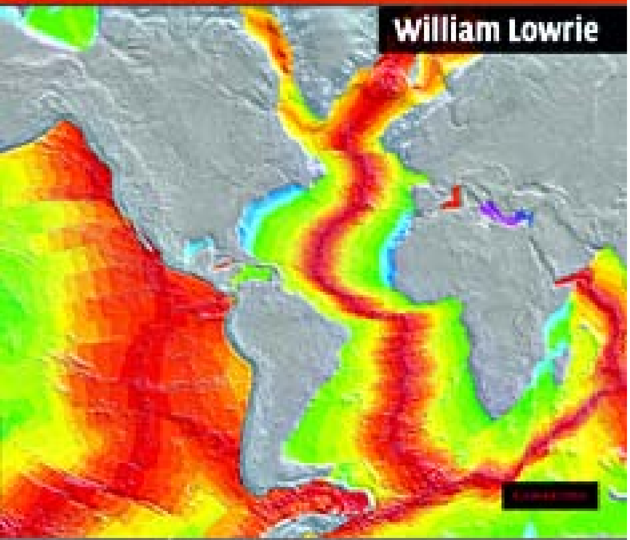
Second Edition

Fundamentals of Geophysics

William Lowrie



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Fundamentals of Geophysics
Second Edition

This second edition of *Fundamentals of Geophysics* has been completely revised and updated, and is the ideal geophysics textbook for undergraduate students of geoscience with only an introductory level of knowledge in physics and mathematics.

Presenting a comprehensive overview of the fundamental principles of each major branch of geophysics (gravity, seismology, geochronology, thermodynamics, geoelectricity, and geomagnetism), this text also considers geophysics within the wider context of plate tectonics, geodynamics, and planetary science. Basic principles are explained with the aid of numerous figures, and important geophysical results are illustrated with examples from scientific literature. Step-by-step mathematical treatments are given where necessary, allowing students to easily follow the derivations. Text boxes highlight topics of interest for more advanced students.

Each chapter contains a short historical summary and ends with a reading list that directs students to a range of simpler, alternative, or more advanced, resources. This new edition also includes review questions to help evaluate the reader's understanding of the topics covered, and quantitative exercises at the end of each chapter. Solutions to the exercises are available to instructors.

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Fundamentals of Geophysics

Second Edition

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Preface to the second edition

In the ten years that have passed since the publication of the first edition of this textbook exciting advances have taken place in every discipline of geophysics. Computer-based improvements in technology have led the way, allowing more sophistication in the acquisition and processing of geophysical data. Advances in mass spectrometry have made it possible to analyze minute samples of matter in exquisite detail and have contributed to an improved understanding of the origin of our planet and the evolution of the solar system. Space research has led to better knowledge of the other planets in the solar system, and has revealed distant objects in orbit around the Sun. As a result, the definition of a planet has been changed. Satellite-based technology has provided more refined measurement of the gravity and magnetic fields of the Earth, and has enabled direct observation from space of minute surface changes related to volcanic and tectonic events. The structure, composition and dynamic behavior of the deep interior of the Earth have become better understood owing to refinements in seismic tomography. Fast computers and sophisticated algorithms have allowed scientists to construct plausible models of slow geodynamic behavior in the Earth's mantle and core, and to elucidate the processes giving rise to the Earth's magnetic field. The application of advanced computer analysis in high-resolution seismic reflection and ground-penetrating radar investigations has made it possible to describe subtle features of environmental interest in near-surface structures. Rock magnetic techniques applied to sediments have helped us to understand slow natural processes as well as more rapid anthropological changes that affect our environment, and to evaluate climates in the distant geological past. Climatic history in the more recent past can now be deduced from the analysis of temperature in boreholes.

Although the many advances in geophysical research depend strongly on the aid of computer science, the fundamental principles of geophysical methods remain the same; they constitute the foundation on which progress is based. In revising this textbook, I have heeded the advice of teachers who have used it and who recommended that I change as little as possible and only as much as necessary (to paraphrase medical advice on the use of medication). The reviews of the first edition, the feedback from numerous students and teachers, and the advice of friends and colleagues helped me greatly in deciding what to do.

The structure of the book has been changed slightly compared to the first edition. The final chapter on geodynamics has been removed and its contents integrated into the earlier chapters, where they fit better. Text-boxes have been introduced to handle material that merited further explanation, or more extensive treatment than seemed appropriate for the body of the text. Two appendices have been added to handle more adequately the three-dimensional wave equation and the cooling of a half-space, respectively. At the end of each chapter is a list of review questions that should help students to evaluate their knowledge of what they have read. Each chapter is also accompanied by a set of exercises. They are intended to provide practice in handling some of the numerical aspects of the topics discussed in the chapter. They should help the student to become more familiar with geophysical techniques and to develop a better understanding of the fundamental principles.

The first edition was mostly free of errata, in large measure because of the patient, accurate and meticulous proofreading by my wife Marcia, whom I sincerely thank. Some mistakes still occurred, mostly in the more than 350 equations, and were spotted and communicated to me by colleagues and students in time to be corrected in the second printing of the first edition. Regarding the students, this did not improve (or harm) their grades, but I was impressed and pleased that they were reading the book so carefully. Among the colleagues, I especially thank Bob Carmichael for painstakingly listing many corrections and Ray Brown for posing important questions. Constructive criticisms and useful suggestions for additions and changes to the individual revised chapters in this edition were made by Mark Bukowinski, Clark Wilson, Doug Christensen, Jim Dewey, Henry Pollack, Ladislaus Rybach, Chris Heinrich, Hans-Ruedi Maurer and Mike Fuller. I am very grateful to these colleagues for the time they expended and their unselfish efforts to help me. If errors persist in this edition, it is not their fault but due to my negligence.

The publisher of this textbook, Cambridge University Press, is a not-for-profit charitable institution. One of their activities is to promote academic literature in the "third world." With my agreement, they decided to publish a separate low-cost version of the first edition, for sale only in developing countries. This version accounted for about one-third of the sales of the first edition. As a result, earth science students in developing countries could be helped in their studies of geophysics; several sent me appreciative messages, which I treasure.

The bulk of this edition has been written following my retirement two years ago, after 30 years as professor of geophysics at ETH Zürich. My new emeritus status should have provided lots of time for the project, but somehow it took longer than I expected. My wife Marcia exhibited her usual forbearance and understanding for my obsession. I thank her for her support, encouragement and practical suggestions, which have been as important for this as for the first edition. This edition is dedicated to her, as well as to my late parents.

William Lowrie
Zürich
August, 2006

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1 The Earth as a planet

1.1 THE SOLAR SYSTEM

1.1.1 The discovery and description of the planets

To appreciate how impressive the night sky must have been to early man it is necessary today to go to a place remote from the distracting lights and pollution of urban centers. Viewed from the wilderness the firmaments appear to the naked eye as a canopy of shining points, fixed in space relative to each other. Early observers noted that the star pattern appeared to move regularly and used this as a basis for determining the timing of events. More than 3000 years ago, in about the thirteenth century BC, the year and month were combined in a working calendar by the Chinese, and about 350 BC the Chinese astronomer Shih Shen prepared a catalog of the positions of 800 stars. The ancient Greeks observed that several celestial bodies moved back and forth against this fixed background and called them the *planetes*, meaning "wanderers." In addition to the Sun and Moon, the naked eye could discern the planets Mercury, Venus, Mars, Jupiter and Saturn.

Geometrical ideas were introduced into astronomy by the Greek philosopher Thales in the sixth century BC. This advance enabled the Greeks to develop astronomy to its highest point in the ancient world. Aristotle (384–322 BC) summarized the Greek work performed prior to his time and proposed a model of the universe with the Earth at its center. This *geocentric* model became imbedded in religious conviction and remained in authority until late into the Middle Ages. It did not go undisputed; Aristarchus of Samos (c.310–c.230 BC) determined the sizes and distances of the Sun and Moon relative to the Earth and proposed a *heliocentric* (sun-centered) cosmology. The methods of trigonometry developed by Hipparchus (190–120 BC) enabled the determination of astronomical distances by observation of the angular positions of celestial bodies. Ptolemy, a Greco-Egyptian astronomer in the second century AD, applied these methods to the known planets and was able to predict their motions with remarkable accuracy considering the primitiveness of available instrumentation.

Until the invention of the telescope in the early seventeenth century the main instrument used by astronomers for determining the positions and distances of heavenly bodies was the *astrolabe*. This device consisted of a disk of wood or metal with the circumference marked off in degrees. At its center was pivoted a movable pointer called the *alidade*. Angular distances could be determined by sighting on a body with the alidade and reading off its elevation from the graduated scale. The inventor of the astrolabe is not known, but it is often ascribed to Hipparchus (190–120 BC). It remained an important tool for navigators until the invention of the sextant in the eighteenth century.

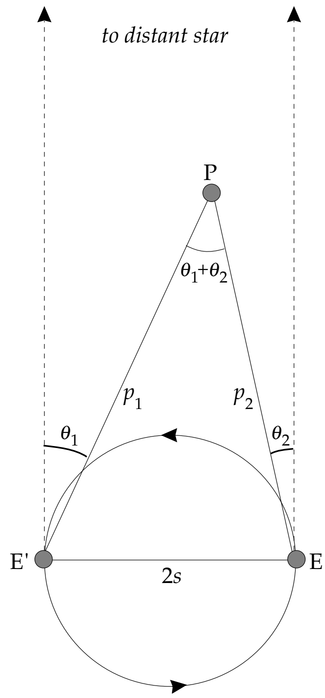

Fig. 1.1 Illustration of the method of parallax in which two measured angles (θ_1 and θ_2) are used to compute the distances (p_1 and p_2) of a planet from the Earth in terms of the Earth–Sun distance (s).

The angular observations were converted into distances by applying the method of parallax. This is simply illustrated by the following example. Consider the planet P as viewed from the Earth at different positions in the latter's orbit around the Sun (Fig. 1.1). For simplicity, treat planet P as a stationary object (i.e., disregard the planet's orbital motion). The angle between a sighting on the planet and on a fixed star will appear to change because of the Earth's orbital motion around the Sun. Let the measured extreme angles be θ_1 and θ_2 and the distance of the Earth from the Sun be s; the distance between the extreme positions E and E′ of the orbit is then $2s$. The distances p_1 and p_2 of the planet from the Earth are computed in terms of the Earth–Sun distance by applying the trigonometric law of sines:

$$\frac{p_1}{2s} = \frac{\sin(90-\theta_2)}{\sin(\theta_1+\theta_2)} = \frac{\cos\theta_2}{\sin(\theta_1+\theta_2)}$$
$$\frac{p_2}{2s} = \frac{\cos\theta_1}{\sin(\theta_1+\theta_2)} \tag{1.1}$$

Further trigonometric calculations give the distances of the planets from the Sun. The principle of parallax was also used to determine relative distances in the Aristotelian geocentric system, according to which the fixed stars, Sun, Moon and planets are considered to be in motion about the Earth.

In 1543, the year of his death, the Polish astronomer Nicolas Copernicus published a revolutionary work in which he asserted that the Earth was not the center of the universe. According to his model the Earth rotated about its own axis, and it and the other planets revolved about the Sun. Copernicus calculated the sidereal period of each planet about the Sun; this is the time required for a planet to make one revolution and return to the same angular position relative to a fixed star. He also determined the radii of their orbits about the Sun in terms of the Earth–Sun distance. The mean radius of the Earth's orbit about the Sun is called an *astronomical unit*; it equals 149,597,871 km. Accurate values of these parameters were calculated from observations compiled during an interval of 20 years by the Danish astronomer Tycho Brahe (1546–1601). On his death the records passed to his assistant, Johannes Kepler (1571–1630). Kepler succeeded in fitting the observations into a heliocentric model for the system of known planets. The three laws in which Kepler summarized his deductions were later to prove vital to Isaac Newton for verifying the law of Universal Gravitation. It is remarkable that the database used by Kepler was founded on observations that were unaided by the telescope, which was not invented until early in the seventeenth century.

1.1.2 Kepler's laws of planetary motion

Kepler took many years to fit the observations of Tycho Brahe into three laws of planetary motion. The first and second laws (Fig. 1.2) were published in 1609 and the third law appeared in 1619. The laws may be formulated as follows:

(1) the orbit of each planet is an ellipse with the Sun at one focus;
(2) the orbital radius of a planet sweeps out equal areas in equal intervals of time;
(3) the ratio of the square of a planet's period (T^2) to the cube of the semi-major axis of its orbit (a^3) is a constant for all the planets, including the Earth.

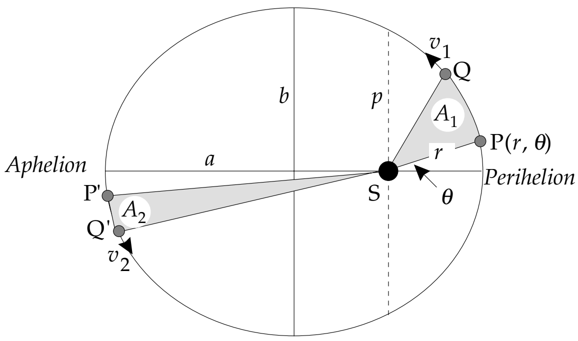

Fig. 1.2 Kepler's first two laws of planetary motion: (1) each planetary orbit is an ellipse with the Sun at one focus, and (2) the radius to a planet sweeps out equal areas in equal intervals of time.

Kepler's three laws are purely empirical, derived from accurate observations. In fact they are expressions of more fundamental physical laws. The elliptical shapes of planetary orbits (Box 1.1) described by the first law are a consequence of the *conservation of energy* of a planet orbiting the Sun under the effect of a central attraction that varies as the *inverse square* of distance. The second law describing the rate of motion of the planet around its orbit follows directly from the *conservation of angular momentum* of the planet. The third law results from the balance between the force of gravitation attracting the planet towards the Sun and the centrifugal force away from the Sun due to its orbital speed. The third law is easily proved for circular orbits (see Section 2.3.2.3).

Kepler's laws were developed for the solar system but are applicable to any closed planetary system. They govern the motion of any natural or artificial satellite about a parent body. Kepler's third law relates the period (T) and the semi-major axis (a) of the orbit of the satellite to the mass (M) of the parent body through the equation

$$GM = \frac{4\pi^2}{T^2}a^3 \tag{1.2}$$

where G is the gravitational constant. This relationship was extremely important for determining the masses of those planets that have natural satellites. It can now be applied to determine the masses of planets using the orbits of artificial satellites.

Special terms are used in describing elliptical orbits. The nearest and furthest points of a planetary orbit around the Sun are called *perihelion* and *aphelion*, respectively. The terms *perigee* and *apogee* refer to the corresponding nearest and furthest points of the orbit of the Moon or a satellite about the Earth.

1.1.3 Characteristics of the planets

Galileo Galilei (1564–1642) is often regarded as a founder of modern science. He made fundamental discoveries in astronomy and physics, including the formulation of the laws of motion. He was one of the first scientists to use the telescope to acquire more detailed information about

Box 1.1: Orbital parameters

The orbit of a planet or comet in the solar system is an ellipse with the Sun at one of its focal points. This condition arises from the conservation of energy in a force field obeying an inverse square law. The total energy (E) of an orbiting mass is the sum of its kinetic energy (K) and potential energy (U). For an object with mass m and velocity v in orbit at distance r from the Sun (mass S)

$$\frac{1}{2}mv^2 - G\frac{mS}{r} = E = \text{constant} \tag{1}$$

If the kinetic energy is greater than the potential energy of the gravitational attraction to the Sun ($E>0$), the object will escape from the solar system. Its path is a *hyperbola*. The same case results if $E=0$, but the path is a parabola. If $E<0$, the gravitational attraction binds the object to the Sun; the path is an ellipse with the Sun at one focal point (Fig. B1.1.1). An ellipse is defined as the locus of all points in a plane whose distances s_1 and s_2 from two fixed points F_1 and F_2 in the plane have a constant sum, defined as $2a$:

$$s_1 + s_2 = 2a \tag{2}$$

The distance $2a$ is the length of the major axis of the ellipse; the minor axis perpendicular to it has length $2b$, which is related to the major axis by the eccentricity of the ellipse, e:

$$e = \sqrt{1 - \frac{b^2}{a^2}} \tag{3}$$

The equation of a point on the ellipse with Cartesian coordinates (x, y) defined relative to the center of the figure is

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \tag{4}$$

The elliptical orbit of the Earth around the Sun defines the ecliptic plane. The angle between the orbital plane and the ecliptic is called the inclination of the orbit, and for most planets except Mercury (inclination 7°) and Pluto (inclination 17°) this is a small angle. A line perpendicular to the ecliptic defines the North and South ecliptic poles. If the fingers of one's right hand are wrapped around Earth's orbit in the direction of motion, the thumb points to the North ecliptic pole, which is in the constellation Draco ("the dragon"). Viewed from above this pole, all planets move around the Sun in a counterclockwise (prograde) sense.

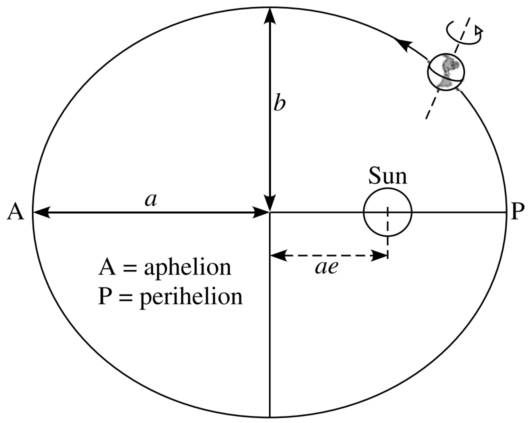

Fig. B1.1.1 The parameters of an elliptical orbit.

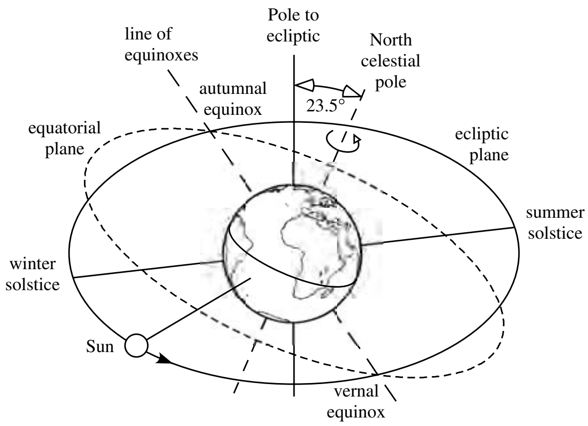

Fig. B1.1.2 The relationship between the ecliptic plane, Earth's equatorial plane and the line of equinoxes.

The rotation axis of the Earth is tilted away from the perpendicular to the ecliptic forming the angle of obliquity (Fig. B1.1.2), which is currently 23.5°. The equatorial plane is tilted at the same angle to the ecliptic, which it intersects along the line of equinoxes. During the annual motion of the Earth around the Sun, this line twice points to the Sun: on March 20, defining the vernal (spring) equinox, and on September 23, defining the autumnal equinox. On these dates day and night have equal length everywhere on Earth. The summer and winter solstices occur on June 21 and December 22, respectively, when the apparent motion of the Sun appears to reach its highest and lowest points in the sky.

the planets. In 1610 Galileo discovered the four largest satellites of Jupiter (called Io, Europa, Ganymede and Callisto), and observed that (like the Moon) the planet Venus exhibited different phases of illumination, from full disk to partial crescent. This was persuasive evidence in favor of the Copernican view of the solar system.

In 1686 Newton applied his theory of Universal Gravitation to observations of the orbit of Callisto and

Table 1.1 *Dimensions and rotational characteristics of the planets (data sources: Beatty* et al., *1999; McCarthy and Petit, 2004; National Space Science Data Center, 2004 [http://nssdc.gsfc.nasa.gov/planetary/])*

The great planets and Pluto are gaseous. For these planets the surface on which the pressure is 1 atmosphere is taken as the effective radius. In the definition of polar flattening, a and c are respectively the semi-major and semi-minor axes of the spheroidal shape.

Planet	Mass M [10^{24} kg]	Mass relative to Earth	Mean density [$\mathrm{kg\,m^{-3}}$]	Equatorial radius [km]	Sidereal rotation period [days]	Polar flattening $f=(a-c)/a$	Obliquity of rotation axis [°]
Terrestrial planets and the Moon							
Mercury	0.3302	0.0553	5,427	2,440	58.81	0.0	0.1
Venus	4.869	0.815	5,243	6,052	243.7	0.0	177.4
Earth	5.974	1.000	5,515	6,378	0.9973	0.003353	23.45
Moon	0.0735	0.0123	3,347	1,738	27.32	0.0012	6.68
Mars	0.6419	0.1074	3,933	3,397	1.0275	0.00648	25.19
Great planets and Pluto							
Jupiter	1,899	317.8	1,326	71,492	0.414	0.0649	3.12
Saturn	568.5	95.2	687	60,268	0.444	0.098	26.73
Uranus	86.8	14.4	1,270	25,559	0.720	0.023	97.86
Neptune	102.4	17.15	1,638	24,766	0.671	0.017	29.6
Pluto	0.125	0.0021	1,750	1,195	6.405	—	122.5

calculated the mass of Jupiter (J) relative to that of the Earth (E). The value of the gravitational constant G was not yet known; it was first determined by Lord Cavendish in 1798. However, Newton calculated the value of GJ to be 124,400,000 $\mathrm{km^3\,s^{-2}}$. This was a very good determination; the modern value for GJ is 126,712,767 $\mathrm{km^3\,s^{-2}}$. Observations of the Moon's orbit about the Earth showed that the value GE was 398,600 $\mathrm{km^3\,s^{-2}}$. Hence Newton inferred the mass of Jupiter to be more than 300 times that of the Earth.

In 1781 William Herschel discovered Uranus, the first planet to be found by telescope. The orbital motion of Uranus was observed to have inconsistencies, and it was inferred that the anomalies were due to the perturbation of the orbit by a yet undiscovered planet. The predicted new planet, Neptune, was discovered in 1846. Although Neptune was able to account for most of the anomalies of the orbit of Uranus, it was subsequently realized that small residual anomalies remained. In 1914 Percival Lowell predicted the existence of an even more distant planet, the search for which culminated in the detection of Pluto in 1930.

The masses of the planets can be determined by applying Kepler's third law to the observed orbits of natural and artificial satellites and to the tracks of passing spacecraft. Estimation of the sizes and shapes of the planets depends on data from several sources. Early astronomers used occultations of the stars by the planets; an occultation is the eclipse of one celestial body by another, such as when a planet passes between the Earth and a star. The duration of an occultation depends on the diameter of the planet, its distance from the Earth and its orbital speed.

The dimensions of the planets (Table 1.1) have been determined with improved precision in modern times by the availability of data from spacecraft, especially from radar-ranging and Doppler tracking (see Box 1.2). Radar-ranging involves measuring the distance between an orbiting (or passing) spacecraft and the planet's surface from the two-way travel-time of a pulse of electromagnetic waves in the radar frequency range. The separation can be measured with a precision of a few centimeters. If the radar signal is reflected from a planet that is moving away from the spacecraft the frequency of the reflection is lower than that of the transmitted signal; the opposite effect is observed when the planet and spacecraft approach each other. The Doppler frequency shift yields the relative velocity of the spacecraft and planet. Together, these radar methods allow accurate determination of the path of the spacecraft, which is affected by the mass of the planet and the shape of its gravitational equipotential surfaces (see Section 2.2.3).

The rate of rotation of a planet about its own axis can be determined by observing the motion of features on its surface. Where this is not possible (e.g., the surface of Uranus is featureless) other techniques must be employed. In the case of Uranus the rotational period of 17.2 hr was determined from periodic radio emissions produced by electrical charges trapped in its magnetic field; they were detected by the Voyager 2 spacecraft when it flew by the planet in 1986. All planets revolve around the Sun in the same sense, which is counterclockwise when viewed from above the plane of the Earth's orbit (called the *ecliptic* plane). Except for Pluto, the orbital plane of each planet is inclined to the ecliptic at a small angle (Table 1.2). Most of the planets rotate about their rotation axis in the same sense as their orbital motion about the Sun, which is termed *prograde*. Venus rotates in the opposite, *retrograde* sense. The angle between a rotation axis and the ecliptic plane is called the

Box 1.2: Radar and the Doppler effect

The name *radar* derives from the acronym for RA*dio* D*etection* A*nd* R*anging*, a defensive system developed during World War II for the location of enemy aircraft. An electromagnetic signal in the microwave frequency range (see Fig. 4.59), consisting of a continuous wave or a series of short pulses, is transmitted toward a target, from which a fraction of the incident energy is reflected to a receiver. The laws of optics for visible light apply equally to radar waves, which are subject to reflection, refraction and diffraction. Visible light has short wavelengths (400–700 nm) and is scattered by the atmosphere, especially by clouds. Radar signals have longer wavelengths (~1 cm to 30 cm) and can pass through clouds and the atmosphere of a planet with little dispersion. The radar signal is transmitted in a narrow beam of known azimuth, so that the returning echo allows exact location of the direction to the target. The signal travels at the speed of light so the distance, or range, to the target may be determined from the time difference at the source between the transmitted and reflected signals.

The transmitted and reflected radar signals lose energy in transit due to atmospheric absorption, but more importantly, the amplitude of the reflected signal is further affected by the nature of the reflecting surface. Each part of the target's surface illuminated by the radar beam contributes to the reflected signal. If the surface is inclined obliquely to the incoming beam, little energy will reflect back to the source. The reflectivity and roughness of the reflecting surface determine how much of the incident energy is absorbed or scattered. The intensity of the reflected signal can thus be used to characterize the type and orientation of the reflecting surface, e.g., whether it is bare or forested, flat or mountainous.

The *Doppler effect*, first described in 1842 by an Austrian physicist, Christian Doppler, explains how the relative motion between source and detector influences the observed frequency of light and sound waves. For example, suppose a stationary radar source emits a signal consisting of n_0 pulses per second. The frequency of pulses reflected from a stationary target at distance d is also n_0, and the two-way travel-time of each pulse is equal to $2(d/c)$, where c is the speed of light. If the target is moving toward the radar source, its velocity v shortens the distance between the radar source and the target by $(vt/2)$, where t is the new two-way travel-time:

$$t = 2\left(\frac{d-(vt/2)}{c}\right) = t_0 - \frac{v}{c}t \qquad (1)$$

$$t = t_0/(1+v/c) \qquad (2)$$

The travel-time of each reflected pulse is shortened, so the number of reflected pulses (n) received per second is correspondingly higher than the number emitted:

$$n = n_0(1+v/c) \qquad (3)$$

The opposite situation arises if the target is moving away from the source: the frequency of the reflected signal is lower than that emitted. Similar principles apply if the radar source is mounted on a moving platform, such as an aircraft or satellite. The Doppler change in signal frequency in each case allows remote measurement of the relative velocity between an object and a radar transmitter.

In another important application, the Doppler effect provides evidence that the universe is expanding. The observed frequency of light from a star (i.e., its color) depends on the velocity of its motion relative to an observer on Earth. The color of the star shifts toward the red end of the spectrum (lower frequency) if the star is receding from Earth and toward the blue end (higher frequency) if it is approaching Earth. The color of light from many distant galaxies has a "red shift," implying that these galaxies are receding from the Earth.

obliquity of the axis. The rotation axes of Uranus and Pluto lie close to their orbital planes; they are tilted away from the pole to the orbital plane at angles greater than 90°, so that, strictly speaking, their rotations are also retrograde.

The relative sizes of the planets are shown in Fig. 1.3. They form three categories on the basis of their physical properties (Table 1.1). The *terrestrial planets* (Mercury, Venus, Earth and Mars) resemble the Earth in size and density. They have a solid, rocky composition and they rotate about their own axes at the same rate or slower than the Earth. The great, or *Jovian*, planets (Jupiter, Saturn, Uranus and Neptune) are much larger than the Earth and have much lower densities. Their compositions are largely gaseous and they rotate more rapidly than the Earth. Pluto's large orbit is highly elliptical and more steeply inclined to the ecliptic than that of any other planet. Its physical properties are different from both the great planets and the terrestrial planets. These nine bodies are called the *major planets*. There are other large objects in orbit around the Sun, called *minor planets*, which do not fulfil the criteria common to the definition of the major planets. The discovery of large objects in the solar system beyond the orbit of Neptune has stimulated debate among astronomers about what these criteria should be. As a result, Pluto has been reclassified as a "*dwarf planet*."

1.1.3.1 Bode's law

In 1772 the German astronomer Johann Bode devised an empirical formula to express the approximate distances of

Table 1.2 *Dimensions and characteristics of the planetary orbits (data sources: Beatty* et al., *1999; McCarthy and Petit, 2004; National Space Science Data Center, 2004 [http://nssdc.gsfc.nasa.gov/planetary/])*

Planet	Mean orbital radius [AU]	Semi-major axis [10^6 km]	Eccentricity of orbit	Inclination of orbit to ecliptic [°]	Mean orbital velocity [km s^{-1}]	Sidereal period of orbit [yr]
Terrestrial planets and the Moon						
Mercury	0.3830	57.91	0.2056	7.00	47.87	0.2408
Venus	0.7234	108.2	0.0068	3.39	35.02	0.6152
Earth	1.0000	149.6	0.01671	0.0	29.79	1.000
Moon (about Earth)	0.00257	0.3844	0.0549	5.145	1.023	0.0748
Mars	1.520	227.9	0.0934	1.85	24.13	1.881
Great planets and Pluto						
Jupiter	5.202	778.4	0.0484	1.305	13.07	11.86
Saturn	9.576	1,427	0.0542	2.484	9.69	29.4
Uranus	19.19	2,871	0.0472	0.77	6.81	83.7
Neptune	30.07	4,498	0.00859	1.77	5.43	164.9
Pluto	38.62	5,906	0.249	17.1	4.72	248

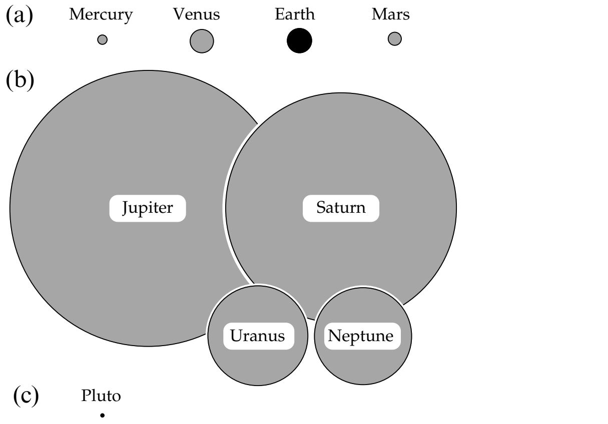

Fig. 1.3 The relative sizes of the planets: (a) the terrestrial planets, (b) the great (Jovian) planets and (c) Pluto, which is diminutive compared to the others.

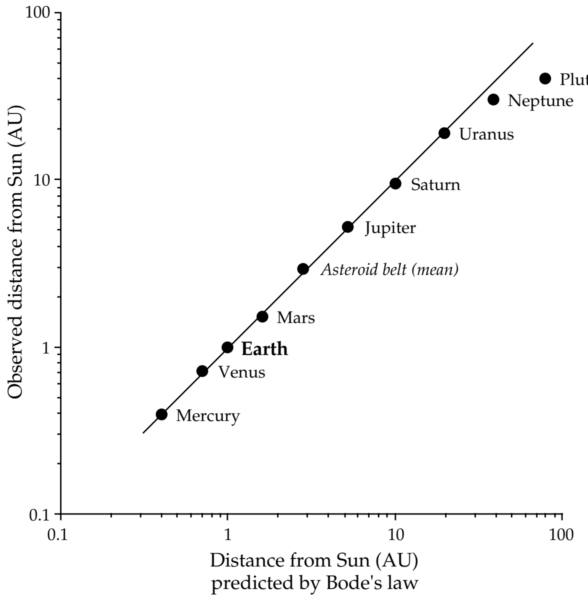

Fig. 1.4 Bode's empirical law for the distances of the planets from the Sun.

the planets from the Sun. A series of numbers is created in the following way: the first number is zero, the second is 0.3, and the rest are obtained by doubling the previous number. This gives the sequence 0, 0.3, 0.6, 1.2, 2.4, 4.8, 9.6, 19.2, 38.4, 76.8, etc. Each number is then augmented by 0.4 to give the sequence: 0.4, 0.7, 1.0, 1.6, 2.8, 5.2, 10.0, 19.6, 38.8, 77.2, etc. This series can be expressed mathematically as follows:

$$\begin{aligned} d_n &= 0.4 \quad \text{for } n = 1 \\ d_n &= 0.4 + 0.3 \times 2^{n-2} \quad \text{for } n \geq 2 \end{aligned} \tag{1.3}$$

This expression gives the distance d_n in astronomical units (AU) of the nth planet from the Sun. It is usually known as Bode's law but, as the same relationship had been suggested earlier by J. D. Titius of Wittenberg, it is sometimes called Titius–Bode's law. Examination of Fig. 1.4 and comparison with Table 1.2 show that this relationship holds remarkably well, except for Neptune and Pluto. A possible interpretation of the discrepancies is that the orbits of these planets are no longer their original orbits.

Bode's law predicts a fifth planet at 2.8 AU from the Sun, between the orbits of Mars and Jupiter. In the last years of the eighteenth century astronomers searched intensively for this missing planet. In 1801 a small planetoid, Ceres, was found at a distance of 2.77 AU from the Sun. Subsequently, it was found that numerous small planetoids occupied a broad band of solar orbits centered about 2.9 AU, now called the *asteroid belt*. Pallas was found in 1802, Juno in 1804, and Vesta, the only asteroid that can be seen with the naked eye, was found in 1807. By 1890 more than 300 asteroids had been identified. In 1891 astronomers began to record their paths on photographic plates. Thousands of asteroids occupying a broad belt between Mars and Jupiter, at distances of 2.15–3.3 AU from the Sun, have since been tracked and cataloged.

Bode's law is not a true law in the scientific sense. It should be regarded as an intriguing empirical relationship. Some astronomers hold that the regularity of the planetary distances from the Sun cannot be mere chance but must be a manifestation of physical laws. However, this may be wishful thinking. No combination of physical laws has yet been assembled that accounts for Bode's law.

1.1.3.2 The terrestrial planets and the Moon

Mercury is the closest planet to the Sun. This proximity and its small size make it difficult to study telescopically. Its orbit has a large eccentricity (0.206). At perihelion the planet comes within 46.0 million km (0.313 AU) of the Sun, but at aphelion the distance is 69.8 million km (0.47 AU). Until 1965 the rotational period was thought to be the same as the period of revolution (88 days), so that it would keep the same face to the Sun, in the same way that the Moon does to the Earth. However, in 1965 Doppler radar measurements showed that this is not the case. In 1974 and 1975 images from the close passage of Mariner 10, the only spacecraft to have visited the planet, gave a period of rotation of 58.8 days, and Doppler tracking gave a radius of 2439 km.

The spin and orbital motions of Mercury are both prograde and are coupled in the ratio 3:2. The spin period is 58.79 Earth days, almost exactly 2/3 of its orbital period of 87.97 Earth days. For an observer on the planet this has the unusual consequence that a Mercury day lasts longer than a Mercury year! During one orbital revolution about the Sun (one Mercury year) an observer on the surface rotates about the spin axis 1.5 times and thus advances by an extra half turn. If the Mercury year started at sunrise, it would end at sunset, so the observer on Mercury would spend the entire 88 Earth days exposed to solar heating, which causes the surface temperature to exceed 700 K. During the following Mercury year, the axial rotation advances by a further half-turn, during which the observer is on the night side of the planet for 88 days, and the temperature sinks below 100 K. After 2 solar orbits and 3 axial rotations, the observer is back at the starting point. The range of temperatures on the surface of Mercury is the most extreme in the solar system.

Although the mass of Mercury is only about 5.5% that of the Earth, its mean density of 5427 kg m^{-3} is comparable to that of the Earth (5515 kg m^{-3}) and is the second highest in the solar system. This suggests that, like Earth, Mercury's interior is dominated by a large iron core, whose radius is estimated to be about 1800–1900 km. It is enclosed in an outer shell 500–600 km thick, equivalent to Earth's mantle and crust. The core may be partly molten. Mercury has a weak planetary magnetic field.

Venus is the brightest object in the sky after the Sun and Moon. Its orbit brings it closer to Earth than any other planet, which made it an early object of study by telescope. Its occultation with the Sun was observed telescopically as early as 1639. Estimates of its radius based on occultations indicated about 6120 km. Galileo observed that the apparent size of Venus changed with its position in orbit and, like the Moon, the appearance of Venus showed different phases from crescent-shaped to full. This was important evidence in favor of the Copernican heliocentric model of the solar system, which had not yet replaced the Aristotelian geocentric model.

Venus has the most nearly circular orbit of any planet, with an eccentricity of only 0.007 and mean radius of 0.72 AU (Table 1.2). Its orbital period is 224.7 Earth days, and the period of rotation about its own axis is 243.7 Earth days, longer than the Venusian year. Its spin axis is tilted at 177° to the pole to the ecliptic, thus making its spin *retrograde*. The combination of these motions results in the length of a Venusian day (the time between successive sunrises on the planet) being equal to about 117 Earth days.

Venus is very similar in size and probable composition to the Earth. During a near-crescent phase the planet is ringed by a faint glow indicating the presence of an atmosphere. This has been confirmed by several spacecraft that have visited the planet since the first visit by Mariner 2 in 1962. The atmosphere consists mainly of carbon dioxide and is very dense; the surface atmospheric pressure is 92 times that on Earth. Thick cloud cover results in a strong greenhouse effect that produces stable temperatures up to 740 K, slightly higher than the maximum day-time values on Mercury, making Venus the hottest of the planets. The thick clouds obscure any view of the surface, which has however been surveyed with radar. The Magellan spacecraft, which was placed in a nearly polar orbit around the planet in 1990, carried a radar-imaging system with an optimum resolution of 100 meters, and a radar altimeter system to measure the topography and some properties of the planet's surface.

Venus is unique among the planets in rotating in a *retrograde* sense about an axis that is almost normal to the ecliptic (Table 1.1). Like Mercury, it has a high Earth-like density (5243 kg m^{-3}). On the basis of its density together with gravity estimates from Magellan's orbit, it is thought that the interior of Venus may be similar to that of Earth, with a rocky mantle surrounding an iron core about 3000 km in radius, that is possibly at least partly molten. However, in contrast to the Earth, Venus has no detectable magnetic field.

The **Earth** moves around the Sun in a slightly elliptical orbit. The parameters of the orbital motion are important, because they define astronomical units of distance and time. The Earth's rotation about its own axis from one solar zenith to the next one defines the solar day (see Section 4.1.1.2). The length of time taken for it to complete one orbital revolution about the Sun defines the solar year, which is equal to 365.242 solar days. The eccentricity of the orbit is presently 0.01671 but it varies between a minimum of 0.001 and a maximum of 0.060 with a period of about 100,000 yr due to the influence of the other planets. The mean radius of the orbit (149,597,871 km) is called an *astronomical unit* (*AU*). Distances within the solar system are usually expressed as multiples of this unit. The distances to extra-galactic celestial bodies are expressed as multiples of a light-year (the distance travelled by light in one year). The Sun's light takes about 8 min 20 s to reach the Earth. Owing to the difficulty of determining the gravitational constant the mass of the Earth (E) is not known with high precision, but is estimated to be 5.9737×10^{24} kg. In contrast, the product GE is known accurately; it is equal to $3.986004418 \times 10^{14}$ $m^3\ s^{-2}$. The rotation axis of the Earth is presently inclined at 23.439° to the pole of the ecliptic. However, the effects of other planets also cause the angle of *obliquity* to vary between a minimum of 21.9° and a maximum of 24.3°, with a period of about 41,000 yr.

The **Moon** is Earth's only natural satellite. The distance of the Moon from the Earth was first estimated with the method of parallax. Instead of observing the Moon from different positions of the Earth's orbit, as shown in Fig. 1.1, the Moon's position relative to a fixed star was observed at times 12 hours apart, close to moonrise and moonset, when the Earth had rotated through half a revolution. The baseline for the measurement is then the Earth's diameter. The distance of the Moon from the Earth was found to be about 60 times the Earth's radius.

The Moon rotates about its axis in the same sense as its orbital revolution about the Earth. Tidal friction resulting from the Earth's attraction has slowed down the Moon's rotation, so that it now has the same mean period as its revolution, 27.32 days. As a result, the Moon always presents the same face to the Earth. In fact, slightly more than half (about 59%) of the lunar surface can be viewed from the Earth. Several factors contribute to this. First, the plane of the Moon's orbit around the Earth is inclined at 5°9′ to the ecliptic while the Moon's equator is inclined at 1°32′ to the ecliptic. The inclination of the Moon's equator varies by up to 6°41′ to the plane of its orbit. This is called the *libration of latitude*. It allows Earth-based astronomers to see 6°41′ beyond each of the Moon's poles. Secondly, the Moon moves with variable velocity around its elliptical orbit, while its own rotation is constant. Near perigee the Moon's orbital velocity is fastest (in accordance with Kepler's second law) and the rate of revolution exceeds slightly the constant rate of lunar rotation. Similarly, near apogee the Moon's orbital velocity is slowest and the rate of revolution is slightly less than the rate of rotation. The rotational differences are called the Moon's *libration of longitude*. Their effect is to expose zones of longitude beyond the average edges of the Moon. Finally, the Earth's diameter is quite large compared to the Moon's distance from Earth. During Earth's rotation the Moon is viewed from different angles that allow about one additional degree of longitude to be seen at the Moon's edge.

The distance to the Moon and its rotational rate are well known from laser-ranging using reflectors placed on the Moon by astronauts. The accuracy of laser-ranging is about 2–3 cm. The Moon has a slightly elliptical orbit about the Earth, with eccentricity 0.0549 and mean radius 384,100 km. The Moon's own radius of 1738 km makes it much larger relative to its parent body than the natural satellites of the other planets except for Pluto's moon, Charon. Its low density of 3347 kg m^{-3} may be due to the absence of an iron core. The internal composition and dynamics of the Moon have been inferred from instruments placed on the surface and rocks recovered from the Apollo and Luna manned missions. Below a crust that is on average 68 km thick the Moon has a mantle and a small core about 340 km in radius. In contrast to the Earth, the interior is not active, and so the Moon does not have a global magnetic field.

Mars, popularly called the red planet because of its hue when viewed from Earth, has been known since prehistoric times and was also an object of early telescopic study. In 1666 Gian Domenico Cassini determined the rotational period at just over 24 hr; radio-tracking from two Viking spacecraft that landed on Mars in 1976, more than three centuries later, gave a period of 24.623 hr. The orbit of Mars is quite elliptical (eccentricity 0.0934). The large difference between perihelion and aphelion causes large temperature variations on the planet. The average surface temperature is about 218 K, but temperatures range from 140 K at the poles in winter to 300 K on the day side in summer. Mars has two natural satellites, Phobos and Deimos. Observations of their orbits gave early estimates of the mass of the planet. Its size was established quite early telescopically from occultations. Its shape is known very precisely from spacecraft observations. The polar flattening is about double that of the Earth. The rotation rates of Earth and Mars are almost the same, but the lower mean density of Mars results in smaller gravitational forces, so at any radial distance the relative importance of the centrifugal acceleration is larger on Mars than on Earth.

In 2004 the Mars Expedition Rover vehicles *Spirit* and *Opportunity* landed on Mars, and transmitted photographs and geological information to Earth. Three spacecraft (*Mars Global Surveyor*, *Mars Odyssey*, and *Mars Express*) were placed in orbit to carry out surveys of the planet. These and earlier orbiting spacecraft and Martian landers have revealed details of the planet that cannot be determined with a distant telescope (including the Earth-orbiting Hubble telescope). Much of the Martian surface is very old and cratered, but there are also much younger rift valleys, ridges, hills and plains. The topography is varied and dramatic, with mountains that rise to 24 km, a 4000 km long canyon system, and impact craters up to 2000 km across and 6 km deep.

The internal structure of Mars can be inferred from the results of these missions. Mars has a relatively low mean density (3933 kg m^{-3}) compared to the other terrestrial planets. Its mass is only about a tenth that of Earth

(Table 1.1), so the pressures in the planet are lower and the interior is less densely compressed. Mars has an internal structure similar to that of the Earth. A thin crust, 35 km thick in the northern hemisphere and 80 km thick in the southern hemisphere, surrounds a rocky mantle whose rigidity decreases with depth as the internal temperature increases. The planet has a dense core 1500–1800 km in radius, thought to be composed of iron with a relatively large fraction of sulfur. Minute perturbations of the orbit of *Mars Global Surveyor*, caused by deformations of Mars due to solar tides, have provided more detailed information about the internal structure. They indicate that, like the Earth, Mars probably has a solid inner core and a fluid outer core that is, however, too small to generate a global magnetic field.

The **Asteroids** occur in many sizes, ranging from several hundred kilometers in diameter, down to bodies that are too small to discern from Earth. There are 26 asteroids larger than 200 km in diameter, but there are probably more than a million with diameters around 1 km. Some asteroids have been photographed by spacecraft in fly-by missions: in 1997 the NEAR-Shoemaker spacecraft orbited and landed on the asteroid Eros. Hubble Space Telescope imagery has revealed details of Ceres (diameter 950 km), Pallas (diameter 830 km) and Vesta (diameter 525 km), which suggest that it may be more appropriate to call these three bodies protoplanets (i.e., still in the process of accretion from planetesimals) rather than asteroids. All three are differentiated and have a layered internal structure like a planet, although the compositions of the internal layers are different. Ceres has an oblate spheroidal shape and a silicate core, and is the most massive asteroid; it has recently been reclassified as a "*dwarf planet*." Vesta's shape is more irregular and it has an iron core.

Asteroids are classified by type, reflecting their composition (stony carbonaceous or metallic nickel–iron), and by the location of their orbits. *Main belt* asteroids have near-circular orbits with radii 2–4 AU between Mars and Jupiter. The *Centaur* asteroids have strongly elliptical orbits that take them into the outer solar system. The *Aten* and *Apollo* asteroids follow elliptical Earth-crossing orbits. The collision of one of these asteroids with the Earth would have a cataclysmic outcome. A 1 km diameter asteroid would create a 10 km diameter crater and release as much energy as the simultaneous detonation of most or all of the nuclear weapons in the world's arsenals. In 1980 Luis and Walter Alvarez and their colleagues showed on the basis of an anomalous concentration of extra-terrestrial iridium at the Cretaceous–Tertiary boundary at Gubbio, Italy, that a 10 km diameter asteroid had probably collided with Earth, causing directly or indirectly the mass extinctions of many species, including the demise of the dinosaurs. There are 240 known Apollo bodies; however, there may be as many as 2000 that are 1 km in diameter and many thousands more measuring tens or hundreds of meters.

Scientific opinion is divided on what the asteroid belt represents. One idea is that it may represent fragments of an earlier planet that was broken up in some disaster. Alternatively, it may consist of material that was never able to consolidate into a planet, perhaps due to the powerful gravitational influence of Jupiter.

1.1.3.3 The great planets

The great planets are largely gaseous, consisting mostly of hydrogen and helium, with traces of methane, water and solid matter. Their compositions are inferred indirectly from spectroscopic evidence, because space probes have not penetrated their atmospheres to any great depth. In contrast to the rocky terrestrial planets and the Moon, the radius of a great planet does not correspond to a solid surface, but is taken to be the level that corresponds to a pressure of one bar, which is approximately Earth's atmospheric pressure at sea-level.

Each of the great planets is encircled by a set of concentric rings, made up of numerous particles. The rings around Saturn, discovered by Galileo in 1610, are the most spectacular. For more than three centuries they appeared to be a feature unique to Saturn, but in 1977 discrete rings were also detected around Uranus. In 1979 the Voyager 1 spacecraft detected faint rings around Jupiter, and in 1989 the Voyager 2 spacecraft confirmed that Neptune also has a ring system.

Jupiter has been studied from ground-based observatories for centuries, and more recently with the Hubble Space Telescope, but our detailed knowledge of the planet comes primarily from unmanned space probes that sent photographs and scientific data back to Earth. Between 1972 and 1977 the planet was visited by the Pioneer 10 and 11, Voyager 1 and 2, and Ulysses spacecraft. The spacecraft Galileo orbited Jupiter for eight years, from 1995 to 2003, and sent an instrumental probe into the atmosphere. It penetrated to a depth of 140 km before being crushed by the atmospheric pressure.

Jupiter is by far the largest of all the planets. Its mass (19×10^{26} kg) is 318 times that of the Earth (Table 1.1) and 2.5 times the mass of all the other planets added together (7.7×10^{26} kg). Despite its enormous size the planet has a very low density of only 1326 kg m^{-3}, from which it can be inferred that its composition is dominated by hydrogen and helium. Jupiter has at least 63 satellites, of which the four largest – Io, Europa, Ganymede and Callisto – were discovered in 1610 by Galileo. The orbital motions of Io, Europa and Ganymede are synchronous, with periods locked in the ratio 1:2:4. In a few hundred million years, Callisto will also become synchronous with a period 8 times that of Io. Ganymede is the largest satellite in the solar system; with a radius of 2631 km it is slightly larger than the planet Mercury. Some of the outermost satellites are less than 30 km in radius, revolve in retrograde orbits and may be captured asteroids. Jupiter has a system of rings, which are like those of Saturn but are fainter and smaller, and were first detected during analysis of data from

Voyager 1. Subsequently, they were investigated in detail during the Galileo mission.

Jupiter is thought to have a small, hot, rocky core. This is surrounded by concentric layers of hydrogen, first in a liquid-metallic state (which means that its atoms, although not bonded to each other, are so tightly packed that the electrons can move easily from atom to atom), then non-metallic liquid, and finally gaseous. The planet's atmosphere consists of approximately 86% hydrogen and 14% helium, with traces of methane, water and ammonia. The liquid-metallic hydrogen layer is a good conductor of electrical currents. These are the source of a powerful magnetic field that is many times stronger than the Earth's and enormous in extent. It stretches for several million kilometers toward the Sun and for several hundred million kilometers away from it. The magnetic field traps charged particles from the Sun, forming a zone of intense radiation outside Jupiter's atmosphere that would be fatal to a human being exposed to it. The motions of the electric charges cause radio emissions. These are modulated by the rotation of the planet and are used to estimate the period of rotation, which is about 9.9 hr.

Jupiter's moon Europa is the focus of great interest because of the possible existence of water below its icy crust, which is smooth and reflects sunlight brightly. The Voyager spacecraft took high-resolution images of the moon's surface, and gravity and magnetic data were acquired during close passages of the Galileo spacecraft. Europa has a radius of 1565 km, so is only slightly smaller than Earth's Moon, and is inferred to have an iron–nickel core within a rocky mantle, and an outer shell of water below a thick surface ice layer.

Saturn is the second largest planet in the solar system. Its equatorial radius is 60,268 km and its mean density is merely 687 kg m^{-3} (the lowest in the solar system and less than that of water). Thin concentric rings in its equatorial plane give the planet a striking appearance. The obliquity of its rotation axis to the ecliptic is 26.7°, similar to that of the Earth (Table 1.1). Consequently, as Saturn moves along its orbit the rings appear at different angles to an observer on Earth. Galileo studied the planet by telescope in 1610 but the early instrument could not resolve details and he was unable to interpret his observations as a ring system. The rings were explained by Christiaan Huygens in 1655 using a more powerful telescope. In 1675, Domenico Cassini observed that Saturn's rings consisted of numerous small rings with gaps between them. The rings are composed of particles of ice, rock and debris, ranging in size from dust particles up to a few cubic meters, which are in orbit around the planet. The origin of the rings is unknown; one theory is that they are the remains of an earlier moon that disintegrated, either due to an extra-planetary impact or as a result of being torn apart by bodily tides caused by Saturn's gravity.

In addition to its ring system Saturn has more than 30 moons, the largest of which, Titan, has a radius of 2575 km and is the only moon in the solar system with a dense atmosphere. Observations of the orbit of Titan allowed the first estimate of the mass of Saturn to be made in 1831. Saturn was visited by the Pioneer 11 spacecraft in 1979 and later by Voyager 1 and Voyager 2. In 2004 the spacecraft Cassini entered orbit around Saturn, and launched an instrumental probe, Huygens, that landed on Titan in January 2005. Data from the probe were obtained during the descent by parachute through Titan's atmosphere and after landing, and relayed to Earth by the orbiting Cassini spacecraft.

Saturn's period of rotation has been deduced from modulated radio emissions associated with its magnetic field. The equatorial zone has a period of 10 hr 14 min, while higher latitudes have a period of about 10 hr 39 min. The shape of the planet is known from occultations of radio signals from the Voyager spacecrafts. The rapid rotation and fluid condition result in Saturn having the greatest degree of polar flattening of any planet, amounting to almost 10%. Its mean density of 687 kg m^{-3} is the lowest of all the planets, implying that Saturn, like Jupiter, is made up mainly of hydrogen and helium and contains few heavy elements. The planet probably also has a similar layered structure, with rocky core overlain successively by layers of liquid-metallic hydrogen and molecular hydrogen. However, the gravitational field of Jupiter compresses hydrogen to a metallic state, which has a high density. This gives Jupiter a higher mean density than Saturn. Saturn has a planetary magnetic field that is weaker than Jupiter's but probably originates in the same way.

Uranus is so remote from the Earth that Earth-bound telescopic observation reveals no surface features. Until the fly-past of Voyager 2 in 1986 much had to be surmised indirectly and was inaccurate. Voyager 2 provided detailed information about the size, mass and surface of the planet and its satellites, and of the structure of the planet's ring system. The planet's radius is 25,559 km and its mean density is 1270 kg m^{-3}. The rotational period, 17.24 hr, was inferred from periodic radio emissions detected by Voyager which are believed to arise from charged particles trapped in the magnetic field and thus rotating with the planet. The rotation results in a polar flattening of 2.3%. Prior to Voyager, there were five known moons. Voyager discovered a further 10 small moons, and a further 12 more distant from the planet have been discovered subsequently, bringing the total of Uranus' known moons to 27. The composition and internal structure of Uranus are probably different from those of Jupiter and Saturn. The higher mean density of Uranus suggests that it contains proportionately less hydrogen and more rock and ice. The rotation period is too long for a layered structure with melted ices of methane, ammonia and water around a molten rocky core. It agrees better with a model in which heavier materials are less concentrated in a central core, and the rock, ices and gases are more uniformly distributed.

Several paradoxes remain associated with Uranus. The axis of rotation is tilted at an angle of 98° to the pole to the planet's orbit, and thus lies close to the ecliptic plane. The reason for the extreme tilt, compared to the other planets, is unknown. The planet has a prograde rotation about this axis. However, if the other end of the rotation axis, inclined at an angle of 82°, is taken as reference, the planet's spin can be regarded as retrograde. Both interpretations are equivalent. The anomalous axial orientation means that during the 84 years of an orbit round the Sun the polar regions as well as the equator experience extreme solar insolation. The magnetic field of Uranus is also anomalous: it is inclined at a large angle to the rotation axis and its center is displaced axially from the center of the planet.

Neptune is the outermost of the gaseous giant planets. It can only be seen from Earth with a good telescope. By the early nineteenth century, the motion of Uranus had become well enough charted that inconsistencies were evident. French and English astronomers independently predicted the existence of an eighth planet, and the predictions led to the discovery of Neptune in 1846. The planet had been noticed by Galileo in 1612, but due to its slow motion he mistook it for a fixed star. The period of Neptune's orbital rotation is almost 165 yr, so the planet has not yet completed a full orbit since its discovery. As a result, and because of its extreme distance from Earth, the dimensions of the planet and its orbit were not well known until 1989, when Voyager 2 became the first – and, so far, the only – spacecraft to visit Neptune.

Neptune's orbit is nearly circular and lies close to the ecliptic. The rotation axis has an Earth-like obliquity of 29.6° and its axial rotation has a period of 16.11 hr, which causes a polar flattening of 1.7%. The planet has a radius of 24,766 km and a mean density of 1638 kg m^{-3}. The internal structure of Neptune is probably like that of Uranus: a small rocky core (about the size of planet Earth) is surrounded by a non-layered mixture of rock, water, ammonia and methane. The atmosphere is predominantly of hydrogen, helium and methane, which absorbs red light and gives the planet its blue color.

The Voyager 2 mission revealed that Neptune has 13 moons and a faint ring system. The largest of the moons, Triton, has a diameter about 40% of Earth's and its density (2060 kg m^{-3}) is higher than that of most other large moons in the solar system. Its orbit is steeply inclined at 157° to Neptune's equator, making it the only large natural satellite in the solar system that rotates about its planet in *retrograde* sense. The moon's physical characteristics, which resemble the planet Pluto, and its retrograde orbital motion suggest that Triton was captured from elsewhere in the outer solar system.

1.1.3.4 Pluto and the outer solar system

Until its reclassification in 2006 as a "*dwarf planet*," Pluto was the smallest planet in the solar system, about two-thirds the diameter of Earth's Moon. It has many unusual characteristics. Its orbit has the largest inclination to the ecliptic (17.1°) of any major planet and it is highly eccentric (0.249), with aphelion at 49.3 AU and perihelion at 29.7 AU. This brings Pluto inside Neptune's orbit for 20 years of its 248-year orbital period; the paths of Pluto and Neptune do not intersect. The orbital period is resonant with that of Neptune in the ratio 3:2 (i.e., Pluto's period is exactly 1.5 times Neptune's). These features preclude any collision between the planets.

Pluto is so far from Earth that it appears only as a speck of light to Earth-based telescopes and its surface features can be resolved only broadly with the Hubble Space Telescope. It is the only planet that has not been visited by a spacecraft. It was discovered fortuitously in 1930 after a systematic search for a more distant planet to explain presumed discrepancies in the orbit of Neptune which, however, were later found to be due to inaccurate estimates of Neptune's mass. The mass and diameter of Pluto were uncertain for some decades until in 1978 a moon, Charon, was found to be orbiting Pluto at a mean distance of 19,600 km. Pluto's mass is only 0.21% that of the Earth. Charon's mass is about 10–15% of Pluto's, making it the largest moon in the solar system relative to its primary planet. The radii of Pluto and Charon are estimated from observations with the Hubble Space Telescope to be 1137 km and 586 km, respectively, with a relative error of about 1%. The mass and diameter of Pluto give an estimated density about 2000 kg m^{-3} from which it is inferred that Pluto's composition may be a mixture of about 70% rock and 30% ice, like that of Triton, Neptune's moon. Charon's estimated density is lower, about 1300 kg m^{-3}, which suggests that there may be less rock in its composition.

Pluto's rotation axis is inclined at about 122° to its orbital plane, so the planet's axial rotation is *retrograde*, and has a period of 6.387 days. Charon also orbits Pluto in a retrograde sense. As a result of tidal forces, Charon's orbital period is synchronous with both its own axial rotation and Pluto's. Thus, the planet and moon constantly present the same face to each other. Because of the rotational synchronism and the large relative mass of Charon, some consider Pluto–Charon to be a double planet. However, this is unlikely because their different densities suggest that the bodies originated independently. Observations with the Hubble Space Telescope in 2005 revealed the presence of two other small moons – provisionally named 2005 P1 and 2005 P2 – in orbit around Pluto in the same sense as Charon, but at a larger distance of about 44,000 km. All three moons have the same color spectrum, which differs from Pluto's and suggests that the moons were captured in a single collision with another large body. However, the origins of Pluto, Charon and the smaller moons are as yet unknown, and are a matter of scientific conjecture.

Since the early 1990s thousands of new objects have been identified beyond the orbit of Neptune. The trans-Neptunian objects (Box 1.3) are mostly small, but at least one, Eris, is comparable in size to Pluto. The new discoveries fueled discussion about Pluto's status as a planet. In 2006 the definition of what constitutes a planet was modified. To be a planet an object must (1) be in orbit around a star (Sun), (2) be large enough so that its own gravitation results in a spherical or spheroidal shape, (3) not be so large as to initiate nuclear fusion, and (4) have cleared the neighborhood around its orbit of planetesimals. Conditions (1) and (3) are met by all objects orbiting the Sun. An object that meets conditions (1) and (2) and is not a satellite of another body is called a "*dwarf planet*." Pluto falls in this new category, along with the asteroid Ceres and the scattered disk object Eris (Box 1.3).

1.1.3.5 Angular momentum

An important characteristic that constrains models of the origin of the solar system is the difference between the distributions of mass and angular momentum. To determine the angular momentum of a rotating body it is necessary to know its moment of inertia. For a particle of mass m the moment of inertia (I) about an axis at distance r is defined as:

$$I = mr^2 \tag{1.4}$$

The angular momentum (h) is defined as the product of its moment of inertia (I) about an axis and its rate of rotation (Ω) about that axis:

$$h = I\Omega \tag{1.5}$$

Each planet revolves in a nearly circular orbit around the Sun and at the same time rotates about its own axis. Thus there are two contributions to its angular momentum (Table 1.3). The angular momentum of a planet's revolution about the Sun is obtained quite simply. The solar system is so immense that the physical size of each planet is tiny compared to the size of its orbit. The moment of inertia of a planet about the Sun is computed by inserting the mass of the planet and its orbital radius (Table 1.3) in Eq. (1.4); the orbital angular momentum of the planet follows by combining the computed moment of inertia with the rate of orbital revolution as in Eq. (1.5). To determine the moment of inertia of a solid body about an axis that passes through it (e.g., the rotational axis of a planet) is more complicated. Equation (1.4) must be computed and summed for all particles in the planet. If the planet is represented by a sphere of mass M and mean radius R, the moment of inertia C about the axis of rotation is given by

$$C = kMR^2 \tag{1.6}$$

where the constant k is determined by the density distribution within the planet. For example, if the density is uniform inside the sphere, the value of k is exactly 2/5, or 0.4; for a hollow sphere it is 2/3. If density increases with depth in the planet, e.g., if it has a dense core, the value of k is less than 0.4; for the Earth, $k = 0.3308$. For some planets the variation of density with depth is not well known, but for most planets there is enough information to calculate the moment of inertia about the axis of rotation; combined with the rate of rotation as in Eq. (1.5), this gives the rotational angular momentum.

The angular momentum of a planet's revolution about the Sun is much greater (on average about 60,000 times) than the angular momentum of its rotation about its own axis (Table 1.3). Whereas more than 99.9% of the total mass of the solar system is concentrated in the Sun, more than 99% of the angular momentum is carried by the orbital motion of the planets, especially the four great planets. Of these Jupiter is a special case: it accounts for over 70% of the mass and more than 60% of the angular momentum of the planets.

1.1.4 The origin of the solar system

There have been numerous theories for the origin of the solar system. Age determinations on meteorites indicate that the solar system originated about $(4.5-4.6)\times10^9$ years ago. A successful theory of how it originated must account satisfactorily for the observed characteristics of the planets. The most important of these properties are the following.

(1) Except for Pluto, the planetary orbits lie in or close to the same plane, which contains the Sun and the orbit of the Earth (the ecliptic plane).
(2) The planets revolve about the Sun in the same sense, which is counterclockwise when viewed from above the ecliptic plane. This sense of rotation is defined as prograde.
(3) The rotations of the planets about their own axes are also mostly prograde. The exceptions are Venus, which has a retrograde rotation; Uranus, whose axis of rotation lies nearly in the plane of its orbit; and Pluto, whose rotation axis and orbital plane are oblique to the ecliptic.
(4) Each planet is roughly twice as far from the Sun as its closest neighbor (Bode's law).
(5) The compositions of the planets make up two distinct groups: the terrestrial planets lying close to the Sun are small and have high densities, whereas the great planets far from the Sun are large and have low densities.
(6) The Sun has almost 99.9% of the mass of the solar system, but the planets account for more than 99% of the angular momentum.

The first theory based on scientific observation was the *nebular hypothesis* introduced by the German philosopher Immanuel Kant in 1755 and formulated by the French astronomer Pierre Simon de Laplace in 1796. According to this hypothesis the planets and their satellites were