a maneuver, such as launch or insertion into a planetary orbit. ΔV is proportional to the thrust per unit mass and the burn time. Because the relative orbital positions of the planets change over time, different launch dates from Earth have different ΔV requirements; this leads to optimum "launch windows" for each target body.

Rocket engines combust stored propellant, mixed with a source of oxygen, to produce hot gas exhaust, whose expulsion through a nozzle produces thrust. The propellants are usually liquid hydrocarbons. Some spacecraft have utilized electric propulsion, expelling reaction mass (such as heavy ionized atoms) at high speeds. Spacecraft may employ several kinds of engines for use during launch, interplanetary travel, and maneuvering. Many spacecraft now utilize gravity assist – making use of the relative motion and gravity of a planet to alter the path and speed of the spacecraft as it swings by. This saves propellant and reduces mission cost.

The least costly planetary exploration missions are flybys, because they require little or no fuel for operations at the targets. Orbiters require propellant and/or tricky maneuvers that utilize atmospheric drag to slow the spacecraft for orbital insertion, as well as station keeping. Stationary landers must successfully navigate to the ground, using retrorockets, parachutes, and other means. Rovers require additional technology for traversing. The energy needed for all of these spacecraft is provided by photovoltaic solar panels that convert sunlight into electricity or by radioisotope thermoelectric generators (RTGs) that convert heat generated by decay of suitable radioactive materials into electricity. Sending spacecraft data back to Earth occurs by direct-to-Earth radio transmissions or, for landed spacecraft, relay through orbiters that can store information and send it to Earth at a later time. Radio communications are received by the Deep Space Network (DSN), a collection of large antennae located around the planet. Future interplanetary communications may be based on optical lasers.

Planetary geoscience benefits greatly from geologic samples that can be studied in the laboratory. **Sample return missions** require not only the capability to land, rove, or operate in close proximity to the target body, but also the means of acquiring and storing samples and returning them to Earth with minimal damage. Samples from bodies that could potentially harbor life must address rigorous planetary protection protocols.

disk from which the planets formed. Distances in the Solar System are measured in astronomical units (AU), equal to the distance between the Sun and the Earth. Planetary orbits are ellipses, so we describe a planet's distance as the semi-major axis of its orbital ellipse.

Some of the orbital and global characteristics of the terrestrial planets are compared in Table 1.1. Additional data are tabulated in Lodders and Fegley (1998). The tabulated **uncompressed densities** are corrected for self-compression (which is greater for larger planets with higher gravity), and they give a better indication of the relative proportions of dense metal and less dense silicate.

1.2.1 Earth's Moon

The Moon is the largest satellite, relative to the size of the planet it orbits. It rotates synchronously with the Earth, always showing the same face. The lunar surface is heavily cratered, and ejecta from the largest impact basins form the basis for its chronostratigraphy. Gravity anomalies are associated with large basins. The Moon has an ancient feldspar-rich crust ("highlands") that floated in a magma ocean, an ultramafic mantle that is the source region for younger basalts ("maria") that fill impact basins, and a small metal core. A thick veneer of pulverized rock (regolith) covers the surface. Originally thought

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Table 1.1 **Comparison of the terrestrial planets**

	Mercury	Venus	Earth	Mars	Moon
Semi-major axis	0.39 AU	0.72 AU	1.0 AU	1.50 AU	
Orbital period	0.24 yr	0.62 yr	1.0 yr	1.88 yr	27.3 d
Rotation period	58.6 d	−243 d	24 h	24.7 h	
Radius	2436 km	6051 km	6368 km	3390 km	1738 km
Mass	3.3×10^{23} kg	4.87×10^{24} kg	5.97×10^{24} kg	6.42×10^{23} kg	7.4×10^{22} kg
Mean density (ρ)	5.4 g/cm^3	5.3 g/cm^3	5.5 g/cm^3	3.9 g/cm^3	3.3 g/cm^3
Uncompressed ρ	5.3 g/cm^3	4.4 g/cm^3	4.4 g/cm^3	3.8 g/cm^3	3.2 g/cm^3
Atmosphere	~None	92 bar	1 bar	0.06 bar	None
Moons	0	0	1	2	

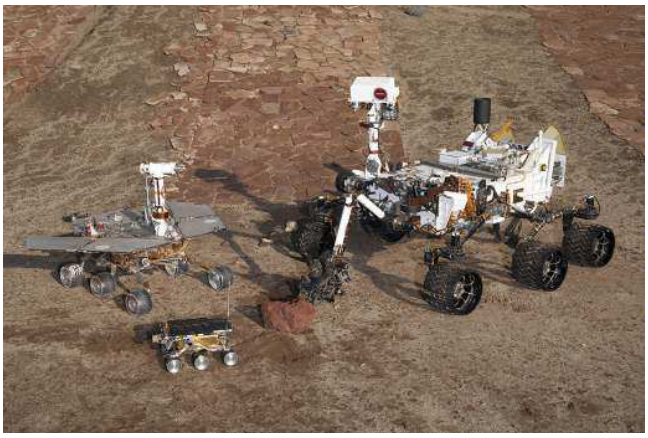

Figure 1.2 A family portrait of Mars rovers in the “Mars yard” at the Jet Propulsion Laboratory. Sojourner (*Mars Pathfinder*) in the foreground, Spirit and Opportunity (*Mars Exploration Rovers*) on the left, and Curiosity (*Mars Science Laboratory*) on the right. NASA and JPL image.

to be bone dry, recent data reveal traces of ice near the poles and of magmatic water in basalts.

The Soviet Union sent the first spacecraft to the Moon: *Luna 3* flew by the Moon in 1959 and sent back the first images of the far side. In 1966, *Luna 9* managed a controlled landing, and *Luna 10* first achieved lunar orbit. The USA also flew a number of unmanned *Surveyor* missions to different landing sites on the Moon. NASA’s *Apollo* program conducted the first geologic exploration between 1968 and 1972: *Apollo 8* and *Apollo 10* were the first manned orbital flights, and six missions beginning with *Apollo 11* in 1969 landed astronauts on the surface. These manned missions returned the first lunar samples to Earth. Also during this time, the Soviet Union conducted additional unmanned *Luna* missions with rovers that collected and returned lunar soil samples to Earth. The locations of sampling sites, mostly in mare regions, are shown in Figure 1.4. It is not exaggerating to say that

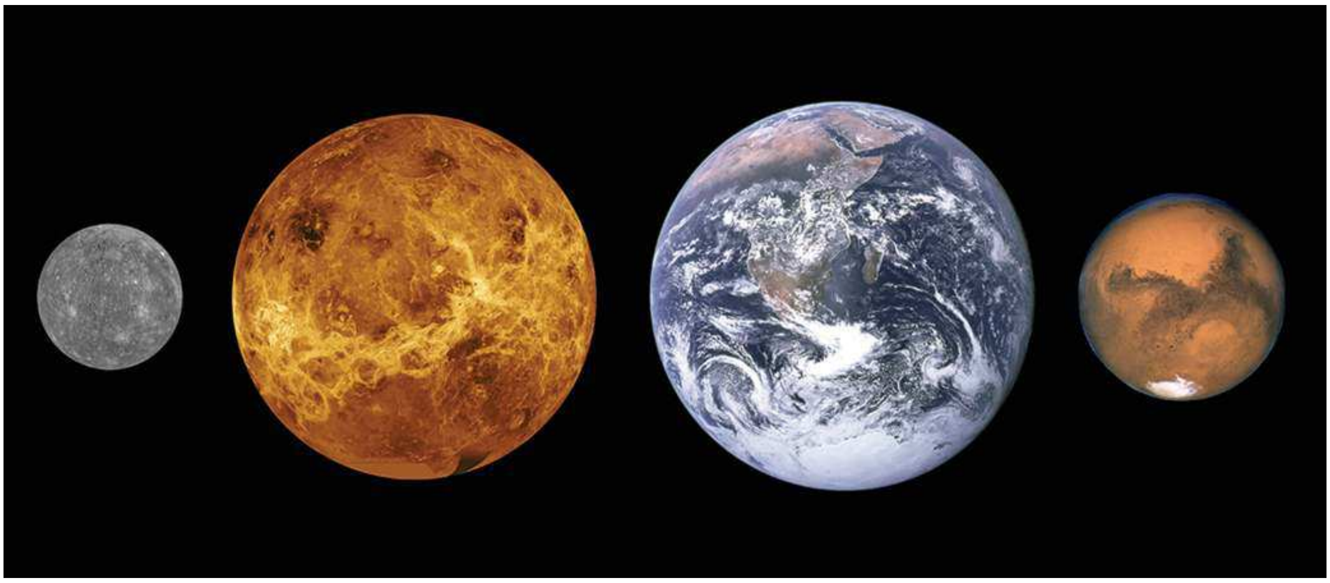

Figure 1.3 Images of Mercury, Venus, Earth, and Mars (left to right), to scale. NASA image.

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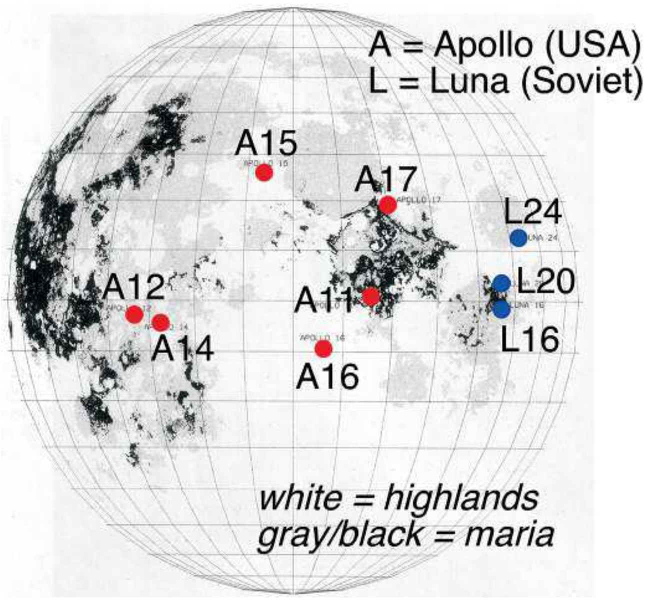

Figure 1.4 Locations on the Moon from which samples have been returned to Earth.

samples of rocks and soils returned by these missions have revolutionized lunar science.

Major milestones in lunar exploration following *Apollo* have mostly employed orbiters. NASA's *Clementine* in 1994 and *Lunar Prospector* in 1998 mapped surface compositions and potential fields. ESA's *SMART-1* in 2003, JAXA's *Kaguya* (also called *SELENE*), CNSA's *Chang'e 1* in 2007, and ISRO's *Chandrayaan-1* in 2008 performed remote sensing measurements. NASA's *Lunar Reconnaissance Orbiter* and the *LCROSS* impactor in 2009 characterized the radiation environment and potential resources, including water. In 2011, the *GRAIL* mission, consisting of two orbiters named *Ebb* and *Flow*, refined our understanding of lunar gravity. In 2013, NASA's *LADEE* studied the atmosphere and airborne dust, and CNSA's *Chang'e 3* and *4* carried rovers to the lunar surface.

1.2.2 Mars

More spacecraft missions have been sent to Mars than to any other planet. Mars is divided into ancient, heavily cratered highlands in the southern hemisphere and younger, northern lowlands. The planet has gigantic volcanoes and extensive volcanic plains, a system of huge canyons, and layered deposits containing ices at the poles. It has a basaltic crust and a metallic core, and parts of the ancient crust are magnetized. Its climate has changed over time, and early Mars had liquid water and may possibly have been habitable. Clastic and chemical sediments are widespread, and surface soils are heaped into dunes. Analyses by orbiters and rovers, as well as martian meteorites, have provided critical information on the planet's composition and history. Nowadays Mars is a windswept, dusty desert, although significant amounts of water in the form of permafrost occur in the subsurface at higher latitudes. Mars has Earth-like seasons and a thin atmosphere composed mostly of CO_2.

NASA's *Mariner 4* was the first successful flyby in 1964, and *Mariner 9* and the Soviet Union's *Mars 3* orbited Mars in 1971. NASA's *Viking 1* and *Viking 2* missions successfully deployed landers in 1975. The Viking probes analyzed soil and searched unsuccessfully for life. Beginning in 1996, NASA's *Mars Global Surveyor* mapped the composition of the planet's surface from orbit. *Mars Pathfinder* landed in the same year, deploying its Sojourner rover. NASA's *Mars Odyssey*, launched in 2001, and ESA's *Mars Express*, launched in 2003, obtained orbital images and spectra to understand surface geology and a radar sounder to probe the subsurface. The *Mars Exploration Rovers* Spirit and Opportunity landed in 2004 and conducted extensive science traverses for far longer than their designed lifetimes. In 2005, NASA's *Mars Reconnaissance Orbiter* began conducting remote-sensing measurements, and *Phoenix* landed near a pole and probed for ice. The *Mars Science Laboratory* Curiosity rover has explored the geology of an ancient lakebed since 2012. ISRO's *Mangalyaan* and NASA's *MAVEN*, both launched in 2013, are studying the martian atmosphere. The *Trace Gas Orbiter*, a collaboration between ESA and ROSCOSMOS, began atmospheric mapping in 2018, searching for methane and other minor gases. *InSight*, which landed in 2018, will study Mars' interior structure and heat flow. NASA's *Mars-2020* rover and ESA's *ExoMars* rover will land in 2020; *Mars-2020* will cache rock and soil samples for possible return to Earth as an international effort later in that decade, and *ExoMars* will search for organic compounds in the martian subsurface.

1.2.3 Venus

Venus is sometimes called Earth's sister because of its similar size and mass, but it rotates in the opposite direction from most planets. It has a dense atmosphere, mostly of CO_2, causing its surface to be blisteringly hot, with a mean temperature of 735 K. These hostile conditions and an obscuring shroud of clouds make exploration difficult. Radar imagery indicates that the surface is mostly smooth volcanic plains, but with two highlands regions. Volcanic features occur nearly everywhere and volcanism may be ongoing. The thick atmosphere screens out small impactors, and global resurfacing may have removed larger craters. Venus has a large metal core similar to Earth's, but no magnetic field. It has lost its

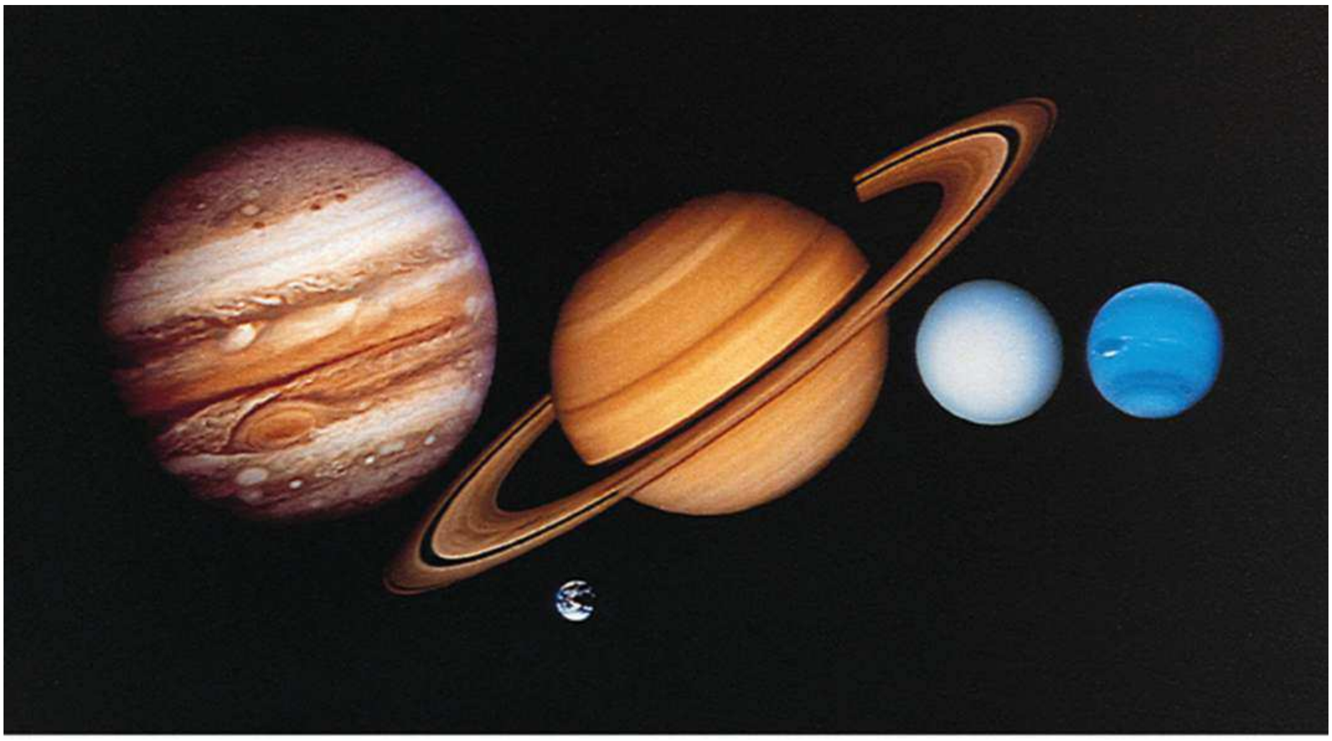

Figure 1.5 Images of Jupiter, Saturn, Uranus, and Neptune (left to right), with Earth (below Saturn) for scale. NASA images.

water, making its crust too strong to allow plate tectonics, which hampers heat loss.

NASA's *Mariner 2* in 1962, followed by *Mariner 5* in 1967, flew by Venus and probed the atmosphere and magnetic field. Between 1969 and 1983, the Soviet Union's *Venera* program sent numerous orbiters that analyzed the atmosphere and landers that imaged and measured the chemistry of surface rocks. Beginning in 1978, NASA's *Pioneer Venus Orbiter* conducted atmospheric experiments and made radar maps of the surface. Two *Vega* missions in 1984 continued the Soviet program of orbital and landed measurements. NASA's *Magellan* mission in 1990 provided global radar maps of the planet's surface. ESA's *Venus Express* operated from 2006 to 2014, observing atmospheric dynamics and the magnetic field.

1.2.4 Mercury

Mercury, the smallest and innermost planet, rotates three times for every two revolutions around the Sun – that is, it is in a spin–orbit resonance. Its high density indicates a huge metallic core that generates a magnetic field. Its surface is heavily cratered and covered with volcanic plains, making it appear almost lunar-like and indicating that geologic activity has ceased. Compression features reveal global shrinkage of the planet. Mercury's proximity to the Sun and lack of an atmosphere cause surface temperatures to vary wildly (between 100 and 700 K at the equator, daily).

Only two NASA spacecraft missions have made close observations of Mercury. *Mariner 10* flew past the planet three times in 1974 and 1975, and imaged less than half the surface. It also detected Mercury's magnetic field – a surprise since Mercury rotates so slowly. *MESSENGER* made passes in 2008 and 2009 before achieving orbit in 2011. It collected data until 2015, when it was allowed to crash into the surface. Its camera completed imaging of the whole surface and spectrometers characterized its chemical composition. In addition to studying its geologic history, the spacecraft quantified the size and state of the core and the magnetic field. *BepiColumbo* is actually two orbiters, one provided by ESA for surface imaging and one provided by JAXA for analyzing the magnetic field. It launched in 2018, although it will not reach Mercury's orbit until 2024.

1.3 Xenoplanets: Gas Giants and Ice Giants

The **giant planets** (Figure 1.5) are foreign to our geologic experience. They are commonly referred to as **gas giants**

Table 1.2 **Comparison of the giant planets**

	Jupiter	Saturn	Uranus	Neptune
Semi-major axis	5.2 AU	9.5 AU	19.2 AU	30.0 AU
Orbital period	11.9 yr	29.5 yr	84.0 yr	164.8 yr
Rotation period	10.0 h	10.2 h	17.2 h	16.1 h
Radius	71,400 km	60,270 km	25,600 km	24,750 km
Mass	1.90×10^{27} kg	5.68×10^{26} kg	8.68×10^{25} kg	1.02×10^{26} kg
Mean density (ρ)	1.33 g/cm^3	0.69 g/cm^3	1.27 g/cm^3	1.64 g/cm^3
Moons	69 + rings	62 + rings	27 + rings	14 + rings

(Jupiter and Saturn) and **ice giants** (Uranus and Neptune), depending on whether they are predominately composed of hydrogen and helium gas or of water, ammonia, and methane ices, respectively. The term "gas giant" is misleading, as their constituents are above the critical point and thus there is no distinction between gas and liquid. High pressures in the interiors of the ice giants transform ices into dense structures not seen elsewhere. Some orbital and global characteristics of the giant planets are given in Table 1.2.

1.3.1 Jupiter

The mass of Jupiter is about 2.5 times the mass of all the other planets combined. Its rotation, taking only about ten hours, is the fastest of the planets. It consists mostly of hydrogen and helium, and has no solid surface. The outer atmosphere is segregated into horizontal bands and has hurricane-like storms. Jupiter is thought to have a core of silicate rock and metal, surrounded by a mantle of dense metallic hydrogen extending out to 78 percent of the planet's radius. Above this is a layer of supercritical hydrogen and helium, which grades upward into the gaseous atmosphere. Jupiter has a strong magnetic field, generated by currents in the metallic hydrogen layer.

A number of spacecraft have flown by Jupiter, most en route to other targets, and obtained images and other data. NASA's *Pioneer 10* in 1973 and *Pioneer 11* in 1974 refined estimates of the planet's mass. NASA's iconic *Voyager 1 and 2* arrived five years later. These spacecraft focused on the geology of Jupiter's moons, and also discovered the existence of rings. Other flybys include *Ulysses* in 1992 and 2004, *Cassini* in 2000, and *New Horizons* in 2007.

The first mission to orbit Jupiter was NASA's *Galileo*, arriving in 1995 and operating for eight years. Besides investigating the Galilean moons on multiple passes and observing the impact of a comet onto Jupiter, it released a probe that parachuted through 150 km of Jupiter's atmosphere before it was crushed by the increasing pressure. NASA's *Juno* orbiter arrived in 2016 and is now measuring Jupiter's composition, as well as its gravity and magnetic fields.

1.3.2 Saturn

Like Jupiter, Saturn has a core of rock and metal, surrounded by metallic hydrogen, overlain by supercritical hydrogen and helium, and finally a gaseous atmosphere. Its pale yellow color is due to ammonia crystals in the atmosphere. Its magnetic field is much weaker than Jupiter's, and its mean density is less than that of water. Saturn's most prominent feature is, of course, its rings. These extend outward to 120,700 km from the equator, but are only about 20 m thick. The ring particles, ranging in size from dust to boulders, consist of water ice crystals with small amounts of organic and amorphous carbon.

Saturn was visited by *Pioneer 11* in 1979, *Voyager 1* in 1980, and *Voyager 2* in 1981. During flybys, these spacecraft imaged the rings and moons. The *Cassini* spacecraft, a collaboration between NASA and ESA, entered Saturn's orbit in 2004. This mission provided high-resolution images of the planet and its rings, and made significant discoveries about its moons. The mission ended in 2017, as the spacecraft plummeted into Saturn.

1.3.3 Uranus

Uranus is the least massive of the giant planets, although its diameter is slightly larger than Neptune's. It has a magnetic field, a ring system, and moons. It appears nearly featureless in visible light. Its rotation axis is tilted sideways, nearly into the ecliptic plane, so only a narrow strip near the equator experiences a day–night cycle and each pole receives 42 years of continuous sunlight followed by 42 years of darkness. Uranus is composed mostly of water, ammonia, and methane ices, along with other hydrocarbons. Underlying its icy mantle is a small core of silicate rock and metal. An overlying aquamarine-colored atmosphere is mostly hydrogen and helium, with methane as a coloring agent.

The only spacecraft to visit Uranus was *Voyager 2*, which flew by in 1986. It analyzed the composition and structure of the atmosphere, the magnetic field, and observed its moons and rings.

1.3.4 Neptune

Neptune is the densest giant planet. Its atmosphere is composed mostly of hydrogen and helium, with small

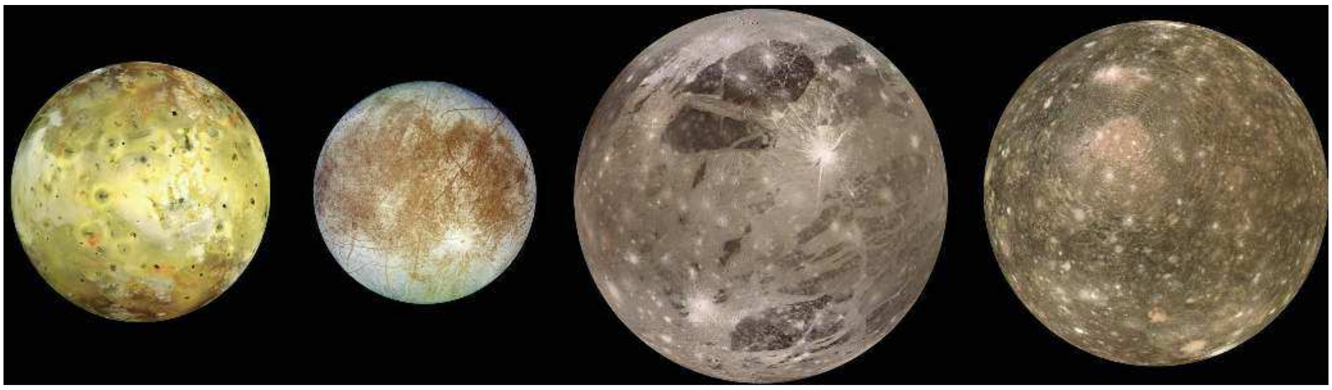

Figure 1.6 Images of the Galilean moons of Jupiter: Io, Europa, Ganymede, and Callisto (left to right), to scale. NASA images.

amounts of hydrocarbons and possible nitrogen. As for Uranus, traces of methane account for the planet's blue color. Unlike Uranus, however, its atmosphere has active weather patterns. The outer gas envelope grades downward into ices of water, ammonia, and methane. Below that is a core of silicate rock and metal. Neptune's magnetic field is strongly titled relative to its rotation axis.

Voyager 2 has been Neptune's only visitor, passing by in 1989 on its way out of the Solar System. The spacecraft imaged Neptune and its rings, measured the orientation of the magnetic field, and discovered a number of satellites. Because of its extreme distance and the dearth of exploration missions, much of what we know about Neptune (and Uranus) is based on observations using the Hubble Space Telescope and large Earth-based telescopes with adaptive optics.

1.4 The Most Interesting Moons

The giant planets themselves are not very amenable to geologic investigation, since they have no solid surfaces. However, their satellite systems are like miniature Solar Systems, and these moons can be studied using the same geologic tools that we apply to the terrestrial planets.

The numbers of moons for each giant planet are given in Table 1.2. There are far too many to describe here, and we know very little about most of them anyway. Instead, we will focus on the largest and most geologically interesting of the moons of Jupiter, Saturn, and Neptune; none of the moons of Uranus are particularly noteworthy, at least at our present level of ignorance.

1.4.1 Galilean Moons of Jupiter

The four largest satellites of Jupiter, collectively called **Galilean moons** after their discoverer, are Io, Europa, Ganymede, and Callisto (Figure 1.6). All are massive enough to have adopted nearly spherical shapes. The largest, Ganymede, has a diameter (5268 km) greater than Mercury. Io, Europa, and Ganymede are in a 4:2:1 orbital resonance with each other. All lie within the radiation and magnetic fields of Jupiter, making exploration difficult.

Io has the highest density (3.5 g/cm^3) of the Galilean satellites, as the others have significant amounts of ice. It is a differentiated body composed of silicate rock, with a core of molten iron or iron sulfide. Its surface features more than 400 volcanoes, and so many of these are currently erupting that it qualifies as the most geologically active body in the Solar System.

Europa has a smooth (at global scale) and bright surface composed of ice. Reddish brown markings crisscross its tectonically active surface, and the occurrence of only a few craters testify to resurfacing. Below the icy crust is a salty ocean that has been hypothesized to be a possible abode for life, making Europa a high-priority target for further exploration. The interior of Europa is rock and likely a metallic core.

Ganymede is also believed to have a briny ocean, sandwiched between layers of ice. Below that is a mantle of rock and a core of iron. The icy surface of Ganymede is separated into dark, highly cratered (hence older) terrains and brighter, younger regions with grooves and ridges.

Callisto is the least dense (1.83 g/cm^3) of the Galilean moons, with approximately equal amounts of ice and rock. It too may harbor a subsurface ocean. Its icy crust shows some tectonic features and numerous impact scars.

Pioneer 10 and 11 obtained low-resolution images of the moons when they flew past Jupiter in 1973 and 1974. In 1979, *Voyager 1 and 2* discovered volcanic eruptions on Io and a disrupted icy crust on Europa. The *Galileo* orbiter, arriving in 1995, made close approaches to the moons and found evidence for possible subsurface oceans on the outer three bodies. The *Cassini* probe in 2000 and *New Horizons* in 2007 flew by and made observations of the moons' orbital interactions with Jupiter. In 2016, *Juno*