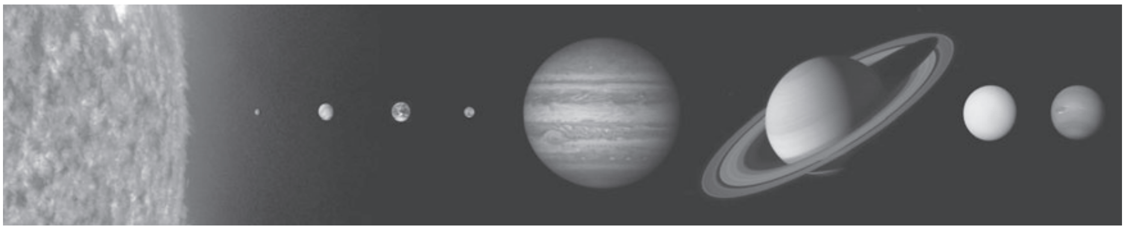
CHAPTER 1

Introduction



There are in fact two things, science and opinion; the former begets knowledge, the latter ignorance.

Hippocrates, *Law*, 460–377 BCE

Cambridge University Press
978-0-521-85330-9 - Fundamental Planetary Science: Physics, Chemistry and Habitability
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Excerpt
More information

Why are we so fascinated by planets? After all, planets make up a tiny fraction (probably substantially less than 1%) of ordinary matter in the Universe[1]. And why do terrestrial planets, which contain less than 1% of the planetary mass within our Solar System, hold a particular place in our hearts? The simple answer is that we live on a terrestrial planet. But there is a broader, more inclusive, version of that answer: To the best of our knowledge, planets or moons with solid surfaces are the only places where life can begin and evolve into advanced forms.

In this chapter, we introduce the subject of planetary sciences and provide some background needed for the remainder of the book. The history of planetary observations dates back thousands of years, and the prehistory likely extends much, much further back; we present a brief overview in the next section. We then give an inventory of objects in our Solar System in §1.2. This is followed in §1.3 by a discussion of definitions of the word ‘planet’ and of words describing various smaller and larger objects.

Despite the far larger number of planets known around other stars, most of our knowledge of planetary sciences was developed from observations of bodies within our own planetary system. This information is far from complete, and understanding observables is key to assessing the reliability of data; §1.4 discusses what aspects of planetary bodies we can observe.

Many lower-level planetary textbooks begin by covering the formation of our Solar System because that makes the most sense from a chronological perspective. However, although we can observe distant circumstellar disks that appear to be planetary nurseries, our observations of these disks are far less precise than those of objects orbiting the Sun. Furthermore, the accretion of planets takes a long time compared with the few decades since such observations began. Therefore, most of our understanding of planetary formation comes from a synthesis of theoretical modeling with data from our own Solar System and extrasolar planets. We thus defer our main discussion of this subject, which is among the most intellectually challenging in planetary science, until near the end of this book. Nonetheless, scientists have modeled the origin of planets for hundreds of years, and our understandings of this process have provided the best estimates of certain planetary properties that are not directly observable, such as interior composition. Because interpretation of data and planetary formation models often go hand in hand, we present a brief summary of current models of planetary formation in the final section of this chapter.

[1] **Dark matter**, most of which is **nonbaryonic** (i.e., not composed of protons or neutrons), is an order of magnitude more abundant than ordinary matter, which is also referred to as **luminous matter**. **Dark energy** has more than twice the mass-energy density of all types of matter in the Universe combined.

1.1 A Brief History of the Planetary Sciences

The sky appears quite spectacular on a clear night away from the light of modern cities. Ancient civilizations were particularly intrigued by several brilliant ‘stars’ that move among the far more numerous ‘fixed’ (stationary) stars. The Greeks called these objects **planets**, or wandering stars. Old drawings and manuscripts by people from all over the world, including the Chinese, Greeks and Anasazi, attest to their interest in comets, solar eclipses and other celestial phenomena. And observations of planets surely date to well before the dawn of writing and historical records, perhaps predating humanity itself. Some migratory birds use the patterns of stars in the night sky to guide their journeys and might be aware that a few of these objects move relative to the others. Indeed, some sharp-eyed and keen-witted dinosaurs may have realized that a few points of light in the night sky moved relative to the fixed pattern produced by most 'stars' more than 100 million years ago, but as dinosaurs never (to our knowledge) developed a written language, it is unlikely that such speculation will ever be confirmed.

The Copernican–Keplerian–Galilean–Newtonian revolution in the sixteenth and seventeenth centuries completely changed humanity's view of the dimensions and dynamics of the Solar System, including the relative sizes and masses of the bodies and the forces that make them orbit about one another. Gradual progress was made over the next few centuries, but the next revolution had to await the space age.

The age of planetary exploration began in October of 1959, with the Soviet Union's spacecraft *Luna 3* returning the first pictures of the farside of Earth's Moon (Fig. F.1). Over the next three decades, spacecraft visited all eight known terrestrial and giant planets in the Solar System, including our own. These spacecraft have returned data concerning the planets, their rings and moons. Spacecraft images of many objects showed details never suspected from earlier Earth-based pictures. Spectra from γ-rays to radio wavelengths revealed previously undetected gases and geological features on planets and moons, and radio detectors and magnetometers transected the giant magnetic fields surrounding many of the planets. The planets and their satellites have become familiar to us as individual bodies. The immense diversity of planetary and satellite surfaces, atmospheres and magnetic fields has surprised even the most imaginative researchers. Unexpected types of structure were observed in Saturn's rings, and whole new classes of rings and ring systems were seen around all four giant planets. Some of the new discoveries have been explained, but others remain mysterious.

Five comets and ten asteroids have thus far been explored close up by spacecraft (Table F.2), and there have been several missions to study the Sun and the solar wind. The Sun's gravitational domain extends thousands of times the distance to the farthest known planet, Neptune. Yet the vast outer regions of the Solar System are so poorly explored that many bodies remain to be detected, possibly including some of planetary size.

Hundreds of planets are now known to orbit stars other than the Sun. Although we know far less about any of these extrasolar planets than we do about the planets in our Solar System, it is clear that many of them have gross properties (orbits, masses, radii) quite different from any object orbiting our Sun, and they are thus causing us to revise some of our models of how planets form and evolve.

Biologists have redrawn the tree of life over the past few decades. We have learned of the interrelationships between all forms of life on Earth and of life's great diversity. This diversity enables some species to live in environments that would be considered quite extreme to humans and suggests that conditions capable of sustaining life exist on other planets and moons in our Solar System and beyond.

The renewed importance of the planetary sciences as a subfield of astronomy implies that some exposure to Solar System studies is an important component to the education of astronomers. Planetary sciences' close relationship to geophysics, atmospheric and space sciences means that the study of the planets offers the unique opportunity for comparison available to Earth scientists. The properties of planets are key to astrobiology, and understanding the basics of life is useful to planetary scientists.

1.2 Inventory of the Solar System

What is the **Solar System**? Our naturally geocentric view gives a highly distorted picture; thus, it is better to phrase the question as: What is seen by an objective observer from afar? The **Sun**, of course; the Sun has a luminosity 4×10^8 times as large as the total luminosity (reflected plus emitted) of Jupiter, the second brightest object in the Solar

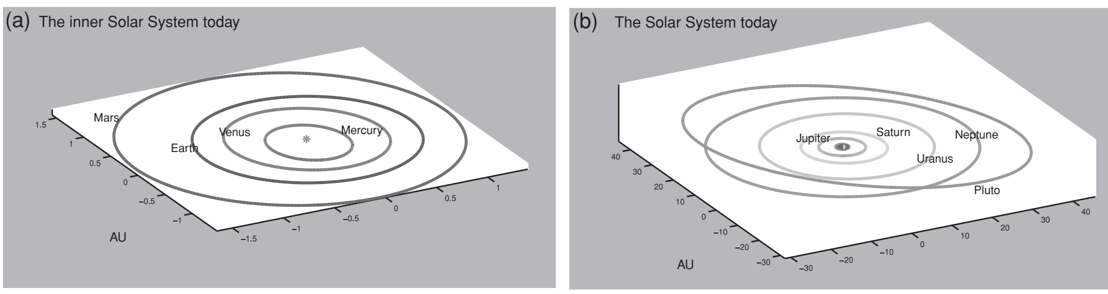

Figure 1.1 The orbits of (a) the four terrestrial planets and (b) all eight major planets in the Solar System and Pluto, are shown to scale. The axes are in AU. The movies show variations in the orbits over the past 3 million years; these changes are caused by mutual perturbations among the planets (see Chapter 2). Figure 2.12 presents plots of the variations in planetary eccentricities from the same integrations. (Illustrations courtesy Jonathan Levine)

System. The Sun also contains >99.8% of the mass of the known Solar System. By these measures, the Solar System can be thought of as the Sun plus some debris. However, by other measures, the planets are not insignificant. More than 98% of the angular momentum in the Solar System lies in orbital motions of the planets. Moreover, the Sun is a fundamentally different type of body from the planets – a ball of plasma powered by nuclear fusion in its core – but the smaller bodies in the Solar System are composed of molecular matter, some of which is in the solid state. This book focusses on the debris in orbit about the Sun, although we do include a summary of the properties of stars, including our Sun, in §3.3, and an overview of the outer layers of the Sun and its effect on the interplanetary medium in §§7.1 and 7.2. The debris encircling the Sun is composed of the giant planets, the terrestrial planets and numerous and varied smaller objects.

Figures 1.1 to 1.3 present three differing views of the Solar System. The orbits of the major planets and Pluto are diagrammed in Figure 1.1. Two different levels of reduction are displayed because of the relative closeness of the four terrestrial planets and the much larger spacings in the outer Solar System. Note the high inclination of Pluto's orbit relative to the orbits of the major planets. Figure 1.2 plots the sizes of various classes of Solar System objects as a function of location. The jovian (giant) planets dominate the outer Solar System, and the terrestrial planets dominate the inner Solar System. Small objects tend to be concentrated in regions where orbits are stable or at least long lived. Images of the planets and the largest planetary satellites are presented to scale in Figure 1.3. Figure 1.4 shows close-up views of those comets and asteroids that had been imaged by interplanetary spacecraft as of 2010.

1.2.1 Giant Planets

Jupiter dominates our planetary system. Its mass, 318 Earth masses ($M_\oplus$), exceeds twice that of all other known Solar System planets combined. Thus, as a second approximation, the Solar System can be viewed as the Sun, Jupiter and some debris. The largest of this debris is **Saturn**, with a mass of nearly 100 $M_\oplus$. Saturn, similar to Jupiter, is made mostly of hydrogen (H) and helium (He). Each of these planets probably possesses a heavy element 'core' of mass $\sim$10 $M_\oplus$. The third and fourth largest planets are **Neptune** and **Uranus**, each having a mass roughly one-sixth that of Saturn. These planets belong to a different class, with most of their masses provided by a combination of three

Cambridge University Press
978-0-521-85330-9 - Fundamental Planetary Science: Physics, Chemistry and Habitability
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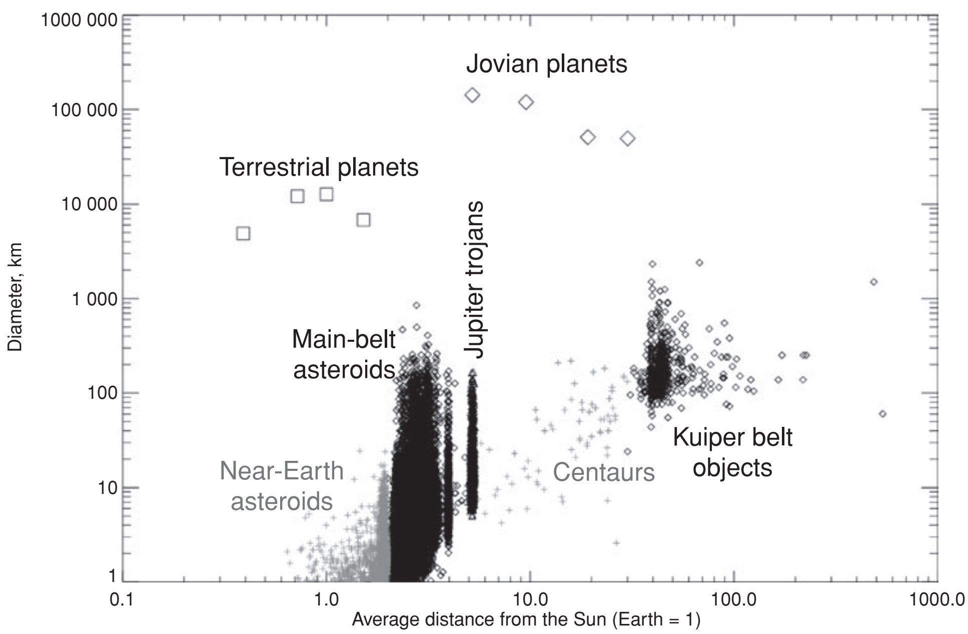

Figure 1.2 Inventory of objects orbiting the Sun. Small bodies are discussed in Chapter 12. The orbits of Jupiter Trojans are described in §2.2.1 and those of Centaurs are discussed in §12.2.2. (Courtesy John Spencer)

common astrophysical 'ices', water (H_2O), ammonia (NH_3), methane (CH_4), together with 'rock', high temperature condensates consisting primarily of silicates and metals, yet most of their volumes are occupied by relatively low mass (1–4 $M_\oplus$) H–He dominated atmospheres. The four largest planets are known collectively as the **giant planets**; Jupiter and Saturn are called **gas giants**, with radii of ∼70 000 km and 60 000 km, respectively, and Uranus and Neptune are referred to as **ice giants** (although the 'ices' are present in fluid rather than solid form), with radii of ∼25 000 km. All four giant planets possess strong magnetic fields. These planets orbit the Sun at distances of approximately 5, 10, 20 and 30 AU, respectively. (One **astronomical unit**, 1 AU, is defined to be the semimajor axis of a massless [test] particle whose orbital period about the Sun is one year. As our planet has a finite mass, the semimajor axis of Earth's orbit is slightly larger than 1 AU.)

1.2.2 Terrestrial Planets

The mass of the remaining known 'debris' totals less than one-fifth that of the smallest giant planet, and their orbital angular momenta are also much smaller. This debris consists of all of the solid bodies in the Solar System, and despite its small mass, it contains a wide variety of objects that are interesting chemically, geologically, dynamically, and, in at least one case, biologically. The hierarchy continues within this group, with two large **terrestrial**[2] planets, **Earth** and **Venus**, each with a radius of about 6000 km, at approximately 1 and 0.7 AU from the Sun, respectively. Our Solar System also contains two small terrestrial planets,

[2] In this text, the word 'terrestrial' is used to mean Earth-like or related to the planet Earth, as is the convention in planetary sciences and astronomy. Geoscientists and biologists generally use the same word to signify a relationship with land masses.

(a)

(b)

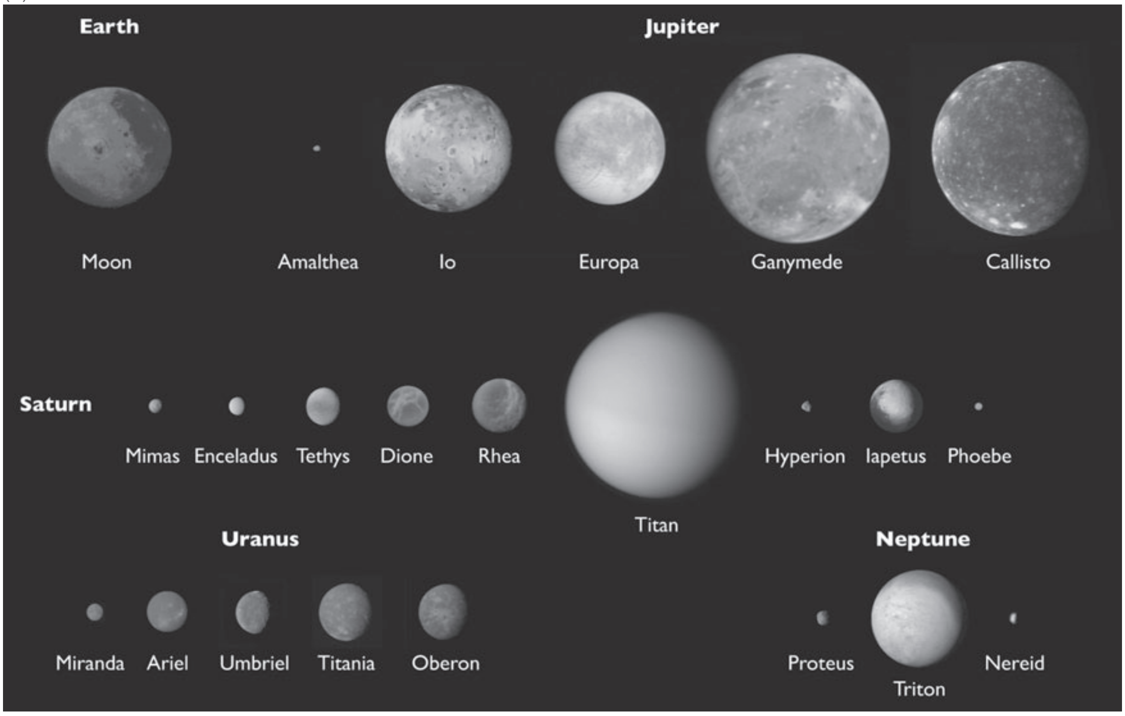

Figure 1.3 COLOR PLATE (a) Images of the planets with radii depicted to scale, ordered by distance from the Sun. (Courtesy International Astronomical Union/Martin Kornmesser) (b) Images of the largest satellites of the four giant planets and Earth's Moon, which are depicted in order of distance from their planet. Note that these moons span a wide range of size, albedo (reflectivity) and surface characteristics; most are spherical, but some of the smallest objects pictured are quite irregular in shape. (Courtesy Paul Schenk)

Mars with a radius of ~3500 km and orbiting at ~1.5 AU and **Mercury** with a radius of ~2500 km orbiting at ~0.4 AU.

All four terrestrial planets have atmospheres. Atmospheric composition and density vary widely among the terrestrial planets, with Mercury's atmosphere being exceedingly thin. However, even the most massive terrestrial planet atmosphere, that of Venus, is minuscule by giant planet standards. Earth and Mercury each have an internally

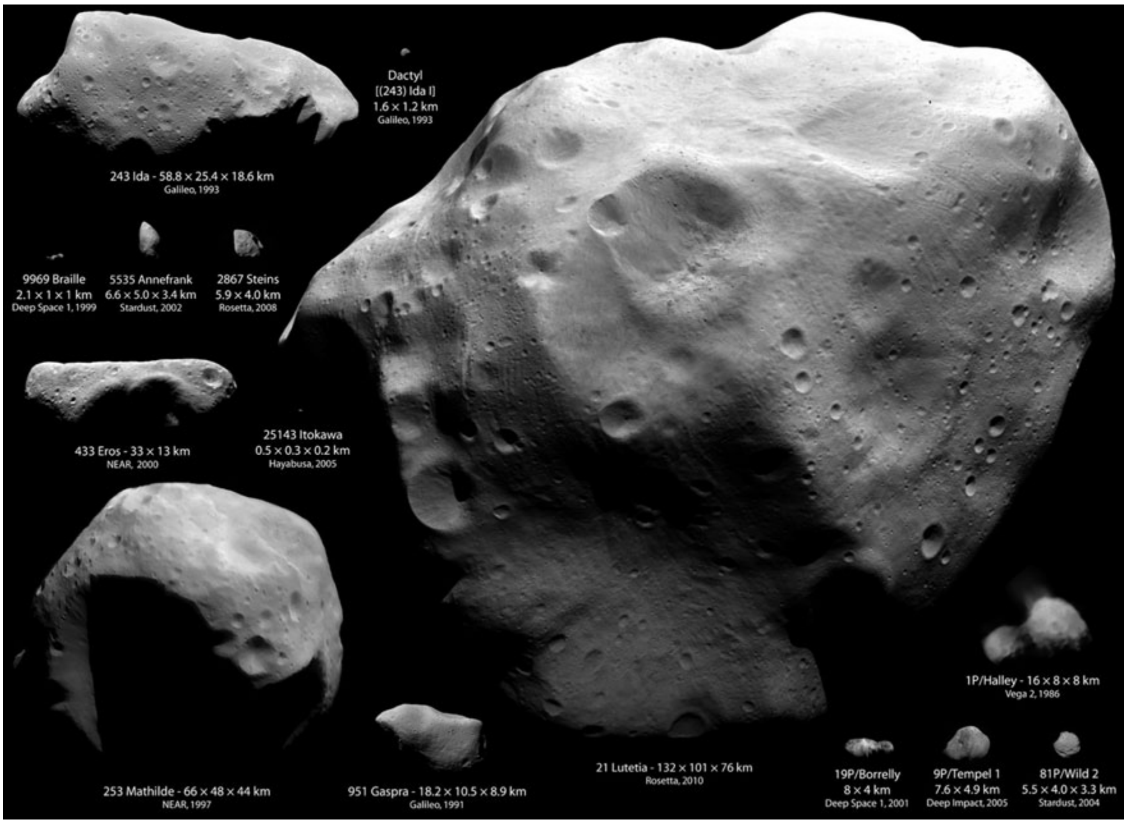

Figure 1.4 Views of the first four comets (lower right) and nine asteroid systems that were imaged close-up by interplanetary spacecraft, shown at the same scale. The object name and dimensions, as well as the name of the imaging spacecraft and the year of the encounter, are listed below each image. Note the wide range of sizes. Dactyl is a moon of Ida.

generated magnetic field, and evidence suggests that Mars possessed one in the distant past.

1.2.3 Minor Planets and Comets

The **Kuiper belt** is a thick disk of ice/rock bodies beyond the orbit of Neptune. The two largest members of the Kuiper belt to have been sighted are **Eris**, whose **heliocentric distance**, the distance from the Sun, oscillates between 38 and 97 AU, and **Pluto**, whose heliocentric distance varies from 29 to 50 AU. The radii of Eris and Pluto exceed 1000 km. Pluto is known to possess an atmosphere. Numerous smaller members of the Kuiper belt have been cataloged, but the census of these distant objects is incomplete even at large sizes. **Asteroids**, which are minor planets that all have radii <500 km, are found primarily between the orbits of Mars and Jupiter.

Smaller objects are also known to exist elsewhere in the Solar System, for example as moons in orbit around planets, and as comets. Comets are ice-rich objects that shed mass when subjected to sufficient solar heating. Comets are thought to have formed in or near the giant planet region and then been 'stored' in the **Oort cloud**, a nearly spherical region at heliocentric distances of $\sim 1-5 \times 10^4$ AU, or in the Kuiper belt or the **scattered disk**. Scattered disk objects (SDOs) have moderate to high eccentricity orbits that lie in whole or in part within the Kuiper belt. Estimates of the total number of comets larger than 1 km in radius in the entire Oort cloud range from $\sim 10^{12}$ to $\sim 10^{13}$. The total number of Kuiper belt objects (KBO) larger than 1 km in radius is estimated to be $\sim 10^{8}$–10^{10}. The total mass and orbital angular momentum of bodies in the scattered disk and Oort cloud are uncertain by more than an order of magnitude. The upper end of current estimates place as much mass in distant unseen icy bodies as is observed in the entire planetary system.

The smallest bodies known to orbit the Sun, such as the dust grains that together produce the faint band in the plane of the planetary orbits known as the **zodiacal cloud**, have been observed collectively but not yet individually detected via remote sensing.

1.2.4 Satellite and Ring Systems

Some of the most interesting objects in the Solar System orbit about the planets. Following the terrestrial planets in mass are the seven major moons of the giant planets and Earth. Two planetary satellites, Jupiter's moon Ganymede and Saturn's moon Titan, are slightly larger than the planet Mercury, but because of their lower densities, they are less than half as massive. Titan's atmosphere is denser than that of Earth. Triton, by far the largest moon of Neptune, has an atmosphere that is much less dense, yet it has winds powerful enough to strongly perturb the paths of particles ejected from geysers on its surface. Very tenuous atmospheres have been detected about several other planetary satellites, including Earth's Moon, Jupiter's Io and Saturn's Enceladus.

Natural satellites have been observed in orbit about most of the planets in the Solar System, as well as many Kuiper belt objects and asteroids. The giant planets all have large satellite systems, consisting of large- and/or medium-sized satellites (Fig. 1.3b) and many smaller moons and rings. Most of the smaller moons orbiting close to their planet were discovered from spacecraft flybys. All major satellites, except Triton, orbit the respective planet in a **prograde** manner (i.e., in the direction that the planet rotates) close to the planet's equatorial plane. Small, close-in moons are also exclusively in low-inclination, low-eccentricity orbits, but small moons orbiting beyond the main satellite systems can travel around the planet in either direction, and their orbits are often highly inclined and eccentric. Earth and Pluto each have one large moon: our Moon has a little over 1% of Earth's mass, and Charon's mass is just over 10% that of Pluto. These moons probably were produced by giant impacts on the Earth and Pluto when the Solar System was a small fraction of its current age. Two tiny moons travel on low-inclination, low-eccentricity orbits about Mars.

The four giant planets all have ring systems, which are primarily located within about 2.5 planetary radii of the planet's center. However, in other respects, the characters of the four ring systems differ greatly. Saturn's rings are bright and broad, full of structure such as density waves, gaps and 'spokes'. Jupiter's ring is very tenuous and composed mostly of small particles. Uranus has nine narrow opaque rings plus broad regions of tenuous dust orbiting close to the plane defined by the planet's equator. Neptune has four rings, two narrow ones and two faint broader rings; the most remarkable part of Neptune's ring system is the ring arcs, which are bright segments within one of the narrow rings.

1.2.5 Tabulations

The orbital and bulk properties of the eight 'major' planets are listed in Tables E.1 to E.3. Symbols for each of these planets, which we often use as subscripts on masses and radii, are also given in Table E.1. Table E.4 gives orbital elements and brightnesses of all inner moons of the eight planets, as well as those outer moons whose radii are estimated to be $\gtrsim 10$ km. Many of the orbital parameters listed in the tables are defined in §2.1. Rotation rates and physical characteristics of these satellites, whenever known, are given in Table E.5. Properties of some the largest 'minor planets',

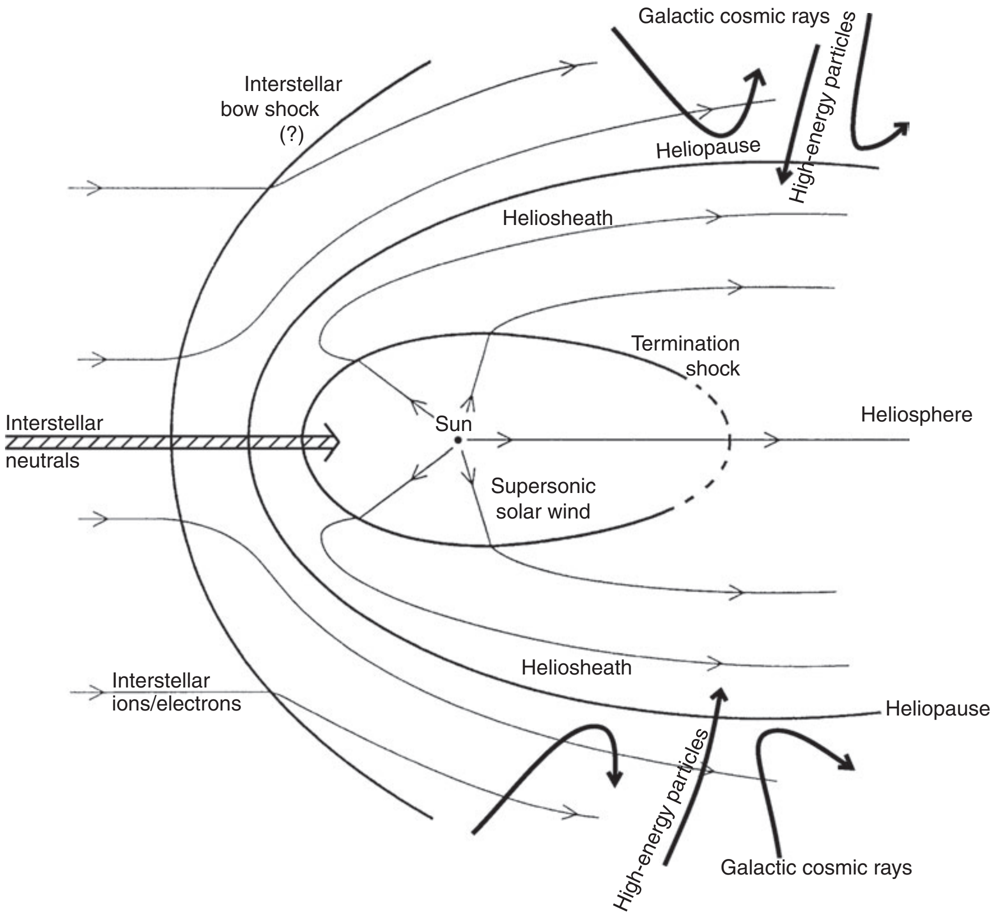

Figure 1.5 Sketch of the teardrop-shaped heliosphere. Within the heliosphere, the solar wind flows radially outwards until it encounters the heliopause, the boundary between the solar wind–dominated region and the interstellar medium. Weak cosmic rays are deflected away by the heliopause, but energetic particles penetrate the region down to the inner Solar System. (Adapted from Gosling 2007)

asteroids and Kuiper belt objects are given in Tables E.6 and E.7, and densities of some minor planets are listed in Table E.8.

The brightness of a celestial body is generally expressed as the **apparent magnitude** at visual wavelengths, m_V. A 6^{th} magnitude ($m_V = 6$) star is just visible to the naked eye in a dark sky. The magnitude scale is logarithmic (mimicking the perception of human vision), and a difference of 5 magnitudes equals a factor of 100 in brightness (i.e., a star with $m_V = 0$ is 100 times brighter than one with $m_V = 5$). The apparent magnitudes of planetary satellites are listed in Table E.4. Those moons with $m_V > 20$ can only be detected with a large telescope or nearby spacecraft.

1.2.6 Heliosphere

All planetary orbits lie within the **heliosphere**, the region of space containing magnetic fields and plasma of solar origin. Figure 1.5 diagrams key components of the heliosphere. The **solar wind** consists of **plasma** (ionized gas) traveling outward from the Sun at supersonic speeds. The solar wind merges with the **interstellar medium** at the **heliopause**, the boundary of the heliosphere.

The composition of the heliosphere is dominated by solar wind protons and electrons, with a typical density of 5×10^6 protons m^{-3} at 1 AU from the Sun, decreasing as the reciprocal distance squared. These particles move outwards at speeds of ~400 km s^{-1} near the solar equator but ~700–800 km s^{-1} closer to the solar poles. In contrast, the local interstellar medium, at a density of less than 1×10^5 atoms m^{-3}, contains mainly hydrogen and helium atoms. The Sun's motion relative to the mean motion of neighboring stars is roughly 26 km s^{-1}. Hence, the heliosphere moves through the interstellar medium at about this speed. The heliosphere is thought to be shaped like a teardrop, with a tail in the downwind direction (Fig. 1.5). Interstellar ions and electrons generally flow around the heliosphere because they cannot cross the solar magnetic fieldlines. Neutrals, however, can enter the heliosphere, and as a result interstellar H and He atoms move through the Solar System in the downstream direction with a typical speed of ~22 (for H)–26 (for He) km s^{-1}.

Just interior to the heliopause is the **termination shock**, where the solar wind is slowed down. Because of variations in solar wind pressure, the location of this shock moves radially with respect to the Sun in accordance with the 11-year solar activity cycle. The *Voyager 1* spacecraft crossed the termination shock in December 2004 at a heliocentric distance of 94.0 AU; *Voyager 2* crossed the shock (multiple times) in August 2007 at ~83.7 AU. The spacecraft are now in the **heliosheath**, between the termination shock and the heliopause. Voyager 1 entered interstellar space on 25 August 2012, when it was at a heliocentric distance of 121 AU.

1.3 What Is a Planet?

The ancient Greeks referred to all moving objects in the sky as planets. To them, there were seven such objects, the Sun, the Moon, Mercury, Venus, Mars, Jupiter and Saturn. The Copernican revolution removed the Sun and Moon from the planet club, but added the Earth. Uranus and Neptune were added as soon as they were discovered in the eighteenth and nineteenth centuries, respectively.

Pluto, by far the brightest Kuiper belt object (KBO) and the first that was discovered, was officially classified as a planet from its discovery in 1930 until 2006; 1 Ceres, the first detected (in 1801) and by far the largest member of the asteroid belt, was also once considered to be a planet, as were the next few asteroids that were discovered. With the detection of other KBOs, debates began with regard to the classification of Pluto as a planet, culminating in August 2006 with the resolution by the International Astronomical Union (IAU):

- A **planet** is a celestial body that (1) is in orbit around the Sun, (2) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (3) has cleared the neighborhood around its orbit.
- A **dwarf planet** is a celestial body that (1) is in orbit around the Sun, (2) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, (3) has not cleared the neighbourhood around its orbit, and (4) is not a satellite.

Just as the discoveries of small bodies orbiting the Sun have forced astronomers to decide how small an object can be and still be worthy of being classified as a planet, detections of substellar objects orbiting other stars have raised the question of an upper size limit to planethood. We adopt the following definitions, which are consistent with current IAU nomenclature:

- **Star**: self-sustaining fusion is sufficient for thermal pressure to balance gravity ($\gtrsim 0.075\ M_\odot \approx 80\ M_{♃}$ for solar composition; the minimum