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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.

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

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	

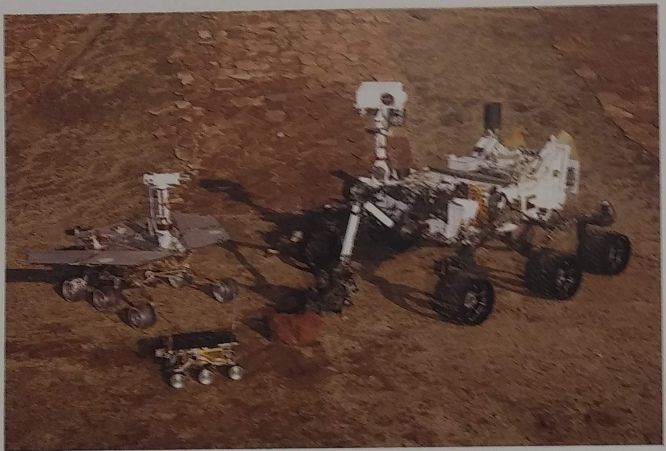

Figure 1.2 A family portrait of Mars rovers in the "Mars yard" at the Jet Propulsion Laboratory. Sojourner (*Mars Pathfinder*) in the foreground, Spirit and Opportunity (*Mars Exploration Rovers*) on the left, and Curiosity (*Mars Science Laboratory*) on the right. NASA and JPL image.

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.

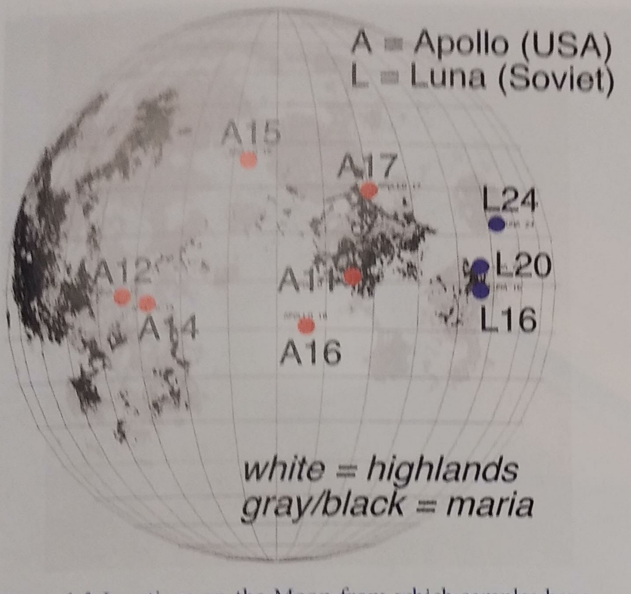

Figure 1.4 Locations on the Moon from which samples have been returned to Earth.

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

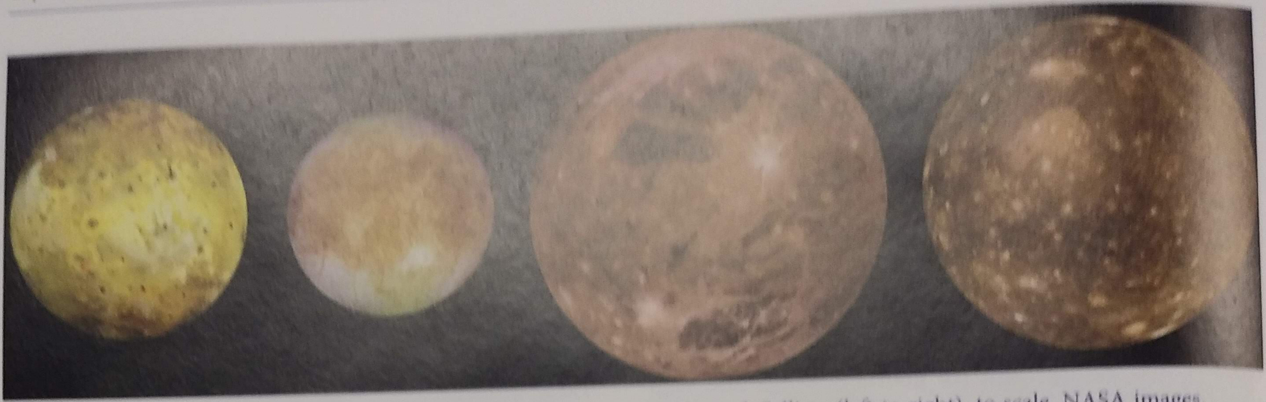

Figure 1.6 Images of the Galilean moons of Jupiter: Io, Europa, Ganymede, and Callisto (left to right), to scale. NASA images.

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* imaged the moons from above their orbital plane and made a movie of their motions.

1.4.2 Titan and Enceladus of Saturn

Titan (Figure 1.7), with a diameter of 5150 km, is the second largest moon in the Solar System, and perhaps the oddest. Its density (1.88 g/cm^3) suggests it is half ices and half silicate rock. This frigid world is characterized by a dense, hazy atmosphere composed of nitrogen, with clouds of methane and ethane and organic smog. Titan's surface is young and has only a few craters. Valleys and channels appear to have been cut by flowing organic liquids. Rocks and sand composed of frozen organic matter litter its surface. It also has lakes of organic liquids, and may have a subsurface ocean.

Enceladus (Figure 1.7) is small (508 km diameter) but nearly spherical. Its density (1.61 g/cm^3) indicates that it is a mixture of ice and rock. Its icy surface includes cratered terrains, as well as smooth areas with few craters. Long fracture systems are warm and emit jets of gas and dust. The eruptions may emanate from a subsurface ocean of water.

Voyager 1 and 2 in 1980 and 1981 obtained images of Titan and Enceladus. *Cassini*, arriving at Saturn in 2004, studied both bodies in detail. It made a number of Titan flybys, discovering hydrocarbon lakes in 2006. Cassini also released its *Huygens* probe, provided by ESA, which descended to the surface in 2005. The probe made measurements of the composition of Titan's atmosphere and took images of the surface. The *Cassini* orbiter also discovered the geyser-like eruptions on Enceladus.

1.4.3 Triton of Neptune

Triton (Figure 1.7), the largest moon of Neptune (2710 km diameter), has a retrograde orbit. Its surface is covered with a transparent layer of frozen nitrogen, over a crust of N_2, H_2O, and CO_2 ices, with an icy mantle and rocky core. Its mean density (2.06 g/cm^3) suggests ices comprise more than one-third of the body's mass. It has few impact craters, suggesting a young, active surface. A handful of geysers of nitrogen gas and dust have been observed erupting. The western hemisphere is called cantaloupe terrain, referring to its resemblance to that melon's skin. Other areas of the surface are furrowed plains formed by icy volcanic flows. Triton's retrograde motion and Pluto-like composition suggest that it is a captured body from the Kuiper belt (see Section 1.5).

Triton was deemed so interesting that *Voyager 2*'s trajectory was altered to allow its investigation. It imaged 40 percent of Triton's surface and measured its chemical composition.

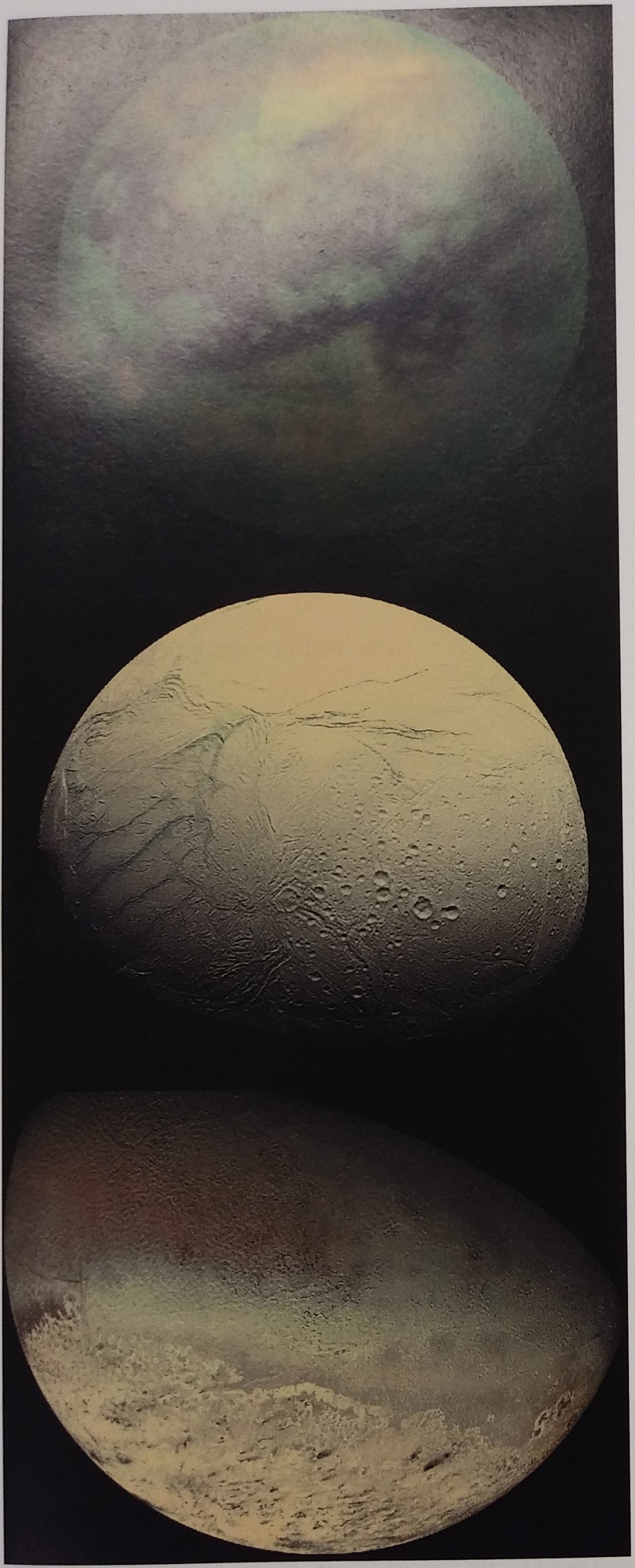

Figure 1.7 Images of the largest moons of Saturn and Neptune: Titan, Enceladus, and Triton (top to bottom), not to scale. Titan is shown in an infrared image to see through its hazy atmosphere. Blue stripes on Enceladus are fractures from which jets erupt. Triton shows distinctive terrains. NASA images.

1.5 Small Bodies, Big Rewards

The Solar System contains millions of smaller bodies orbiting the Sun; their small sizes belie their scientific importance. The largest of these are the **dwarf planets**. This term was adopted by the International Astronomical Union in 2006, and identifies objects that orbit the Sun, are massive enough for their gravity to have pulled them into a spheroidal shape, but have not cleared their orbital neighborhoods of other objects. Using this definition, Pluto was demoted from its prior designation as the ninth planet, and Ceres was promoted from its status as the largest asteroid. Three other currently recognized dwarf planets, located well beyond the orbit of Pluto, are Haumea, Makemake, and Eris. There are sure to be many more. The designation of dwarf planets remains somewhat controversial, and certainly does not recognize the role of geologic activity in planets.

Smaller bodies are designed as **asteroids** (the name means "star-like") and **comets** (from the Greek for "long hair," alluding to their prominent tails). Asteroids have conventionally been defined as rocky or metallic bodies, and comets are recognized by "cometary activity," referring to the release of gas and dust that form a bright coma and tail when ices are sublimated by solar heating. In recent years, the distinction between asteroids and comets has become blurred, because volatile eruptions have been seen on a few asteroids and some kinds of asteroids are known to contain or to have formerly contained ice and probably exhibited cometary activity in the distant past.

Before describing the exploration of these objects, we need to talk about their orbits. Most asteroids reside either in the **Main asteroid belt**, a band more than 30 million kilometers wide located between the orbits of Mars and Jupiter, or at **Lagrange points** around Jupiter (Figure 1.8). A Lagrange point is a position in the orbital configuration of two large bodies, in this case the Sun and Jupiter, where a small body, say an asteroid, can maintain a stable position. Asteroids orbiting Jupiter's L_4 and L_5 points (respectively located ahead and behind Jupiter in its orbit; Figure 1.8) are called Trojans. Centaurs are asteroids located between the outer planets, generally in unstable orbits.

Beyond Neptune lies the **Kuiper belt**, containing more than 1000 known objects and thought to have more than 100,000 objects larger than 100 km in size. The potential to discover so many planets in the Kuiper belt is what led to the designation of dwarf planets. Pluto is the innermost Kuiper belt object. Far beyond the Kuiper belt lies the **Oort cloud**, a theoretical, spherical collection of volatile-rich objects. Small fragments of Kuiper belt and Oort cloud objects perturbed into the inner Solar System become comets.

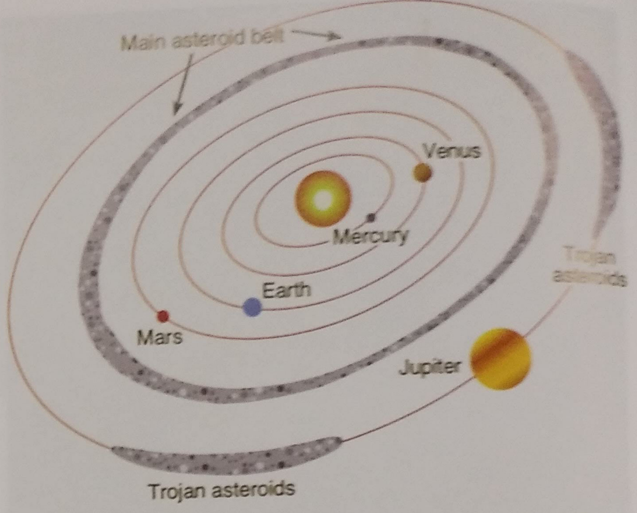

Figure 1.8 Birds-eye view of the Solar System, showing asteroids in the Main belt and Trojan asteroids in Lagrange points around Jupiter.

1.5.1 Dwarf Planets: Ceres and Pluto

Ceres (Figure 1.9) is the first dwarf planet to be encountered by spacecraft, although Neptune's moon Triton (already described in Section 1.4) probably qualifies as a captured dwarf planet in terms of its size. Ceres is located within the Main asteroid belt, and was the first body discovered in that region. It has a diameter of 945 km and is partially differentiated, with a rocky core, altered rock mantle, and icy crust. The mineralogy of the surface consists of hydrated and ammoniated phyllosilicates and carbonates. Although most of its surface is ancient and heavily cratered, a cryovolcano formed recently, suggesting brines exist in the interior.

Pluto (Figure 1.9) is in orbital resonance with Neptune, but its orbit is inclined relative to the ecliptic. It has five moons, with Charon having a diameter just over half that of Pluto, whose diameter is 2380 km. Its density (1.86 g/cm^3) indicates a rocky core, and it likely hosts a subsurface ocean of liquid water. Its crust is composed mostly of nitrogen ice, with traces of methane and carbon monoxide. Its color varies from white, to orange, to black. The surface is virtually uncratered, indicating a very young age. It has mountains (possible volcanoes), and many landforms appear to be glacial in origin.

NASA's *Dawn* spacecraft studied Ceres from orbit during 2015–2018. Its spectrometers mapped the body's mineralogy and chemistry, its camera allowed studies of its geomorphology, and tracking of the spacecraft's orbit allowed the gravity and interior structure of Ceres to be

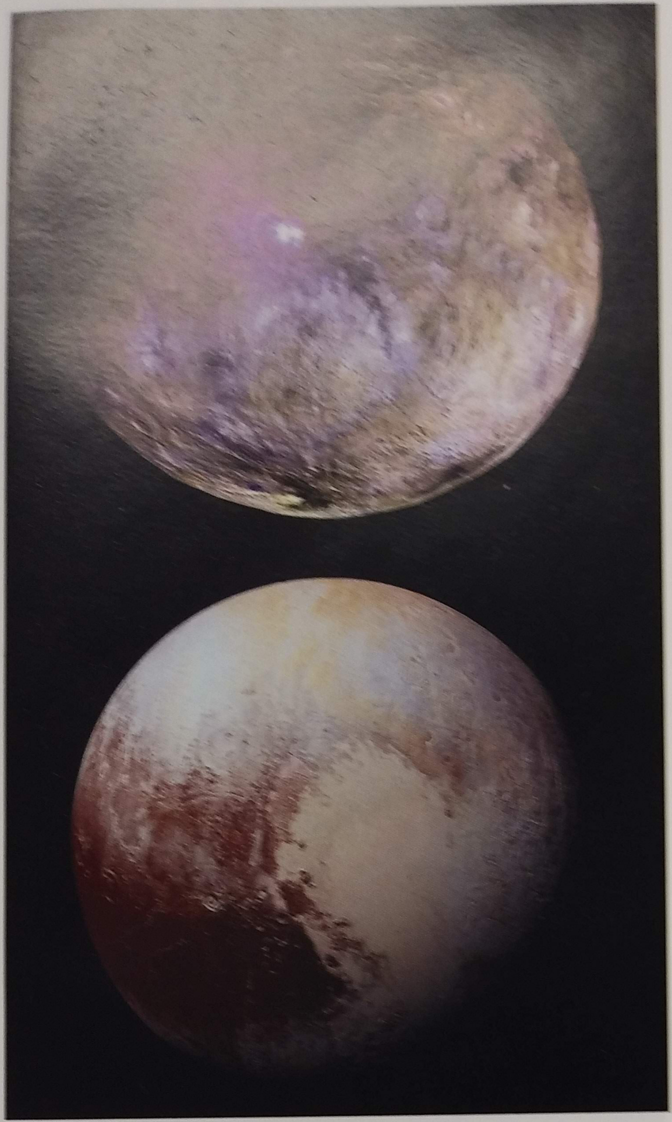

Figure 1.9 Dwarf planets visited by spacecraft: Ceres (top), showing bright spots of carbonate salts in a crater; and Pluto (bottom), showing terrains with distinctive coloration. Colors in both images are enhanced, and the images are not to scale. NASA images.

analyzed. NASA's *New Horizons* flew by Pluto in 2015 and returned images, chemical analyses, and other data. In 2019 it imaged a small icy body, and it is now en route to a body deeper within the Kuiper belt.

1.5.2 Asteroids

More than half of the mass of the Main belt is contained within the four largest bodies: Ceres (now a dwarf planet), Vesta, Pallas, and Hygia. Only a few large asteroids are thought to be intact, and many thousands of smaller asteroids are collisional rubble. Many of these are members of families that have similar orbital parameters and were once parts of the same larger object. Despite popular movies that show spacecraft dodging asteroids as they race through the Main belt, the average spacing between asteroids is actually about three million kilometers.

Asteroid science benefits greatly from spectroscopy using ground-based telescopes, and from analyses of the thousands of asteroid samples that have fallen to Earth as meteorites. By comparing an asteroid's spectrum with laboratory spectra of meteorites, we can infer its mineral composition and thereby determine the kinds of rocks on its surface. Meteorite analyses also document the inorganic and organic chemistry of asteroids, and allow us to infer their geologic histories.

The best-studied asteroid is Vesta, a 500 km diameter rocky body with a large metal core. It is the parent body for more than 1000 meteorites: basalts, ultramafic rocks, and impact breccias formed from mixtures of those rocks. A huge and rather recent impact basin on Vesta is thought to have excavated these meteorites. Vesta's magmatic differentiation is apparent from its igneous rocks and high density ($3.42\,g/cm^3$), indicating the presence of a core, and its heavily cratered surface reveals its ancient age.

A number of small asteroids have been imaged by spacecraft (some are shown in Figure 1.10). The irregular shapes of these bodies indicate their fragmentation during collisions. The only ones whose compositions have been well analyzed so far are Eros and tiny Itokawa, both ordinary chondrites.

Spacecraft missions that have flown by asteroids, beginning in 1991, include *Galileo*, *NEAR Shoemaker*, *Hayabusa*, *Rosetta*, and *Chang'e 2*. In 2000, NASA's *NEAR Shoemaker* became the first mission to orbit an asteroid (Eros), and it ended its mission by gently landing on the surface. JAXA's *Hayabusa* orbited asteroid Itokawa in 2005. It intended to collect a soil sample, but the sampling mechanism failed; nevertheless, dust particles on the spacecraft became the first returned asteroid sample. NASA's *Dawn* orbital exploration of Vesta in 2011 is the most exhaustive asteroid exploration to date. *Hayabusa2* orbited asteroid Ryugu in 2018. NASA's *OSIRIS-REx* arrived at asteroid Bennu in 2018 and is expected to return samples in 2023.

1.5.3 Comets

Comet **nuclei** (Figure 1.11) are popularly called dirty snowballs, reflecting the fact that they are mixtures of rock and ice (mostly water and carbon monoxide), along with abundant organic compounds. Their measured densities are $0.6\,g/cm^3$ or less. Inside their bright comae, the comet nuclei are as dark as black velvet. Their surfaces are coated with lag deposits of dust. The surfaces of irregularly shaped comets are constantly changing as solar warming causes

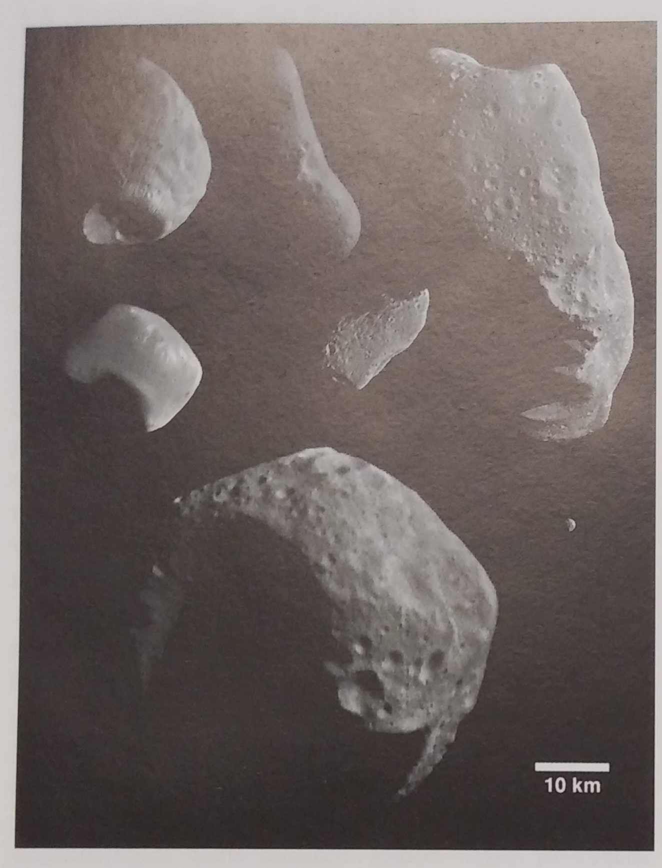

Figure 1.10 Rogues gallery of some small asteroids and martian Moons (thought to be captured asteroids) visited by spacecraft. Clockwise from upper left are Phobos, Eros, Ida, tiny Dactyl, Mathilde, and Deimos, with Gaspra in the center. Reprinted by permission from Cambridge University Press: Cosmochemistry, Harry Y. McSween Jr. and Gary R. Huss, Copyright (2010).

ice to sublimate and sometimes form jets of gas. Some nuclei split apart, suggesting that they are fragile.

Comets are in highly elliptical orbits, and most appear to originate within the Kuiper belt or Oort cloud. The dust trails they leave behind can be sampled as interplanetary dust particles that intersect the Earth's orbit as meteorite showers.

ESA's *Giotto* encountered comet Halley in 1986, and was bombarded by particles that caused a temporary loss of signal. NASA's *Deep Space 1* flew by comet Borrelly in 2001. NASA's *Stardust* mission collected dust ejected from comet Wild 2 in 2004, and returned it to Earth for laboratory analysis. NASA's *Deep Impact* visited Tempel 1 in 2005 and delivered an impactor that created a crater on the comet's surface. ESA's *Rosetta* spacecraft orbited comet Churyumov–Gerasimenko in 2014, conducting the most extensive set of comet observations to date. Its *Philae* lander unfortunately was put down in shadow and keeled over, so it was unable to make many of the planned surface observations and measurements, although it detected organic compounds.

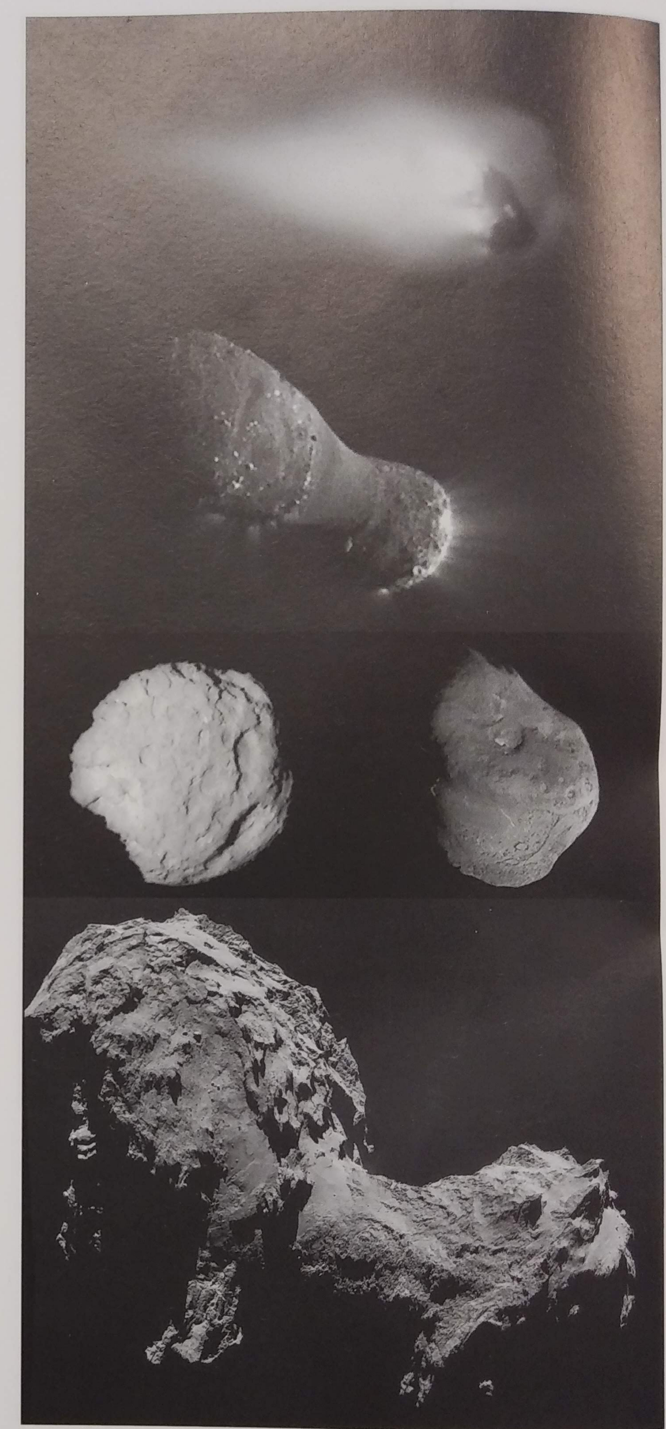

Figure 1.11 Images of some comet nuclei visited by spacecraft: Halley, Hartley 2, Wild 2 and Tempel 1, and Curyumov–Gerasimenko (top to bottom). Images are not to scale. NASA and ESA images.

1.6 A Few Notes on Orbital Dynamics

Although this text focuses on planetary geoscience, it is useful to review a few principles of celestial mechanics. These concepts apply not only to orbiting planets and small bodies, but also to the spacecraft exploring them.

Each body in the Solar System orbits the system's barycenter (taken approximately as the Sun), tracing out elliptical paths with the barycenter at one focal point of the ellipse. At any point along the orbit, the sum of the kinetic and potential energy of the orbiting object remains constant. The potential energy decreases as the body approaches the point closest to the barycenter (called the "perihelion" in the case of objects orbiting the Sun; the farthest point is the "aphelion"), so its kinetic energy, i.e., its orbital velocity, increases.

Although the planets' orbital paths about the Sun are eccentric, they are nearly circular. The low eccentricity is believed to result from their gravitational interactions with the Sun, which has nearly circularized their orbits over time. Some asteroids and their smaller cousins (meteoroids) have been perturbed into highly elliptical orbits that cross the orbits of the inner planets. A few bodies, such as some comets, have hyperbolic orbits. Their velocity is greater than the Solar System escape velocity, so they curve around the Sun at closest approach, and then separate forever.

Planetary orbits lie within a few degrees of the same plane, the **ecliptic** – a characteristic inherited from the spinning disk of dust from which they grew. Smaller bodies, such as some asteroids, comets, and Pluto, have orbits highly inclined to the ecliptic.

So-called **orbital elements** are used to describe how bodies in space move relative to each other. In order to be able to predict an object's future position, we need to know its location and its velocity. Both of these quantities are vectors with three components – x, y, and z for location, and v_x, v_y, and v_z for velocity – so six values are required. However, these Cartesian coordinates change rapidly, making them very cumbersome to tabulate for any Solar System body. Planetary scientists instead have devised different ways of describing orbits that put most of the variability into a single parameter. Six orbital elements are still needed, but five of them only vary slowly.

Johannes Kepler showed in the early 1600s that planets move in elliptical orbits, with the Sun at one focus of the ellipse. The two parameters that describe the size and shape of the ellipse are the semi-major axis (a) and the eccentricity (e). The elliptical orbits of the different bodies in the Solar System are oriented differently in space. The inclination (i) describes the amount that the ellipse is tilted relative to the ecliptic. Two other parameters, the longitude of the ascending node (Ω) and the longitude of perihelion (ω), describe the orientation of the ellipse in space. Together, these five elements describe the orbit – the allowed positions of the body around the Sun. The sixth element, the true anomaly, is the angle between perihelion of the orbit and the object's position at any given time. In a perfect system with only two spherical bodies and no other gravitational effects, the first five elements would never change. Such an unchanging orbit is often referred to as Keplerian.

In reality, planets and moons are not only affected by the Sun's gravity, but also by other bodies. For example, the orbit of the Moon about our planet cannot be accurately described without considering the gravitational effects of both the Earth and the Sun. Orbits can also be affected by distortions in the gravity field, caused by non-spherical shapes or other irregularities in mass distribution – this requires periodic adjustments in orbiting spacecraft. Such effects cause a, e, i, ω, and Ω to change with time. This change is mostly very slow, so assumptions of Keplerian orbits are generally reliable over modest time scales (e.g., thousands to millions of years). However, some configurations can lead to relatively rapid changes in orbital elements.

Summary

BOX 1.2 **EARTH IS A PLANET TOO**

Understanding the workings of our own world has been markedly improved by Earth observations at the planetary scale from orbital vantage points. Moreover, from the study of other planets we can test the generality of the geologic processes we have worked so hard to understand on Earth. Other Solar System bodies also allow us to travel back in time to document the kinds of materials that accreted to form the Earth and to elucidate processes that must have affected it, but have been erased from the geologic record. A few examples of insights that derive from planetary exploration are:

- The early Earth, like the Moon and terrestrial planets, had a magma ocean, formed by heat from the decay of short-lived radionuclides and collisions with other bodies. Global-scale melting had profound implications for differentiation to form the core, mantle, and crust, and affected the partitioning of elements used by our civilization.

- Plate tectonics dominates Earth's geology, but its moving rocky plates are unique among Solar System bodies. Heat loss at plate boundaries differs from that on one-plate planets, affecting the mechanisms of melting and the duration of geologic evolution.
- Basalts, the most common volcanic rocks on Earth, are ubiquitous on other rocky worlds, but the pathways and extents of magma evolution differ, making granitic rocks virtually unrepresented elsewhere.
- Water, liquid or frozen, is not nearly as rare in the Solar System as we once thought. The Earth is not a unique indicator of the way water interacts with a lithosphere, of its effects as a geomorphic agent, and of its possible role in life.
- Impact cratering is the most significant geologic process on other planets, and must have been on the early Earth as well. Large impacts have had disastrous consequences for life, and unraveling this history has allowed us to realize that humans still live in the fast lane.

This travelogue is but a cursory overview of the many geologic wonders in the Solar System. We will return to many of the bodies introduced here in the following chapters, but will focus more on geologic processes and less on cataloging what's there. It is worth reflecting, though, on the mechanical (and rarely, human) explorers that have provided information in enough depth to make planets, moons, and smaller bodies into geologic objects.

We have not touched on the instruments carried on these spacecraft that allow us to address geologic questions. In the next several chapters, we will concentrate on the tools developed and used by planetary geoscientists, before delving into the processes that have shaped our Solar System.

Review Questions

1. Briefly describe the systemic challenges faced by the engineers who design interplanetary spacecraft and the scientists who design the instruments they carry.
2. What are uncompressed mean densities, and what can they tell us about planets?
3. What characteristics do the terrestrial planets share?
4. What characteristics do the giant planets share?
5. How do we subdivide/classify the small bodies of the Solar System?

SUGGESTION FOR FURTHER READING

Lodders, K., and Fegley, B. Jr. (1998) *The Planetary Scientist's Companion*. New York: Oxford University Press. A handy resource that tabulates a wealth of information, with appropriate references, on the physical and chemical properties of Solar System bodies.

REFERENCE

Lodders, K., and Fegley, B. Jr. (1998) *The Planetary Scientist's Companion*. New York: Oxford University Press.