1 The Solar System

PREVIEW

The solar system originated more than 4.5 billion years ago from a rotating cloud of molecular hydrogen and interstellar dust surrounding a star that became the Sun. Collisions and coalescence of particles in the dust cloud led to the formation of a solar system with eight planets and countless smaller bodies that has fascinated mankind since prehistoric times. Our knowledge of the solar system exploded in the recent era of space exploration, and its complete description deserves a library on its own. This chapter provides brief descriptions of the orbits and physical properties of the major planetary bodies. These exhibit natural phenomena originally studied on the Earth, such as gravitational and magnetic fields, seismicity, and tidal motions. They can be understood with geophysical concepts and techniques introduced in later chapters.

1.1 THE PLANETS

The solar system consists of the Sun, the planets and their moons, and other objects that are in orbit around the Sun under its gravitational attraction. The eight planets form two groups, differing in size, composition, and proximity to the Sun (Table 1.1). The four inner (or terrestrial) planets – Mercury, Venus, Earth, and Mars – resemble the Earth in size and density (Fig. 1.1). They have a solid, rocky composition and they rotate about their own axes at the same rate or slower than the Earth. The four outer (or giant) planets – Jupiter, Saturn, Uranus, and Neptune – are much larger than the Earth, with lower densities and higher rotation rates. The inner planets have few moons and no rings; in contrast, the outer planets have many moons and are surrounded by rings of dust. Between Mars and Jupiter lies the asteroid belt, made up of numerous orbiting objects, some as small as dust particles and others up to hundreds of kilometers in diameter.

Jupiter is much larger than any of the other planets; its mass makes up 70% of the total mass of all the planets. Whereas the inner planets consist mainly of rocky and metallic materials, Jupiter and Saturn are gas giants composed 90% of hydrogen and helium, and they have metallic hydrogen cores. Uranus and Neptune are ice giants. They have gaseous atmospheres of hydrogen and helium, but are composed largely of ices of water, ammonia, and methane. Beyond Neptune, and almost twice as far from the Sun, lies the orbit of Pluto, which was long regarded as a planet, although in size it is smaller than the Earth's Moon. 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 giant planets and the terrestrial planets.

In addition to the eight *major planets* and Pluto, there are other large objects in orbit around the Sun. Designated as *minor planets*, they do not fulfill the criteria common to the definition of the major planets. The discovery of large objects in the solar system beyond the orbit of Neptune stimulated astronomers to debate the criteria that should be used to define a planet. In 2006 the International Astronomical Union decided that to be a planet in the solar system an object must satisfy three conditions: (1) it must be in orbit around the Sun; (2) it must be large enough that its own gravitation results in a spherical or spheroidal shape; and (3) it must have cleared the neighborhood around its orbit of planetesimals. An object that meets conditions (1) and (2) and is not a satellite of another body is classified as a "dwarf planet." Pluto's elongate orbit is affected by Neptune and the Kuiper belt bodies, so it fails condition (3) and is now classified as a dwarf planet. Other dwarf planets are the largest asteroid, Ceres, which has a radius of 950 km, and the scattered disk object Eris (Section 1.5.6).

The orbits of the planets around the Sun lie close to each other, forming a flat disk. The plane of the Earth's orbit is called the *ecliptic plane*; the orbits of the other planets lie within a few degrees of it. The shapes of the orbits are slightly elliptical, deviating by only a small amount from being circles. The shapes of the orbits and the motions of the planets are controlled by the laws of conservation of energy and angular momentum, and by the inverse square law of gravitation.

1.1.1 Conservation of Energy and Angular Momentum

To a first approximation the Sun and planets form an isolated system. This is one in which no matter or energy is transferred into or out of the system. The law of *conservation*

Table 1.1 *Dimensions and rotational characteristics of the planets and the Moon*

The great planets and the dwarf planet 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 axis of the spheroidal shape.

Planet	Mass M (10^{24} kg)	Mass relative to the Earth	Mean density (kg m^{-3})	Equatorial radius (km)	Sidereal rotation period (days)	Inverse flattening $f^{-1} = a/(a-c)$	Obliquity of axis to orbit (°)
Terrestrial planets and the Moon							
Mercury	0.33011	0.0553	5427	2439.7	58.65	–	0.034
Venus	4.8675	0.815	5243	6051.8	243.7	–	177.4
Earth	5.9723	1.000	5514	6378.1	0.9973	298.253	23.44
Moon	0.07346	0.0123	3344	1738.1	27.32	827.67	6.68
Mars	0.64171	0.1074	3933	3396.2	1.026	169.81	25.19
Great planets and Pluto							
Jupiter	1898.19	317.83	1326	71,492	0.414	15.41	3.13
Saturn	568.34	95.16	687	60,268	0.444	10.21	26.73
Uranus	86.813	14.54	1271	25,559	0.718	43.62	97.77
Neptune	102.413	17.15	1638	24,764	0.671	58.54	28.32
Pluto	0.01303	0.00218	1854	1187	6.387	–	122.53

Source: NASA Space Science Data Center, 2017, https://nssdc.gsfc.nasa.gov/planetary.

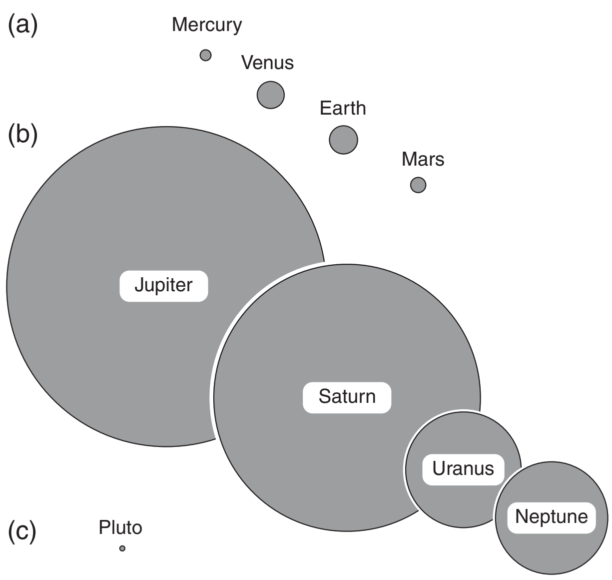

Fig. 1.1 The relative sizes of the planets: (a) the four terrestrial planets, (b) the four giant planets, and (c) the dwarf planet Pluto, which is diminutive compared to the others.

of energy states that the total energy of an isolated system is constant. In the solar system the planets are bound to the Sun by its gravitation, which varies as the inverse square of distance from the Sun's center. These conditions result in each planet having a planar orbit with an elliptical shape (Box 1.1).

A further constraint on planetary motions is the law of *conservation of angular momentum*. This applies to rotating systems and states that the angular momentum of a system remains constant unless it is acted on by an external torque (or turning force). Just as the linear momentum of a body depends on its velocity and mass, the angular momentum of a rotating body depends on its rate of rotation about an axis and the distribution of its mass about that axis, a property known as moment of inertia.

For a point mass m the moment of inertia (I) about an axis at distance r is defined as:

$$I = mr^2. \tag{1.1}$$

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

$$h = I\Omega\ . \tag{1.2}$$

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. 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 1.2) in Eq. (1.1); the orbital angular momentum of the planet follows by combining the computed moment of inertia with the rate of orbital revolution, as in Eq. (1.2).

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 (1.2) 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

$$C = kMr^2, \tag{1.3}$$

Table 1.2 *Dimensions and characteristics of the planetary orbits*

1 AU = 1 astronomical unit = 149,597,870.7 km.

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	47.36	0.2408
Venus	0.7233	108.21	0.00677	3.39	35.02	0.6152
Earth	1.0000	149.60	0.01671	0.000	29.78	1.0000
Moon (about Earth)	0.00257	0.3844	0.0549	5.145	1.022	0.0748
Mars	1.5202	227.92	0.0935	1.851	24.08	1.8808
Great planets and Pluto						
Jupiter	5.2013	778.6	0.0489	1.304	13.06	11.862
Saturn	9.575	1433.5	0.0565	2.485	9.68	29.457
Uranus	19.19	2872.6	0.0457	0.772	6.80	84.011
Neptune	30.05	4495.1	0.0113	1.769	5.43	164.79
Pluto	38.86	5906.4	0.2488	17.16	4.67	247.94

Source: National Space Science Data Center, 2017, https://nssdc.gsfc.nasa.gov/planetary.

where the constant k is determined by the density distribution within the planet. Its value can be calculated exactly for simple geometrical shapes. For example, if the density is uniform inside a solid 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 a 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. (1.2), this gives the rotational angular momentum (Table 1.3).

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. 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 giant 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.

1.1.2 Origin of the Solar System

Numerous theories have been proposed for the origin of the solar system. Age determinations on meteorites indicate that the solar system originated about 4.5–4.6 × 10^9 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:

1. 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; and Uranus, whose axis of rotation lies nearly in the plane of its orbit.
4. Each planet is roughly twice as far from the Sun as its closest neighbor.
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 giant 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 formed at the same time as the Sun. Space was filled by a rotating cloud (*nebula*) of hot primordial gas and dust that, as it cooled, began to contract. To conserve the angular momentum of the system, its rotation speeded up; a familiar analogy is the way a pirouetting skater spins more rapidly when he draws in his outstretched arms. Centrifugal force would have caused concentric rings of matter to be thrown off, which then condensed into planets. A serious objection to this hypothesis is that the mass of material in each ring would be too small to provide the gravitational attraction needed to cause the ring to condense into a planet. Moreover, as the nebula contracted, the largest part of the angular momentum would

Table 1.3 *Distributions of orbital and rotational angular momentum in the solar system*

Note that Venus, Uranus, and Pluto have retrograde axial rotations.

	Planet mass M (10^{24} kg)	Mean orbital rate ω (10^{-9} rad s^{-1})	Mean orbital radius r (10^{9} m)	Orbital angular momentum $M\omega r^2$ (10^{39} kg m^2 s^{-1})	Planet mean radius R (10^{6} m)	Normalized moment of inertia I / MR^2	Moment of inertia I (10^{40} kg m^2)	Axial rotation rate Ω (10^{-6} rad s^{-1})	Rotational angular momentum $I\Omega$ (10^{39} kg m^2 s^{-1})
Terrestrial planets									
Mercury	0.3301	827.3	57.29	0.896	2.440	0.353	6.88×10^{-5}	1.240	8.53×10^{-10}
Venus	4.8675	323.9	108.2	18.46	6.052	0.33	5.88×10^{-3}	–0.2992	1.76×10^{-8}
Earth	5.9723	199.2	149.6	26.63	6.371	0.3308	8.02×10^{-3}	72.92	5.85×10^{-6}
Mars	0.6417	105.9	227.4	3.52	3.390	0.366	2.70×10^{-4}	70.78	1.91×10^{-7}
Great planets and Pluto									
Jupiter	1898.2	16.8	778.1	19,304	69.911	0.254	235.6	175.7	0.4144
Saturn	568.3	6.76	1432	7887	58.232	0.21	40.5	163.8	0.0663
Uranus	86.8	2.37	2871	1697	25.362	0.23	1.28	–101.3	0.00124
Neptune	102.4	1.209	4495	2502	24.622	0.24	1.49	108.1	0.00167
Pluto	0.01303	0.804	5814	0.354	1.187	–	–	–11.4	–
TOTALS	2668	–	–	31,439	–	–	–	–	0.483
The Sun	1,989,100	–	–	–	695.700	0.070	6,737,000	2.865	162.6

Source: National Space Science Data Center, 2017, http://nssdc.gsfc.nasa.gov/planetary.

remain associated with the main mass that condensed to form the Sun, which disagrees with the observed distribution of angular momentum in the solar system.

Several alternative models were postulated subsequently, but have also fallen into disfavor. For example, the *collision hypothesis* assumed that the Sun was formed before the planets. The gravitational attraction of a closely passing star or the blast of a nearby supernova explosion drew out a filament of solar material that condensed to form the planets. However, a major objection to this scenario is that the solar material would have been so hot that it dissipated explosively into space rather than slowly condensing to form the planets.

Current interpretations of the origin of the solar system are based on modifications of the nebular hypothesis. As the cloud of gas and dust contracted, its rate of rotation speeded up, flattening the cloud into a lens-shaped disk. When the core of the contracting cloud became dense enough, gravitation caused it to collapse upon itself to form a proto-Sun in which thermonuclear fusion was initiated. Hydrogen nuclei combined under the intense pressure to form helium nuclei, releasing huge amounts of energy. The material in the spinning disk was initially very hot and gaseous but, as it cooled, solid material condensed out of it as small grains. The grains coalesced as rocky or icy clumps called *planetesimals*. Asteroid-like planetesimals with a silicate, or rocky, composition formed near the Sun, while comet-like planetesimals with an icy composition formed far from the Sun's heat. Collisions and the gravitational attraction between the planetesimals resulted in their further accretion to form the planets. Matter with a high boiling point (e.g., metals and silicates) could condense near to the Sun, forming the terrestrial planets.

The terrestrial planets acquired an internal structural of concentric spherical shells, determined by the chemical composition and density of their constituents. Gravitational forces caused denser materials to sink toward the center of the planet, forming an iron-rich core. Less-dense silicates formed a surrounding shell (or mantle) around the core, with a thin solid outer crust of silicates. Above this layered structure a liquid hydrosphere accumulated, and above it a gaseous atmosphere. The Earth's atmosphere is itself layered, consisting of the troposphere (responsible for weather), stratosphere (containing the protective ozone layer), and the ionosphere (formed by ionization of air molecules by solar radiation). The other planets and some of their moons also have atmospheres with differing compositions.

By contrast to the terrestrial planets, volatile materials (e.g., water, ammonia, methane) were vaporized and driven into space by the stream of particles and radiation from the Sun. Between Mars and Jupiter, at a distance known as the frost line, the warming effect of the solar radiation becomes so low that volatile compounds are solid, in the form of ices. During the condensation of the large cold planets in the frigid distant realms of the solar system, the volatile materials were retained. The gravitational attractions of Jupiter and Saturn may have been strong enough to retain the composition of the original nebula.

It is important to keep in mind that this scenario is a hypothesis – a plausible but not unique explanation of how the solar system formed. It attributes the variable compositions of the planets to accretion at different distances from the Sun. The model can be embellished in many details to account for the characteristics of individual planets. However, the scenario is unsatisfactory because it is mostly qualitative. For example, it does not explain adequately the distribution of angular momentum. Physicists, astronomers, mathematicians, and space scientists are constantly trying new methods of investigation and searching for additional clues that will improve the hypothesis of how the solar system formed.

1.2 THE DISCOVERY OF THE PLANETS AND DETERMINATION OF THEIR ORBITS

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 embedded 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 observing 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.

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. 1.2). 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:

$$\begin{aligned}\frac{p_1}{2s} &= \frac{\sin\left(\frac{\pi}{2}-\theta_2\right)}{\sin(\theta_1+\theta_2)} = \frac{\cos\theta_2}{\sin(\theta_1+\theta_2)}\\ \frac{p_2}{2s} &= \frac{\cos\theta_1}{\sin(\theta_1+\theta_2)}.\end{aligned} \tag{1.4}$$

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.

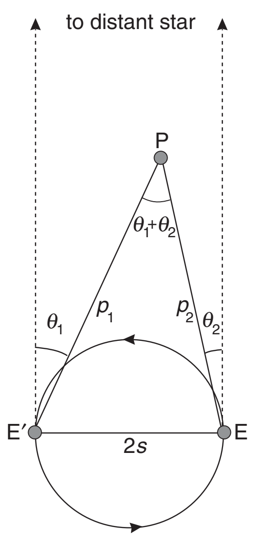

Fig. 1.2 The method of parallax, in which two measured angles (θ_1 and θ_2) are used to compute the distances (p_1 and p_2) of a planet from the Earth in terms of the Earth–Sun distance (s).

1.2.1 Bode's Law

In 1772 the German astronomer Johann Bode devised an empirical formula to express the approximate distances of 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. 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. This series can be expressed mathematically as follows:

$$\begin{aligned}d_n &= 0.4 \quad \text{for} \quad n=1\\ d_n &= 0.4 + 0.3\times 2^{n-2} \quad \text{for} \quad n\geq 2\,.\end{aligned} \tag{1.5}$$

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 was suggested earlier by J. D. Titius of Wittenberg, it is sometimes called Titius–Bode's law. Examination of Fig. 1.3 and comparison with Table 1.2 shows that this relationship holds remarkably well, except for Neptune and Pluto, the latter of which has been demoted to the status of a dwarf planet. It has been suggested 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 around 2.9 AU, now called the *asteroid belt*. Pallas was found in 1802, Juno in

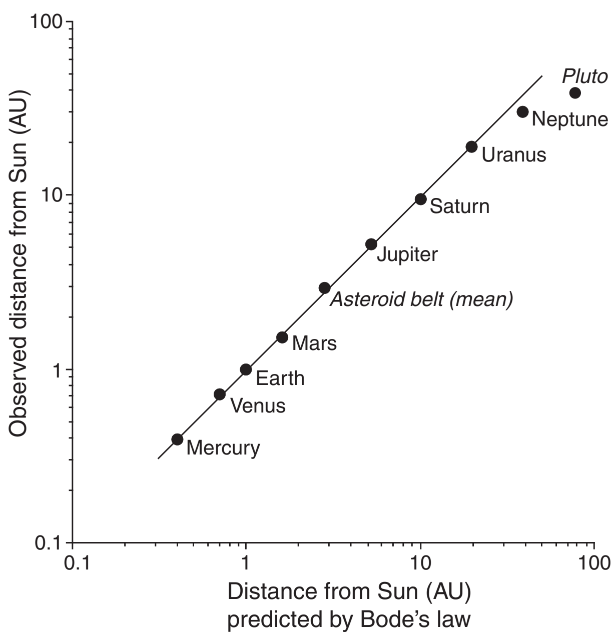

Fig. 1.3 The empirical relationship of Titius–Bode for the distances of the planets from the Sun.

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 law in the scientific sense, and is therefore often referred to as Bode's rule. Though a simple explanation of Bode's law currently does not exist, recent investigations indicate that the complicated gravitational interaction of many planets may indeed lead to an orbital spacing that approximately follows a power law. During the past decades numerous exoplanets – that is, planets belonging to stars other than the Sun – have been discovered. The statistical analysis of their orbits suggests that variants of Bode's law may roughly hold in other solar systems as well.

1.3 KEPLER'S LAWS OF PLANETARY MOTION

In 1543, the year of his death, the Polish astronomer Nicolaus 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* (AU); 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 (Section 3.2.1). It is remarkable that the data base used by Kepler was founded on observations that were unaided by the telescope, which was not invented until early in the seventeenth century.

Kepler took many years to fit the observations of Tycho Brahe into three laws of planetary motion. The first and second laws (Fig. 1.4) 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.

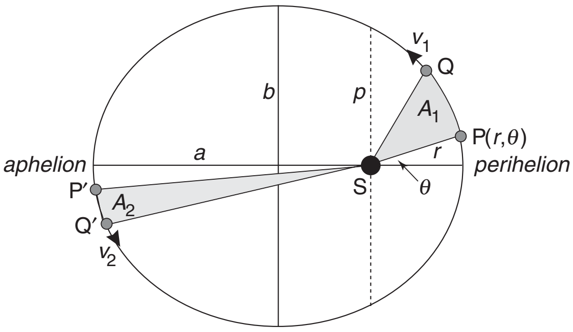

Fig. 1.4 Kepler's first two laws of planetary motion: (1) each planetary orbit is an ellipse with the Sun at one focus, and (2) the radius to a planet sweeps out equal areas in equal intervals of time.

Kepler's three laws were 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 toward 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 3.3.2.3).

Kepler's laws were developed for the solar system but are applicable to any closed planetary system. They govern the motions of any natural and 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

$$GM = \frac{4\pi^2}{T^2}a^3, \tag{1.6}$$

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.

1.4 CHARACTERISTICS OF THE PLANETS AND THEIR ORBITS

Galileo Galilei (1564–1642) is often regarded as a founder of modern science. He made fundamental

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):

$$\frac{1}{2}mv^2 - G\frac{mS}{r} = E = \text{constant}. \quad (1)$$

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 $2a$:

$$s_1 + s_2 = 2a. \quad (2)$$

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 :

$$e = \sqrt{1 - \frac{b^2}{a^2}}. \quad (3)$$

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

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1. \quad (4)$$

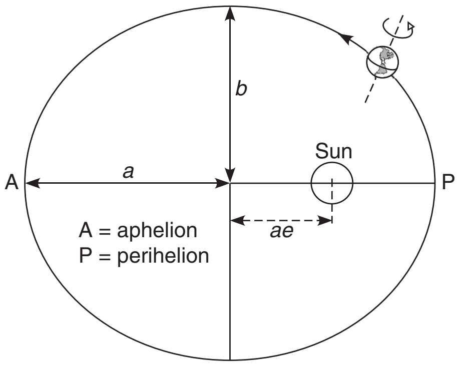

Fig. B1.1.1 The parameters of an elliptical orbit.

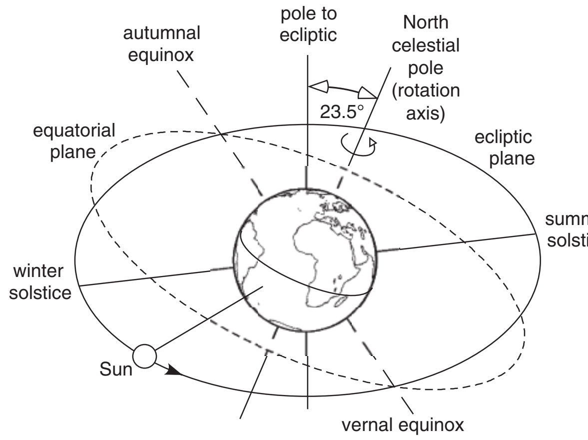

Fig. B1.1.2 The relationship between the ecliptic plane, the Earth's equatorial plane, and the line of equinoxes.

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 the 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.

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 the 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.

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 the planets. In 1610 Galileo discovered the four largest satellites of Jupiter (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 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 km^3 s^{-2}. This was a very good determination; the modern value for GJ is 126,712,767 km^3 s^{-2}. Observations of the Moon's orbit about the Earth showed that the value GE was 398,600 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 and the Moon (Table 1.1) have been determined with high precision in modern times using radar-ranging and laser-ranging techniques (Box 1.2). The measurements have been made from instruments located on the Earth and on spacecraft that have orbited or passed close to the target. Both ranging methods measure the two-way travel-time of a pulse of electromagnetic waves, which travels at the speed of light. Radar-ranging operates at wavelengths in the centimeter range while laser-ranging wavelengths are around a micrometer, including the visible range.

The rate of rotation of a planet about its own axis can be determined by observing the motion of features fixed to its surface. For example, radar beams from powerful transmitters on the Earth may be directed at a chosen planet. The two-way travel time gives the distance to the planet. However, the axial rotation of the planet means that one side is rotating away from the Earth and the other side toward the Earth. The Doppler effect (Box 1.3) shifts the frequency of the echo from the receding edge of the planet

Box 1.2 Radar and Laser Ranging

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. A pulsed electromagnetic signal in the microwave frequency range (see Fig. 10.21) 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.

Laser is the acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation, and is descriptive of the way in which a monochromatic source of light is produced. Some laser "light" is visible – e.g., with wavelength ~550 nm (red) or ~650 nm (green) – but the range of wavelengths for special applications extends from 200 nm (ultraviolet) to greater than 1000 nm (infrared). A monochromatic laser beam has a single frequency and the light vibrations are in phase. This enables the beam to be kept very narrow so that it can be focused on a small target. For example, a laser beam directed at the Moon in the Lunar Laser Ranging experiment (LRR) is estimated to be 6.5 km wide when it reaches the target on the Moon's surface at a mean distance of 385,000 km from the Earth. The short wavelength of laser light provides very high resolution of the distance to a target. Measurements at a global network of observation stations allows tracking of Earth-orbiting satellites with millimeter-level precision.

toward lower frequencies and shifts the echo from the advancing edge toward higher frequencies. The frequency shifts yield the rate of rotation of the planet. In 1965 the 3:2 resonance between the axial rotation rate and orbital rate of Mercury was discovered by this means.

Radar-ranging in combination with Doppler analysis has been used to measure the distances and rotation rates of the planets as far as Saturn, as well as many asteroids and the Moon. 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 hours 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 the 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 *obliquity* of the axis. The rotation axes of Uranus and Pluto lie close to their orbital planes. Each is tilted away from the pole to the orbital plane at an angle greater than 90°, so that, strictly speaking, their rotations are also retrograde.

1.5 THE INNER (TERRESTRIAL) PLANETS AND THE MOON

The inner planets of the solar system are those that orbit closest to the Sun. Known as the terrestrial planets because of their Earth-like properties, they typically have a dense metallic core within a rocky silicate body. Their hard solid surfaces are characterized by topographic features such as valleys, mountains and craters. They have atmospheres that were acquired during their evolution rather than from their original formation, as is the case for the outer planets. None of the inner planets has a system of rings. Mercury and Venus have no natural satellites, and Mars has two small, irregularly shaped moons less than 10 km in diameter. The Earth's natural satellite, the Moon, is the largest in the solar system in relation to the planet it orbits.

1.5.1 Mercury

Mercury is the closest planet to the Sun. This proximity and its small size make it difficult to study Mercury telescopically. Its orbit has a large eccentricity (0.2056). At perihelion the planet is about 46.0 million km (0.3075 AU) from the Sun, but at aphelion the distance is 69.8 million km (0.4667 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 first spacecraft to

Box 1.3 Doppler Radar

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:

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

$$t = \frac{t_0}{(1 + v/c)}. \tag{2}$$

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:

$$n = n_0\left(1 + \frac{v}{c}\right). \tag{3}$$

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 the Earth. The color of the star shifts toward the red end of the spectrum (lower frequency) if the star is receding from the Earth and toward the blue end (higher frequency) if it is approaching the Earth. The color of light from many distant galaxies has a "red shift," implying that these galaxies are receding from the Earth.