1 Introduction

SOCRATES: *Shall we set down astronomy among the subjects of study?*
GLAUCON: *I think so, to know something about the seasons, the months and the years is of use for military purposes, as well as for agriculture and for navigation.*
SOCRATES: *It amuses me to see how afraid you are, lest the common herd of people should accuse you of recommending useless studies.*

Plato, *The Republic VII*

The wonders of the night sky, the Moon and the Sun have fascinated mankind for many millennia. Ancient civilizations were particularly intrigued by several brilliant 'stars' that move among the far more numerous 'fixed' (stationary) stars. The Greeks used the word $\pi\lambda\alpha\nu\eta\tau\eta\zeta$, meaning wandering star, to refer to these objects. Old drawings and manuscripts by people from all over the world, such as the Chinese, Greeks, and Anasazi, attest to their interest in comets, solar eclipses, and other celestial phenomena.

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.

In October of 1959, the Soviet spacecraft Luna 3 returned the first pictures of the farside of Earth's Moon (Appendix F). The age of planetary exploration had begun. 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 which could never have been guessed from previous Earth-based pictures. Spectra from ultraviolet to infrared wavelengths revealed previously undetected gases and geological features on planets and moons, while 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, whereas others remain mysterious.

Six comets and eleven asteroids have thus far been explored by close-up spacecraft, 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.

Thousands of planets are now known to orbit stars other than the Sun. While 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.

In this book, we discuss what has been learned and some of the unanswered questions that remain at the forefront of planetary sciences research today. Topics covered include the orbital, rotational, and bulk properties of planets, moons, and smaller bodies; gravitational interactions, tides, and resonances between bodies; chemistry and dynamics of planetary atmospheres, including cloud physics; planetary geology and geophysics; planetary interiors; magnetospheric physics; meteorites; asteroids; comets; and planetary ring dynamics. The new and rapidly blossoming field of extrasolar planet studies is then introduced. We conclude by combining this knowledge of current Solar System and extrasolar planet properties and processes with astrophysical data and models of ongoing star and planet formation to develop a model for the origin of planetary systems.

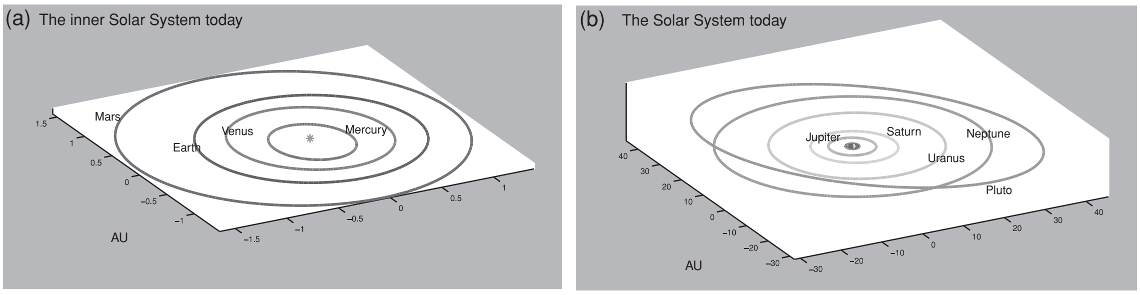

Figure 1.1 The orbits of (a) the four terrestrial planets, and (b) all eight major planets in the Solar System and Pluto, are shown to scale. Two different levels of reduction are displayed because of the relative closeness of the four terrestrial planets and the much larger spacings in the outer Solar System. The axes are in AU. Note the high inclination of Pluto's orbit relative to the orbits of the major planets. The movies show variations in the orbits over the past three million years; these changes are due to mutual perturbations among the planets (Chapter 2). Figure 2.14 presents plots of the variations in planetary eccentricities from the same integrations. (Illustrations courtesy Jonathan Levine)

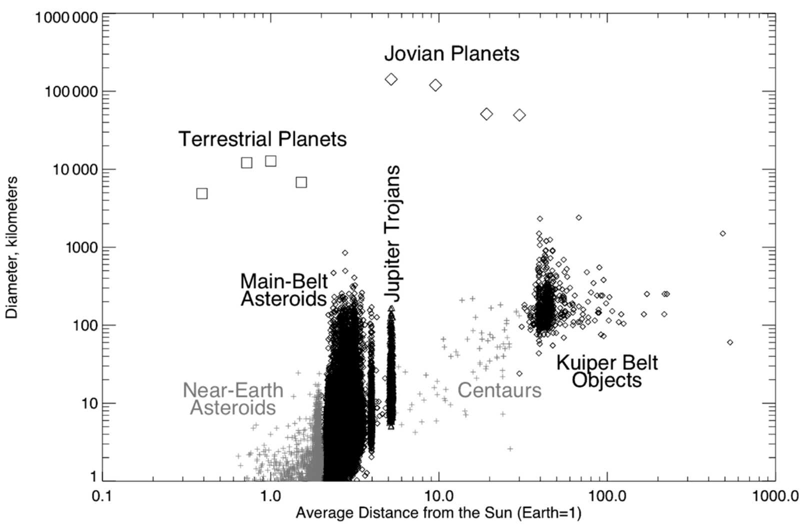

Figure 1.2 Inventory of objects orbiting the Sun. The jovian planets dominate the outer Solar System and the terrestrial planets dominate the inner Solar System. Small objects tend to be concentrated in regions where orbits are stable, or at least long-lived. (Courtesy John Spencer)

1.1 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 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. Over 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, whereas the smaller bodies in the Solar System are composed of molecular matter, some of which is in the solid state. This book focuses on the debris in orbit about the Sun. This debris is comprised of the giant planets, the terrestrial planets, and numerous and varied smaller objects (Figs. 1.1–1.3).

1.1.1 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

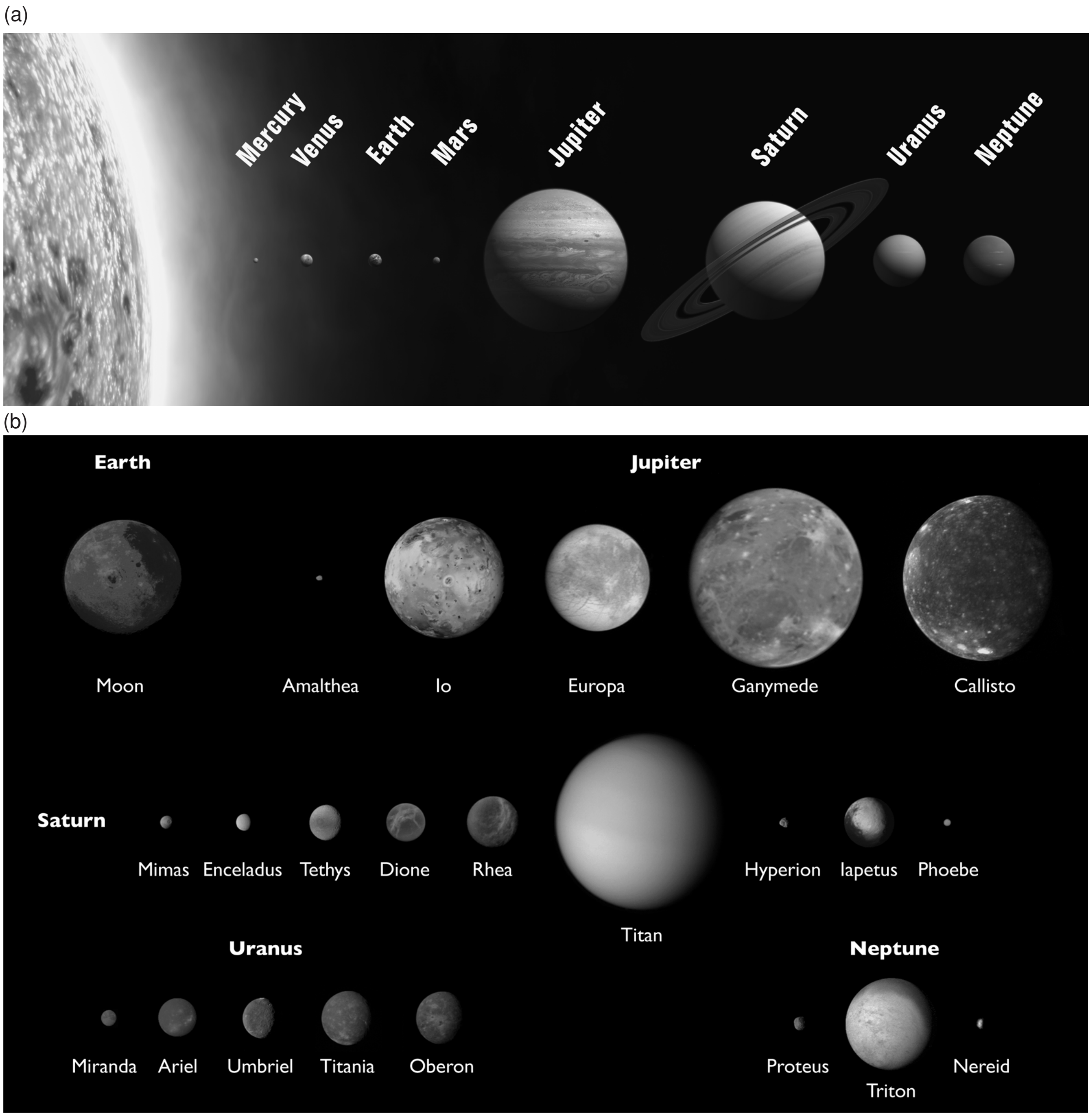

Figure 1.3 COLOR PLATE (a) Images of the planets with radii depicted to scale, ordered by distance from the Sun. (Courtesy International Astronomical Union/Martin Kornmesser) (b) Images of the largest satellites of the four giant planets and Earth's Moon, which are depicted in order of distance from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

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, like 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 common astrophysical 'ices', water (H_2O), ammonia (NH_3), methane (CH_4), together with 'rock', high temperature condensates consisting primarily of silicates and metals, and 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, whereas 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.)

1.1.2 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*[1] 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: *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 varies 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 generated magnetic field, and there are signs that Mars possessed one in the distant past.

1.1.3 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.

[1] 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.

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 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 one kilometer in radius in the entire Oort cloud range from $\sim 10^{12}$ to $\sim 10^{13}$. The total number of Kuiper belt objects 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.

1.1.4 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 and many smaller moons and rings (Fig. 1.3b). Most of the smaller moons orbiting

Table 1.1 Planetary mean orbits and symbols.

Planet	Symbol	a (AU)	e	i (deg)	Ω (deg)	ϖ (deg)	λ_m
Mercury	☿	0.387 098 80	0.205 631 75	7.004 99	48.3309	77.4561	252.2509
Venus	♀	0.723 332 01	0.006 771 77	3.394 47	76.6799	131.5637	181.9798
Earth	⊕	1.000 000 83	0.016 708 617	0.0	0.0	102.9374	100.4665
Mars	♂	1.523 689 46	0.093 400 62	1.849 73	49.5581	336.6023	355.4333
Jupiter	♃	5.202 758 4	0.048 495	1.303 3	100.464	14.331	34.351
Saturn	♄	9.542 824 4	0.055 509	2.488 9	113.666	93.057	50.077
Uranus	⛢	19.192 06	0.046 30	0.773	74.01	173.01	314.06
Neptune	Ψ	30.068 93	0.008 99	1.770	131.78	48.12	304.35

λ_m is mean longitude. All data are for the J2000 epoch and were taken from Yoder (1995).

Pluto, which was classified as a planet from its discovery in 1930 until 2006, also has an official symbol, ♇. The symbol for Earth's Moon is ☾M.

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 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. As with interplanetary dust, individual ring particles have not been observed directly via remote sensing.

1.1.5 Tabulations

The orbital and bulk properties of the eight 'major' planets are listed in Tables 1.1–1.3. Table 1.4 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 1.5. Properties of some the largest 'minor planets', asteroids, and Kuiper belt objects are given in Tables 9.1 and 9.2, and minor planet satellites are discussed in §9.4.4.

1.1.6 Heliosphere

All planetary orbits lie within the *heliosphere*, the region of space containing magnetic fields and plasma of solar origin. The *solar wind* consists of plasma traveling outwards 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 protons cm^{-3} at 1 AU (decreasing as the reciprocal distance squared), and speed of $\sim$400 km s^{-1} near the solar equator but $\sim$700–800 km s^{-1} closer to the solar poles. In contrast, the local interstellar medium, at a density of less than 0.1 atoms cm^{-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. 1.4). Interstellar ions and electrons generally flow around the heliosphere, since they cannot cross the solar magnetic field lines. Neutrals, however, can enter the heliosphere, and as a result interstellar H and He atoms

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Table 1.2 Terrestrial planets: Geophysical data.

	Mercury	Venus	Earth	Mars
Mean radius R (km)	2440 ± 1	$6051.8(4 \pm 1)$	$6371.0(1 \pm 2)$	$3389.9(2 \pm 4)$
Mass ($\times 10^{27}$ g)	0.3302	4.8685	5.9736	0.64185
Density (g cm^{-3})	5.427	5.204	5.515	$3.933(5 \pm 4)$
Flattening ϵ			1/298.257	1/154.409
Equatorial radius (km)			6378.136	3397 ± 4
Sidereal rotation period	58.6462 d	−243.0185 d	23.934 19 h	24.622 962 h
Mean solar day (in days)	175.9421	116.7490	1	1.027 490 7
Equatorial gravity (m s^{-2})	3.701	8.870	9.780 327	3.690
Polar gravity (m s^{-2})			9.832 186	3.758
Core radius (km)	~1600	~3200	3485	~1700
Figure offset ($R_{CF} - R_{CM}$) (km)		0.19 ± 0.01	0.80	2.50 ± 0.07
Offset (lat./long.)		11°/102°	46°/35°	62°/88°
Obliquity to orbit (deg)	~0.1	177.3	23.45	25.19
Sidereal orbit period (yr)	0.240 844 5	0.615 182 6	0.999 978 6	1.880 711 05
Escape velocity v_e (km s^{-1})	4.435	10.361	11.186	5.027
Geometric albedo	0.106	0.65	0.367	0.150
$V(1,0)$[a]	−0.42	−4.40	−3.86	−1.52

All data are from Yoder (1995).

[a] $V(1,0)$ is the visual equivalent magnitude at 1 AU and 0° phase angle.

The apparent visual magnitude at phase angle ϕ, m_v, can be calculated from: $m_v = V(1,0) + C\phi + (5\log_{10})(r_{\odot AU} r_{\Delta AU})$, with C the phase coefficient in magnitudes per degree, $r_{\odot AU}$ the planet's heliocentric distance (in AU) and $r_{\Delta AU}$ the distance from the observer to the planet (in AU).

Table 1.3 Giant planets: Physical data.

	Jupiter	Saturn	Uranus	Neptune
Mass (10^{27} g)	1898.6	568.46	86.832	102.43
Density (g cm^{-3})	1.326	0.6873	1.318	1.638
Equatorial radius (1 bar) (km)	$71\,492 \pm 4$	$60\,268 \pm 4$	$25\,559 \pm 4$	$24\,766 \pm 15$
Polar radius (km)	$66\,854 \pm 10$	$54\,364 \pm 10$	$24\,973 \pm 20$	$24\,342 \pm 30$
Volumetric mean radius (km)	$69\,911 \pm 6$	$58\,232 \pm 6$	$25\,362 \pm 12$	$24\,624 \pm 21$
Flattening ϵ	0.064 87 $\pm 0.000\,15$	0.097 96 $\pm 0.000\,18$	0.022 93 ± 0.0008	0.0171 ± 0.0014
Sidereal rotation period	$9^h55^m29\overset{s}{.}71$	$10^h32^m35^s \pm 13$[a]	-17.24 ± 0.01 h	16.11 ± 0.01 h
Hydrostatic flattening[b]	0.065 09	0.098 29	0.019 87	0.018 04
Equatorial gravity (m s^{-2})	23.12 ± 0.01	8.96 ± 0.01	8.69 ± 0.01	11.00 ± 0.05
Polar gravity (m s^{-2})	27.01 ± 0.01	12.14 ± 0.01	9.19 ± 0.02	11.41 ± 0.03
Obliquity (deg)	3.12	26.73	97.86	29.56
Sidereal orbit period (yr)	11.856 523	29.423 519	83.747 407	163.723 21
Escape velocity v_e (km s^{-1})	59.5	35.5	21.3	23.5
Geometric albedo	0.52	0.47	0.51	0.41
$V(1,0)$	−9.40	−8.88	−7.19	−6.87

Most data are from Yoder (1995).

[a] Saturn's rotation period is from Anderson and Schubert (2007); the true uncertainty in its value is far greater than the formal error listed because different measurement techniques yield values that differ from one another by up to tens of minutes.

[b] Hydrostatic flattening as derived from the gravitational field and magnetic field rotation rate.

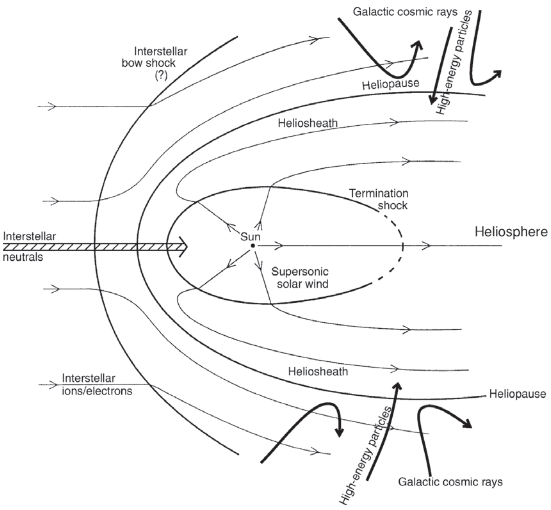

Figure 1.4 Sketch of the teardrop-shaped heliosphere. Within the heliosphere, the solar wind flows radially outward until it encounters the heliopause, the boundary between the solar wind dominated region and the interstellar medium. Weak cosmic rays are deflected away by the heliopause, but energetic particles penetrate the region down to the inner Solar System. (Adapted from Gosling 2007)

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. Due to 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. While Voyager 2 is still in the *heliosheath*, between the termination shock and the heliopause, Voyager 1 crossed the heliopause in 2012 and entered the interstellar medium (§G.7).

1.2 Planetary Properties

All of our knowledge regarding specific characteristics of Solar System objects, including planets, moons, comets, asteroids, rings, and interplanetary dust, is ultimately derived from observations, either astronomical measurements from the ground or Earth-orbiting satellites, or from close-up (often *in situ*) measurements obtained by interplanetary spacecraft. One can determine the following quantities more or less directly from observations:

(1) Orbit
(2) Mass, distribution of mass
(3) Size
(4) Rotation rate and direction
(5) Shape
(6) Temperature
(7) Magnetic field
(8) Surface composition
(9) Surface structure
(10) Atmospheric structure and composition

With the help of various theories, these observations can be used to constrain planetary properties such as bulk composition and interior structure, two attributes which are crucial elements in modeling the formation of the Solar System.

1.2.1 Orbit

In the early part of the seventeenth century, Johannes Kepler deduced three 'laws' of planetary motion directly from observations:

(1) All planets move along elliptical paths with the Sun at one focus.
(2) A line segment connecting any given planet and the Sun sweeps out area at a constant rate.
(3) The square of a planet's orbital period about the Sun, P_{orb}, is proportional to the cube of its semimajor axis, a, i.e., $P_{\mathrm{orb}}^2 \propto a^3$.

A Keplerian orbit is uniquely specified by six orbital elements, a (semimajor axis), e (eccentricity), i (inclination), ω (argument of periapse; or ϖ for the longitude of periapse), Ω (longitude of ascending node), and f (true anomaly). These orbital elements are defined graphically in Figure 2.1 and discussed in more detail in §2.1. The first of these elements are more fundamental than the last: a and e fully define the size and shape of the orbit, i gives the tilt of the orbital plane to some reference plane, the longitudes ϖ and Ω determine the orientation of the orbit, and f (or, indirectly, t_ϖ, the time of periapse passage) tells where the planet is along its orbit at a given time. Alternative sets of orbital elements are also possible, for instance an orbit is fully specified by the planet's location and velocity relative to the Sun at a given time (again six independent scalar quantities), provided the masses of the Sun and planet are known.

Kepler's laws (or more accurate versions thereof) can be derived from Newton's laws of motion and of gravity, which were formulated later in the seventeenth century (§2.1). Relativistic effects also affect planetary orbits, but they are small compared to the gravitational perturbations that the planets exert on one other (Problem 2.15).

All planets and asteroids revolve around the Sun in the direction of solar rotation. Their orbital planes generally lie within a few degrees of each other and close

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Table 1.4 Principal planetary satellites: Orbital data and visual magnitude at opposition.

Planet		Satellite	a (10^3 km)	Orbital period (days)	e	i (deg)	m_v
Earth		Moon	384.40	27.321 661	0.054 900	5.15[a]	−12.7
Mars	I	Phobos	9.375	0.318 910	0.015 1	1.082	11.4
	II	Deimos	23.458	1.262 441	0.000 24	1.791	12.5
Jupiter	XVI	Metis	127.98	0.294 78	0.001 2	0.02	17.5
	XV	Adrastea	128.98	0.298 26	0.001 8	0.054	18.7
	V	Almathea	181.37	0.498 18	0.003 1	0.388	14.1
	XIV	Thebe	221.90	0.674 5	0.017 7	1.070	16.0
	I	Io	421.77	1.769 138	0.004 1*f*	0.040	5.0
	II	Europa	671.08	3.551 810	0.010 1*f*	0.470	5.3
	III	Ganymede	1 070.4	7.154 553	0.001 5*f*	0.195	4.6
	IV	Callisto	1 882.8	16.689 018	0.007	0.28	5.6
	XIII	Leda	11 160	241	0.148	27[a]	19.5
	VI	Himalia	11 460	251	0.163	28.5[a]	14.6
	X	Lysithea	11 720	259	0.107	29[a]	18.3
	VII	Elara	11 737	260	0.207	28[a]	16.3
	XII	Ananka	21 280	610	0.169	147[a]	18.8
	XI	Carme	23 400	702	0.207	163[a]	17.6
	VIII	Pasiphae	23 620	708	0.378	148[a]	17.0
	IX	Sinope	23 940	725	0.275	153[a]	18.1
Saturn	XVIII	Pan	133.584	0.575 05	0.000 01	0.000 1	19.4
	XXXV	Daphnis	136.51	0.594 08	0.000 03	0.004	21
	XV	Atlas	137.670	0.601 69	0.001 2	0.01	19.0
	XVI	Prometheus	139.380	0.612 986	0.002 2	0.007	15.8
	XVII	Pandora	141.710	0.628 804	0.004 2	0.051	16.4
	XI	Epimetheus	151.47[b]	0.694 590[b]	0.010	0.35	15.6
	X	Janus	151.47[b]	0.694 590[b]	0.007	0.16	16.4
	I	Mimas	185.52	0.942 421 8	0.020 2	1.53*f*	12.8
	XXXII	Methone	194.23	1.009 58	0.000	0.02	23
	XLIX	Anthe	197.7	1.037	0.02	0.02	24
	XXXIII	Pallene	212.28	1.153 7	0.004	0.18	22
	II	Enceladus	238.02	1.370 218	0.004 5*f*	0.02	11.8
	III	Tethys	294.66	1.887 802	0.000 0	1.09*f*	10.3
	XIV	Calypso (T−)	294.66[b]	1.887 802[b]	0.000 5	1.50	18.7
	XIII	Telesto (T+)	294.66[b]	1.887 802[b]	0.000 2	1.18	18.5
	IV	Dione	377.71	2.736 915	0.002 2*f*	0.02	10.4
	XII	Helene (T+)	377.71[b]	2.736 915[b]	0.005	0.2	18.4
	XXXIV	Polydeuces (T−)	377.71[b]	2.736 915[b]	0.019	0.18	23
	V	Rhea	527.04	4.517 500	0.001	0.35	9.7
	VI	Titan	1 221.85	15.945 421	0.029 2	0.33	8.4
	VII	Hyperion	1 481.1	21.276 609	0.104 2*f*	0.43	14.4
	VIII	Iapetus	3 561.3	79.330 183	0.028 3	7.52	11.0[c]
	IX	Phoebe	12 952	550.48	0.164	175.3[a]	16.5
	XX	Paaliaq	15 198	687	0.36	45[a]	21.2
	XXVI	Albiorix	16 394	783	0.48	34[a]	20.4
	XXIX	Siarnaq	18 195	896	0.3	46[a]	20.0

(*cont.*)

Table 1.4 (*cont.*)

Planet		Satellite	a (10^3 km)	Orbital period (days)	e	i (deg)	m_v
Uranus	VI	Cordelia	49.752	0.335 033	0.000	0.1	24.2
	VII	Ophelia	53.764	0.376 409	0.010	0.1	23.9
	VIII	Bianca	59.166	0.434 577	0.000 3	0.18	23.1
	IX	Cressida	61.767	0.463 570	0.000 2	0.04	22.3
	X	Desdemona	62.658	0.473 651	0.000 3	0.10	22.5
	XI	Juliet	64.358	0.493 066	0.000 1	0.05	21.7
	XII	Portia	66.097	0.513 196	0.000 5	0.03	21.1
	XIII	Rosalind	69.927	0.558 459	0.000 6	0.09	22.5
	XXVII	Cupid	74.393	0.612 825	∼0	∼0	25.9
	XIV	Belinda	75.256	0.623 525	0.000	0.0	22.1
	XXV	Perdita	76.417	0.638 019	0.003	∼0	23.6
	XV	Puck	86.004	0.761 832	0.000 4	0.3	20.6
	XXVI	Mab	97.736	0.922 958	0.002 5	0.13	25.4
	V	Miranda	129.8	1.413	0.002 7	4.22	15.8
	I	Ariel	191.2	2.520	0.003 4	0.31	13.7
	II	Umbriel	266.0	4.144	0.005 0	0.36	14.5
	III	Titania	435.8	8.706	0.002 2	0.10	13.5
	IV	Oberon	582.6	13.463	0.000 8	0.10	13.7
	XVI	Caliban	7 231	580	0.16	141[a]	22.4
	XX	Stephano	8 004	677	0.23	144[a]	24.1
	XVII	Sycorax	12 179	1288	0.52	159[a]	20.8
	XVIII	Prospero	16 256	1978	0.44	152[a]	23.2
	XIX	Setebos	17 418	2225	0.59	158[a]	23.3
Neptune	III	Naiad	48.227	0.294 396	0.00	4.74	24.6
	IV	Thalassa	50.075	0.311 485	0.00	0.21	23.9
	V	Despina	52.526	0.334 655	0.00	0.07	22.5
	VI	Galatea	61.953	0.428 745	0.00	0.05	22.4
	VII	Larissa	73.548	0.554 654	0.00	0.20	22.0
	VIII	Proteus	117.647	1.122 315	0.00	0.55	20.3
	I	Triton	354.76	5.876 854	0.00	156.834	13.5
	II	Nereid	5 513.4	360.136 19	0.751	7.23[a]	19.7
	IX	Halimede	15 686	1875	0.57	134[a]	24.4
	XI	Sao	22 452	2919	0.30	48[a]	25.7
	XII	Laomedeia	22 580	2982	0.48	35[a]	25.3
	XIII	Neso	46 570	8863	0.53	132[a]	24.7
	X	Psamathe	46 738	9136	0.45	137[a]	25.1

Data are from Yoder (1995), with updates from Showalter and Lissauer (2006), Jacobson *et al.* (2009), Nicholson (2009), Jacobson, (2010), http://ssd.jpl.nasa.gov, and other sources.

i = orbit plane inclination with respect to the parent planet's equator, except where noted.

Abbreviations: T, Trojan-like satellite which leads (+) or trails (−) by ∼60° in longitude the primary satellite with same semimajor axis; f, forced eccentricity or inclination.

[a] measured relative to the planet's heliocentric orbit, because the Sun (rather than the planetary oblateness) controls the local Laplacian plane of these distant satellites.

[b] varies due to coorbital libration; value shown is long-term average.

[c] varies substantially with orbital longitude; average value is shown.

Table 1.5 Planetary satellites: Physical properties and rotation rates.

Satellite	Radius (km)	Mass (10^{23} g)	Density (g cm^{-3})	Geom. albedo	Rot. period (days)
Earth	$6378^2 \times 6357$	59 742	5.515	0.367	0.997
Moon	1737.53 ± 0.03	734.9	3.34	0.12	S
Mars	$3396^2 \times 3376$	6419	3.933	0.150	1.026
MI Phobos	$13.1 \times 11.1 \times 9.3(\pm 0.1)$	1.063×10^{-4}	1.90	0.06	S
MII Deimos	$(7.8 \times 6.0 \times 5.1)(\pm 0.2)$	1.51×10^{-5}	1.50	0.07	S
Jupiter	$71\,492^2 \times 66\,854$	1.8988×10^7	1.326	0.52	0.414
JXVI Metis	$(30 \times 20 \times 17)(\pm 2)$			0.06	S
JXV Adrastea	$(10 \times 8 \times 7)(\pm 2)$			0.1	S
JV Amalthea	$(125 \times 73 \times 64)(\pm 2)$			0.09	S
JXIV Thebe	$(58 \times 49 \times 42)(\pm 2)$			0.05	
JI Io	1821.3 ± 0.2	893.3 ± 1.5	3.53 ± 0.006	0.61	S
JII Europa	1565 ± 8	479.7 ± 1.5	3.02 ± 0.04	0.64	S[a]
JIII Ganymede	2634 ± 10	1482 ± 1	1.94 ± 0.02	0.42	S
JIV Callisto	2403 ± 5	1076 ± 1	1.85 ± 0.004	0.20	S
JVI Himalia	85 ± 10	0.042 ± 0.006			0.324
JVII Elara	40 ± 10				0.5
Saturn	$60\,268^2 \times 54\,364$	5.6850×10^6	0.687	0.47	0.44
SXVIII Pan	$17 \times 16 \times 10$	5×10^{-5}	0.41 ± 0.15	0.5	S
SXXXV Daphnis	$(4.5 \times 4.3 \times 3.1)(\pm 0.8)$	8×10^{-7}	0.34 ± 0.21		
SXV Atlas	$21 \times 18 \times 9$	7×10^{-5}	0.46 ± 0.1	0.9	S
SXVI Prometheus	$68 \times 40 \times 30$	0.001 6	0.48 ± 0.09	0.9	S
SXVII Pandora	$52 \times 41 \times 32$	0.001 37	0.49 ± 0.09	0.9	S
SXI Epimetheus	$65 \times 57 \times 53$	0.0053	0.64	0.8	S
SX Janus	$102 \times 93 \times 76$	0.019	0.63 ± 0.06	0.8	S
SI Mimas	$208 \times 196 \times 191$	0.38	1.15	0.5	S
SXXXIII Pallene	$3 \times 3 \times 2$				
SII Enceladus	$257 \times 251 \times 248$	0.65	1.61	1.0	S
SIII Tethys	533 ± 2	6.27	0.99	0.9	S
SXIV Calypso	$15 \times 11.5 \times 7$			0.6	
SXIII Telesto	$16 \times 12 \times 10$			0.5	
SIV Dione	561.7 ± 0.9	11.0	1.48	0.7	S
SXII Helene	$22 \times 19 \times 13$			0.7	
SXXXIV Polydeuces	$(1.5 \times 1.2 \times 1.0)(\pm 0.4)$				
SV Rhea	764 ± 2	23.1	1.24	0.7	S
SVI Titan	2575 ± 2	1345.7	1.88	0.21	~S
SVII Hyperion	$(180 \times 133 \times 103)(\pm 4)$	0.054	0.6	0.2–0.3	C
SVIII Iapetus	$746 \times 746 \times 712$	18.1 ± 1.5	1.09	0.05–0.5	S
SIX Phoebe	$109 \times 109 \times 102$	0.083	1.64	0.08	0.387
Uranus	$25\,559^2 \times 24\,973$	8.6625×10^5	1.318	0.51	0.718
UVI Cordelia	13 ± 2			0.07	
UVII Ophelia	16 ± 2			0.07	
UVIII Bianca	22 ± 3			0.07	
UIX Cressida	33 ± 4			0.07	
UX Desdemona	29 ± 3			0.07	

(*cont.*)