1 The Sun and its Family

Imagine that you have travelled far into the depths of space. From your distant vantage point the Sun has become just another star amongst the multitude, and the Earth, the other planets, and the host of smaller bodies that orbit the Sun are not visible at all to the unaided eye. The Sun is by far the largest and most massive body in the Solar System, and is the only one hot enough to be obviously luminous. This chapter starts with a description of the Sun. We shall then visit the other bodies in the Solar System, but only briefly, the purpose here being to establish their main characteristics – each of these bodies will be explored in much more detail in subsequent chapters. Chapter 1 then continues with an exploration of the orbits of the various bodies. Each of them also rotates around an axis through its centre, and we shall look at this too. The chapter concludes with aspects of our view of the Solar System as we see it from the Earth.

1.1 The Sun

This is only a very brief account of the Sun, and it is biased towards topics of importance for the Solar System as a whole. Fuller accounts of the Sun are in books listed in Further Reading.

1.1.1 The Solar Photosphere

The bright surface of the Sun is called the **photosphere** (Plate 1). Its radius is 6.96×10^5 km, about 100 times the radius of the Earth. It is rather like the 'surface' of a bank of cloud, in that the light reaching us from the photosphere comes from a range of depths, though the range covers only about one-thousandth of the solar radius, and so we are not seeing very deep into the Sun. It is important to realise that whereas a bank of cloud scatters light from another source, the photosphere is *emitting* light. It is also emitting electromagnetic radiation at other wavelengths, as the solar spectrum in Figure 1.1 demonstrates. The total power radiated is the area under the solar spectrum, and is 3.85×10^{26} watts (W). This is the solar luminosity. The photosphere, for all its brilliance, is a tenuous gas, with a density of order $10^{-3}\,\mathrm{kg\,m^{-3}}$, about 1000 times less than that of the air at the Earth's surface.

The spectrum in Figure 1.1 enables us to estimate the mean photospheric temperature. This is done by comparing the spectrum with that of an **ideal thermal source**, sometimes called a black body. The exact nature of such a source need not concern us. The important point is that its spectrum is uniquely determined by its temperature. Turning this around, if we can fit an ideal thermal source spectrum reasonably well to the spectrum of any other body, then we can estimate the other body's temperature. Figure 1.1 shows a good match between the solar spectrum and the spectrum of an ideal thermal source at a temperature of 5770 K. Also shown is the poor match with an ideal thermal source at 4000 K, where the peak of the spectrum is

Discovering the Solar System, Second Edition Barrie W. Jones

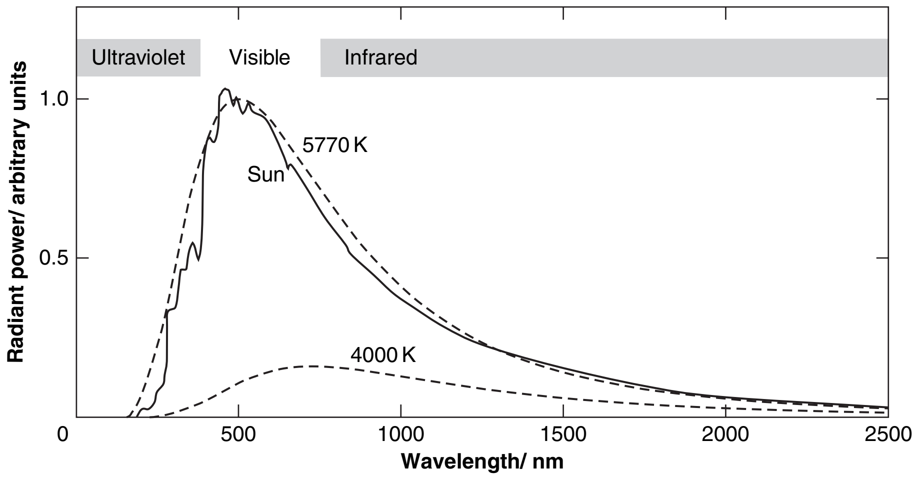

Figure 1.1 The solar spectrum, and the spectra of ideal thermal sources at 5770 K and 4000 K (1 nm = 10^{-9} m).

at longer wavelengths. Also, the power emitted by this source is a lot less. The power shown corresponds to the assumption that the 4000 K source has the same area as the source at 5770 K, and thus brings out the point that the temperature of an ideal thermal source determines not only the wavelength range of the emission, but the power too. Note that 5770 K is a *representative* temperature of the Sun's photosphere; the local temperature varies from place to place.

At a finer wavelength resolution than in Figure 1.1 the solar spectrum displays numerous narrow dips, called spectral absorption lines. These are the result of the absorption of upwelling solar radiation by various atoms and ions, mainly in the photosphere, and therefore the lines provide information about chemical composition. Further information about the Sun's composition is provided by small rocky bodies that continually fall to Earth. They are typically 1–100 cm across, and constitute the **meteorites** (Section 3.3). At 5770 K significant fractions of the atoms of some elements are ionised, and so it is best to define the composition at the photosphere in terms of atomic nuclei, rather than neutral atoms. In the photosphere, hydrogen and helium dominate, with hydrogen the most abundant – all the other chemical elements account for only about 0.2% of the nuclei. Outside the Sun's fusion core (Section 1.1.3) about 91% of the nuclei are hydrogen and about 9% are helium.

Plate 1 shows that the most obvious feature of the photosphere is dark spots. These are called (unsurprisingly) **sunspots**. They range in size from less than 300 km across to around 100 000 km, and their lifetimes range from less than an hour to 6 months or so. They have central temperatures of typically 4200 K, which is why they look darker than the surrounding photosphere. Sunspots are shallow depressions in the photosphere, where strong magnetic fields suppress the convection of heat from the solar interior, hence the lower sunspot temperatures. Their number varies, defining a sunspot cycle. The time between successive maxima ranges from about 8 years to about 15 years with a mean value of 11.1 years. From one cycle to the next the magnetic field of the Sun reverses. Therefore, the magnetic cycle is about 22 years.

Sunspots provide a ready means of studying the Sun's rotation, and reveal that the rotation period at the equator is 25.4 days, increasing with latitude to about 36 days at the poles. This differential rotation is common in fluid bodies in the Solar System.

1.1.2 The Solar Atmosphere

Above the photosphere there is a thin gas that can be regarded as the solar atmosphere. Because of its very low density, at most wavelengths it emits far less power than the underlying photosphere, and so the atmosphere is not normally visible. During total solar eclipses, the Moon just obscures the photosphere, and the weaker light from the atmosphere then becomes visible. In Plate 2 the atmosphere just above the photosphere is not visible, whereas in Plate 3 the short exposure time has emphasised the inner atmosphere. The atmosphere can be studied at other times, either by means of an optical device called a coronagraph that attenuates the radiation from the photosphere, or by making observations at wavelengths where the atmosphere is brighter than the photosphere.

Figure 1.2 shows how the temperature and density in the solar atmosphere vary with altitude above the base of the photosphere. A division of the atmosphere into two main layers is apparent, the chromosphere and the corona, separated by a thin transition region.

The chromosphere

The chromosphere lies immediately above the photosphere. It has much the same composition as the photosphere, so hydrogen dominates. The density declines rapidly with altitude, but the temperature *rises*. The red colour that gives the chromosphere its name ('coloured sphere') is a result of the emission by hydrogen atoms of light at 656.3 nm. This wavelength is called Hα ('aitch-alpha').

The data in Figure 1.2 are for 'quiet' parts of the chromosphere. Its properties are different where magnetic forces hold aloft filamentary clouds of cool gas, extending into the lower corona. The filaments are the red prominences above the limb of the photosphere in Plate 3. Prominences are transitory phenomena, lasting for periods from minutes to a couple of months.

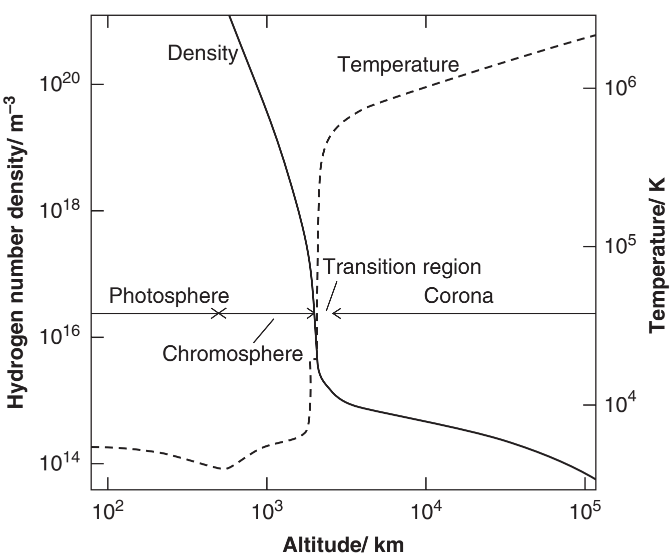

Figure 1.2 The variation of temperature and density in the Sun's atmosphere with altitude above the base of the photosphere.

The chromosphere is also greatly disturbed in regions where a flare occurs. This is a rapid brightening of a small area of the Sun's upper chromosphere or lower corona, usually in regions of the Sun where there are sunspots. The increase in brightness occurs in a few minutes, followed by a decrease taking up to an hour, and the energy release is spread over a very wide range of wavelengths. Flares, like certain prominences, are associated with bursts of ionised gas that escape from the Sun. Magnetic fields are an essential part of the flare process, and it seems probable that the electromagnetic radiation is from electrons that are accelerated close to the speed of light by changes in the magnetic field configuration. As with so many solar phenomena, the details are unclear.

The corona

Above the chromosphere the density continues to fall steeply across a thin transition region that separates the chromosphere from the corona (Figure 1.2).

❐ What distinctive feature of the transition region is apparent in Figure 1.2?

A distinctive feature is the enormous temperature gradient. This leads into the corona, where the gradient is not so steep. The corona extends for several solar radii (Plate 2), and within it the density continues to fall with altitude, but the temperature continues to rise, reaching $3–4 \times 10^6$ K, sometimes higher. Conduction, convection, and radiation from the photosphere cannot explain such temperatures – these mechanisms would not transfer net energy from a body at *lower* temperature (the photosphere) to a body at *higher* temperature (the corona). The main heating mechanism seems to be magnetic – magnetic fields become reconfigured throughout the corona, and induce local electric currents that then heat the corona. Waves involving magnetic fields (magnetohydrodynamic waves) also play a role in certain regions.

The corona is highly variable. At times of maximum sunspot number it is irregular, with long streamers in no preferred directions. At times of sunspot minimum, the visible boundary is more symmetrical, with a concentration of streamers extending from the Sun's equator, and short, narrow streamers from the poles. Coronal 'architecture' owes much to solar magnetic field lines. The white colour of the corona is photospheric light scattered by its constituents. Out to two or three solar radii the scattering is mainly from free electrons, ionisation being nearly total at the high temperatures of the corona. Further out, the scattering is dominated by the trace of fine dust in the interplanetary medium.

The solar wind

The solar atmosphere does not really stop at the corona, but extends into interplanetary space in a flow of gas called the **solar wind**, which deprives the Sun of about one part in 2.5×10^{-14} of its mass per year. Because of the highly ionised state of the corona, and its predominantly hydrogen composition, the wind consists largely of protons and electrons. The temperature of the corona is so high that if the Sun's gravity were the only force it would not be able to contain the corona, and the wind would blow steadily and uniformly in all directions. But the strong magnetic fields in the corona act on the moving charged particles in a manner that reduces the escape rate. Escape is preferential in directions where the confining effect is least strong, and an important type of location of this sort is called a coronal hole. This is a region of exceptionally low density and temperature, where the solar magnetic field lines reach huge distances into interplanetary space. Charged particles travel in helical paths around magnetic field lines, so the outward-directed lines facilitate escape. The escaping particles constitute the fast wind. Elsewhere, where the field lines are confined near the Sun, there is an additional outward flow, though at lower speeds, called the slow wind.

Solar wind particles (somehow) gain speed as they travel outwards, and at the Earth the speeds range from 200 to 900 $km\,s^{-1}$. The density is extremely low – typically about 4 protons and 4 electrons per cm^3, though with large variations. Particularly large enhancements result from what are called coronal mass ejections, often associated with flares and prominences, and perhaps resulting from the opening of magnetic field lines. If the Earth is in the way of a concentrated jet of solar wind, then various effects are produced, such as the aurorae (the northern and southern lights – Plate 26). The solar wind is the main source of the extremely tenuous gas that pervades interplanetary space.

Solar activity

Solar activity is the collective term for those solar phenomena that vary with a periodicity of about 11 years.

❒ What two aspects of solar activity were outlined earlier?

You have already met the sunspot cycle, and it was mentioned that the form of the corona is correlated with it. Prominences (filaments) and flares are further aspects of solar activity, both phenomena being more common at sunspot maximum. The solar luminosity also varies with the sunspot cycle, and on average is about 0.15% *higher* at sunspot maximum than at sunspot minimum. This might seem curious, with sunspots being cooler and therefore less luminous than the rest of the photosphere. However, when there are more sunspots, a greater area of the photosphere is covered in bright luminous patches called faculae.

All the various forms of solar activity are related to solar magnetic fields that ultimately originate deep in the Sun. The origin of these fields will be considered briefly in the following description of the solar interior.

1.1.3 The Solar Interior

To investigate the solar interior, we would really like to burrow through to the centre of the Sun, observing and measuring things as we go. Alas! This approach is entirely impractical. Therefore, the approach adopted, in its broad features, is the same as that used for all inaccessible interiors. A model is constructed and varied until it matches the major properties that we either *can* observe, or can obtain fairly directly and reliably from observations. Usually, a *range* of models can be made to fit, so a model is rarely unique. Many features are, however, common to all models, and such features are believed to be correct. This modelling process will be described in detail in Chapter 4, in relation to planetary interiors. Here, we shall present the *outcome* of the process as applied to the Sun.

A model of the solar interior

Figure 1.3 shows a typical model of the Sun as it is thought to be today. Hydrogen and helium predominate throughout, as observed in the photosphere. Note the enormous increase of pressure with depth, to 10^{16} pascals (Pa) at the Sun's centre – about 10^{11} times atmospheric pressure at sea level on the Earth! The central density is less extreme, 'only' about 14 times that of solid lead as it occurs on the Earth, though the temperatures are so high that the solar interior is everywhere fluid – there are no solids. Another consequence of the high temperatures is that at all but the shallowest depths the atoms are kept fully ionised by the energetic atomic collisions

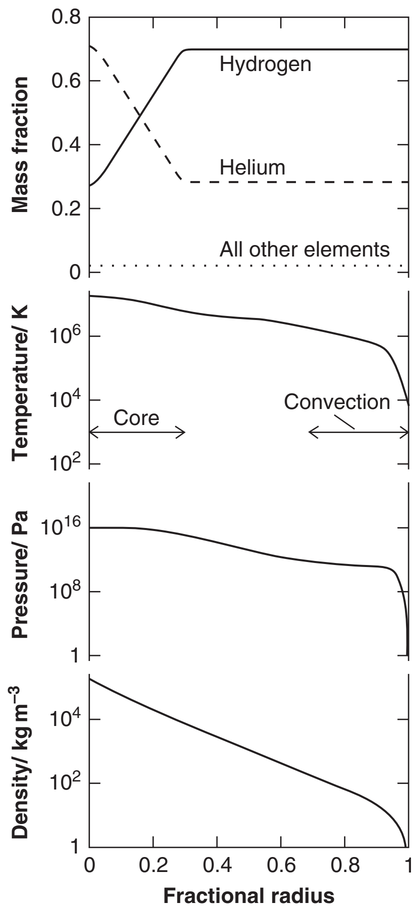

Figure 1.3 A model of the solar interior.

that occur. A highly ionised medium is called a **plasma**. The central temperatures in the Sun are about 1.4×10^7 K, sufficiently high that nuclear reactions can sustain these temperatures and the solar luminosity, and can have done so for the 4600 million years (Ma) since the Sun formed (an age based on various data to be outlined in Chapter 3, notably data from radiometrically dated meteorites). This copious source of internal energy also sustains the pressure gradient that prevents the Sun from contracting.

Though nuclear reactions sustain the central temperatures today, there must have been some other means by which such temperatures were initially attained in order that the nuclear reactions were triggered. This must have been through the gravitational energy released when the Sun contracted from some more dispersed state. With energy being radiated to space only from its outer regions, it would have become hotter in the centre than at the surface. Nuclear reaction rates rise so rapidly with increasing temperature that when the central regions of the young Sun became hot enough for nuclear reaction rates to be significant, there was a fairly sharp boundary between a central core where reaction rates were high, and the rest of the Sun where reactions rates were negligible. This has remained the case ever since. At present the central core extends to about 0.3 of the solar radius (Figure 1.3). This is a fraction $(0.3)^3$ of the Sun's volume, which is only 2.7%. However, the density increases so rapidly with depth that a far greater fraction of the Sun's mass is contained within its central core.

The Sun was initially of uniform composition, many models giving proportions by mass close to 70.9% hydrogen, 27.5% helium, and 1.6% for the total of all the other elements. In such a mixture, at the core temperatures that the Sun has had since its birth, there is only one group of nuclear reactions that is significant – the pp chains. The name arises because the sequence of reactions starts with the interaction of two protons (symbol p) to form a heavier nucleus (deuterium), a proton being the nucleus of the most abundant isotope of hydrogen (^{1}H). When a heavier nucleus results from the joining of two lighter nuclei, this is called **nuclear fusion**. The details of the pp chains will not concern us, but their net effect is the conversion of four protons into the nucleus of the most abundant isotope of helium (^{4}He), which consists of two protons and two neutrons.

The onset of hydrogen fusion in the Sun's core marks the start of its **main sequence** lifetime. A main sequence star is one sustained by core hydrogen fusion, and ends when the core hydrogen has been used up. The main sequence phase occupies most of a star's active lifetime. In the case of the Sun it will be another 6000 Ma or so until it ends, with consequences outlined in Section 11.5.

Various other subatomic particles are involved in the pp cycles, but of central importance are the gamma rays produced – electromagnetic radiation with very short wavelengths. These carry nearly all of the energy liberated by the pp chains' reactions. The gamma rays do not get very far before they interact with the plasma of electrons and nuclei that constitutes the solar core. To understand the interaction, it is necessary to recall that although electromagnetic radiation can be regarded as a wave, it can also be regarded as a stream of particles called **photons**. The wave picture is useful for understanding how radiation gets from one place to another; the photon picture is useful for understanding the interaction of radiation with matter. The energy e of a photon is related to the frequency f of the wave via

$$e = h\,f \tag{1.1}$$

where h is Planck's constant. The frequency of a wave is related to its wavelength via

$$f = c/\lambda \tag{1.2}$$

where c is the wave speed. For electromagnetic radiation in space c is the speed of light, $3.00 \times 10^5\,\mathrm{km\,s^{-1}}$. Table 1.6 lists values of c, h, and other physical constants of relevance to this book. (For ease of reference, the Chapter 1 tables are located at the end of the chapter.)

On average, after only a centimetre or so, a gamma ray in the core either bounces off an electron or nucleus, in a process called scattering, or is absorbed and re-emitted. This maintains the level of random motion of the plasma: in other words, it maintains its high temperature. The gamma ray photons are not all of the same energy. They have a spectrum shaped like that of an ideal thermal source at the temperature of the local plasma. This is true throughout the Sun, so as the photons move outwards their spectrum moves to longer wavelengths, corresponding to the lower temperatures, until at the photosphere the spectrum is that shown in Figure 1.1 (Section 1.1.1). The number of photons is greater than in the core, but they are of much lower average energy. From the moment a gamma ray is emitted in the core to the moment its descendants emerge from the photosphere, a time of several million years will have elapsed.

❐ What is the direct travel time?

The direct travel time at the speed of light c across the solar radius of 6.96×10^5 km is 6.96×10^5 km$/3.00 \times 10^5$ km s^{-1}, i.e. 2.23 seconds!

The transport of energy by radiation is, unsurprisingly, called **radiative transfer**. This occurs *throughout* the Sun. Another mechanism of importance in the Sun is convection, the phenomenon familiar in a warmed pan of liquid, where energy is transported by currents of fluid. When the calculations are done for the Sun, then the outcome is as in Figure 1.3. **Convection** is confined to the outer 29% or so of the solar radius, where it *supplements* radiative transfer as a means of conveying energy outwards. The tops of the convective cells are seen in the photosphere as transient patterns called granules. These are about 1500 km across, and exist for 5–10 minutes. There are also supergranules, about 10 000 km across and extending about as deep.

Because convection does not extend to the core in which the nuclear reactions are occurring, the core is not being replenished, and so it becomes more and more depleted in hydrogen and correspondingly enriched in helium. The core itself is unmixed, and so with temperature increasing with depth, the nuclear reaction rates increase with depth, and therefore so does the enrichment. This feature is apparent in the solar model in Figure 1.3.

The solar magnetic field

The source of any magnetic field is an electric current. If a body contains an electrically conducting fluid, then the motions of the fluid can become organised in a way that constitute a net circulation of electric current, and a magnetic field results. This is just what we have in the solar interior – the solar plasma is highly conducting, and the convection currents sustain its motion. We shall look more closely at this sort of process in Section 4.2. Detailed studies show that the source of the solar field is concentrated towards the base of the convective zone. The differential rotation of the Sun contorts the field in a manner that goes some way to explaining sunspots and other magnetic phenomena.

The increase of solar luminosity

Evolutionary models of the Sun indicate that the solar luminosity was only about 70% of its present value 4600 Ma ago, that it has gradually increased since, and will continue to increase in the future. This increase is of great importance to planetary atmospheres and surfaces, as you will see in later chapters.

1.1.4 The Solar Neutrino Problem

There is one observed feature of the Sun that solar models had difficulty in explaining. This is the rate at which solar neutrinos are detected on the Earth. Solar neutrinos are so unreactive that most of them escape from the Sun and so provide one of the few direct indicators of conditions deep in the solar interior. A neutrino is an elusive particle that comes in three kinds, called flavours. The electron neutrino is produced in the pp chains of nuclear reactions that occur in the solar interior. The rates at which electron neutrinos from the Sun are detected by various installations on the Earth are significantly below the calculated rate. Are the calculated pp reaction rates in the Sun too low?

No, they are not. It is now known that neutrinos oscillate between the three flavours. If, in their 8 minute journey at the speed of light from the solar core to the terrestrial detectors, they settle into this oscillation, then at any instant only some of the neutrinos arriving here are of the electron type. The earlier neutrino detectors could only detect the electron type. Now, all three can and have been detected coming from the Sun, giving a greater flux. This accounts for most of the discrepancy. The rest of it has been accounted for by improvements in solar models that have modified the predictions of the solar neutrino flux.

Question 1.1

The Sun's photospheric temperature, as well as its luminosity, has also increased since its birth. What is the combined effect on the solar spectrum in Figure 1.1?

1.2 The Sun's Family – A Brief Introduction

Within the Solar System we find bodies with a great range of size, as Figure 1.4 shows. The Sun is by far the largest body. Next in size are the four **giant planets**: Jupiter, Saturn, Uranus, and Neptune. We then come to a group of bodies of intermediate size. Prominent are the Earth, Venus, Mars, and Mercury. These four bodies constitute the **terrestrial planets**, so called because they are comparable in size and composition, and are neighbours in space. This intermediate-sized group has an arbitrary lower diameter which we shall take to be that of the planet Pluto, the ninth planet. At least one body well beyond Pluto is slightly larger than Pluto – Eris, of which, more later. Seven planetary satellites are larger than Pluto. As their name suggests, planetary satellites are companions of a planet, bound in orbit around it and with a smaller mass. In spite of their size, this binding means that they are classified as planetary bodies, rather than as planets.

There are plenty of bodies smaller than Pluto: the remaining satellites, of which one of Uranus's satellites Titania is the largest; a swarm of **asteroids**, of which Ceres ('series') is easily the largest; a huge number of comets, or bodies that become comets; and a continuous range of even smaller bodies, right down to tiny particles of dust.

Tables 1.1–1.3 display the radius, and several other properties, of Solar System bodies and of their orbits. Table 1.1 covers the nine planets and Ceres. Table 1.2 covers the planetary satellites,

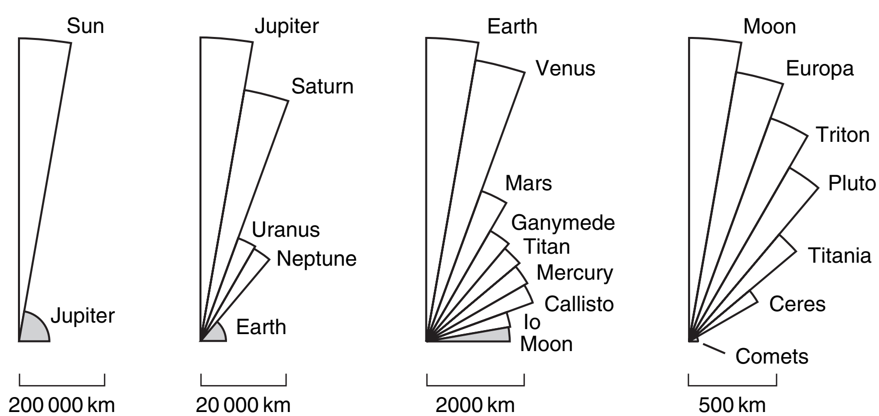

Figure 1.4 Sizes of bodies in the Solar System.

excluding the many satellites of Jupiter and Saturn less that 5 km mean radius, plus a few others of Uranus and Neptune. Table 1.3 covers the 15 largest asteroids.

Figure 1.5 shows the orbits of the planets. These orbits are roughly circular, and lie more or less in the same plane. The plane of the Earth's orbit is called the **ecliptic plane**. The planets move around their orbits at different rates, but in the same direction, anticlockwise as viewed from above the Earth's North Pole – this is called the **prograde direction**. The asteroids are concentrated in the space between Mars and Jupiter, in the asteroid belt. The distances in Figure 1.5 are huge compared even to the solar radius of 6.96×10^5 km. A convenient unit of distance in the Solar System is the average distance of the Earth from the Sun, 1.50×10^8 km, which is given a special name, the **astronomical unit** (AU). Between them, Figures 1.4 and 1.5 provide a map of the Solar System's planetary domain.

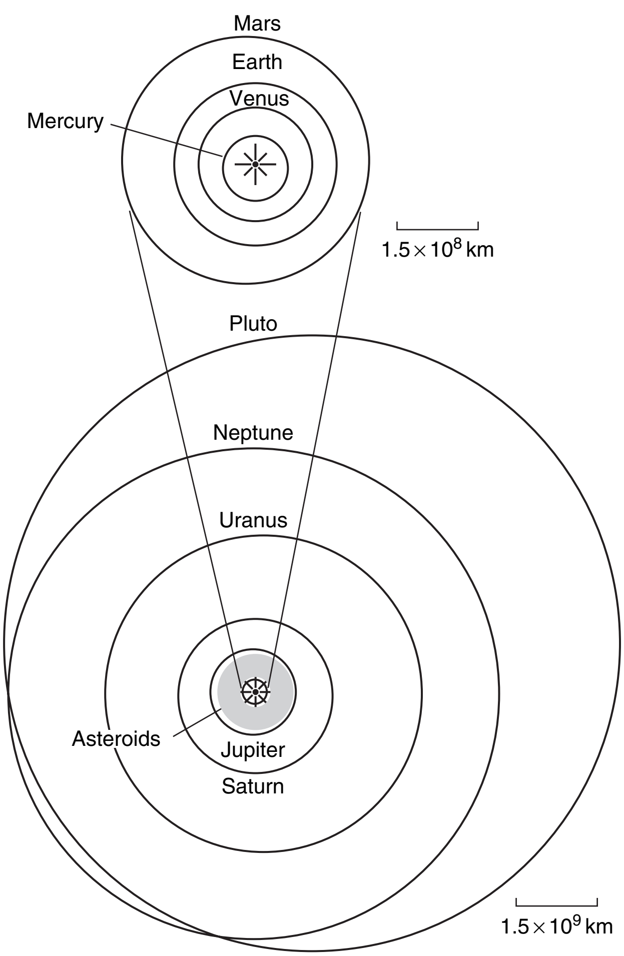

Figure 1.5 The orbits of the planets as they would appear from a distant viewpoint perpendicular to the plane of the Earth's orbit.

1.2.1 The Terrestrial Planets and the Asteroids

The terrestrial planets occupy the inner Solar System (Figure 1.5). They consist largely of rocky materials, with iron-rich cores. Most of the Earth's core is liquid, and this is probably the case for Venus too. Each core is overlain by a mantle of rocky materials (silicates), overlain in turn by a silicate crust. Mercury's surface is heavily cratered by the accumulated effects of impacts from space (Plate 4), indicating little geological resurfacing since the planet was formed. It has a negligible atmosphere. Venus is the Earth's twin in size and mass, and like the Earth it is geologically active, with volcanic features common (Plate 5), but it differs from the Earth in that it has no oceans. The surface of Venus, at a mean temperature of 740 K, is far too hot for liquid water, a consequence of its proximity to the Sun, and its massive, carbon dioxide (CO_2) atmosphere. The Earth is further from the Sun and has an atmosphere about 100 times less massive, mainly nitrogen (N_2) and oxygen (O_2). It is thus cool enough to have oceans, but not so cold that they are frozen (Plate 6). Unlike Mercury and Venus, the Earth has a satellite – the Moon. Figure 1.4 shows that it is a considerable world, larger than Pluto. It is devoid of an appreciable atmosphere and has a heavily cratered surface (Plate 7).

Beyond the Earth we come to Mars, smaller than the Earth but larger than Mercury. It has a thin CO_2 atmosphere through which its cool surface is readily visible (Plate 8). About half of the surface is heavily cratered. The other half is less cratered, and shows evidence of the corresponding past geological activity. Plate 9 is a view at the surface. Mars has two tiny satellites, Phobos and Deimos (Table 1.2). These orbit very close to the planet, and might be captured asteroids.

It is the domain of the asteroids – the asteroid belt – that we cross in the large gulf of space that separates Mars from Jupiter. Asteroids are rocky bodies of which Ceres is by far the largest (Table 1.3), although it is still a good deal smaller than Pluto (Figure 1.4). It is thought that there are about 10^9 asteroids larger than 1 km, and Plate 10 shows just one with a typically irregular shape at this small size. At a size of 1 metre there is a switch in terminology, with smaller bodies being called meteoroids, and these are even more numerous. Those that fall to Earth constitute the meteorites, which have provided much information about the origin, evolution, and composition of the Solar System. Below about 0.01 mm there is another switch in terminology – smaller particles are called dust. This is widely distributed within and beyond the asteroid belt, and is predominantly submicrometre in size (less that 10^{-6} m across). The asteroids are sometimes called minor planets.

1.2.2 The Giant Planets

The giant planets are very different from the terrestrial planets, not just in size (Figure 1.4) but also in composition. Whereas the terrestrial planets are dominated by rocky materials, including iron, Jupiter and Saturn are dominated by hydrogen and helium. There are also materials, notably water (H_2O). The icy materials tend to concentrate towards the centres, where it is so hot, typically 10^4 K, that the icy materials are liquids not solids. Rocky materials make up only a small fraction of the mass of Jupiter and Saturn, and they also tend to concentrate towards the centres. Uranus and Neptune are less dominated by hydrogen and helium, and the central concentration of icy and rocky materials is more marked. All four giant planets are fluid throughout their interiors.

❒ What other body in the Solar System is dominated by hydrogen and helium, and is fluid throughout?

The Sun is also a fluid body, dominated by hydrogen and helium (Section 1.2).

Jupiter is the largest and most massive of the planets. Plate 11 shows the richly structured uppermost layer of cloud, which consists mainly of ammonia (NH_3) particles, coloured by traces of a wide variety of substances, and patterned by atmospheric motions. The prominent banding is parallel to the equator.

Jupiter has a large and richly varied family of satellites. Figure 1.6 is a plan view, drawn to scale, of the orbits of the four largest by far of Jupiter's satellites – Io, Europa, Ganymede, Callisto. They are called the **Galilean satellites**, after the Italian astronomer Galileo Galilei (1564–1642) who discovered them in 1610 when he made some of the very first observations of the heavens with the newly invented telescope. They orbit the planet close to its equatorial plane. These remarkable bodies are shown in Plates 12–15. They range in size from Ganymede, which is somewhat larger than Mercury and is the largest of all planetary satellites, to Europa, which is somewhat smaller than the Moon. Io is a rocky body. The other three contain increasing amounts of water (mainly as ice) with increasing distance from Jupiter. Table 1.2 includes all but the smallest satellites of Jupiter.

We move on to Saturn, which is somewhat smaller than Jupiter, but is otherwise not so very different (Plate 16). We shall say no more about the planet in this chapter, but turn to its family of satellites, and in particular to its largest satellite Titan, an icy–rocky body larger than Mercury, and second only to Ganymede among the satellites. A remarkable thing about Titan is that it has a massive atmosphere. Indeed, per unit area of surface, it has about 10 times more mass of atmosphere than the Earth. The atmosphere is well over 90% N_2 with a few per cent of methane (CH_4), but contains so much hydrocarbon cloud and haze that the surface is almost invisible from outside it (Plate 17).

Saturn is most famous for its rings (Plate 18). These lie in the planet's equatorial plane, and consist of small solid particles. The rings are extremely thin, probably no more than a few hundred metres. They are, however, so extensive that they were observed by Galileo in 1610, though it was the Dutch physicist Christiaan Huygens (1629–1693) who, in 1655, was first to

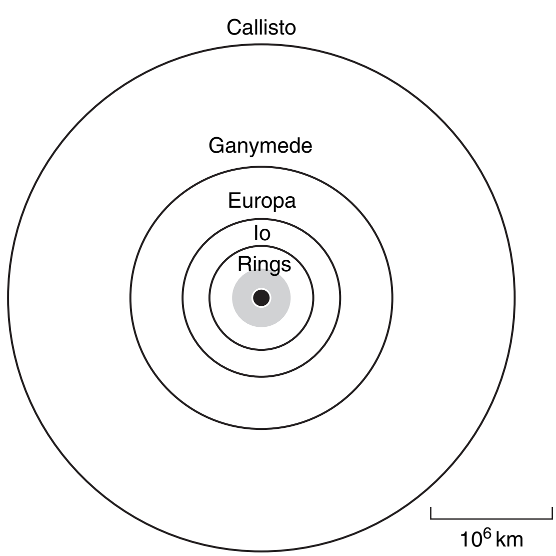

Figure 1.6 The orbits of the Galilean satellites of Jupiter.

realise that they are rings encircling the planet. Plate 18 shows that each main ring is broken up into many ringlets, to form a structure of exquisite complexity. The other three giant planets also have ring systems, but they are far less substantial.

Beyond Saturn we head off across another of the increasingly large gulfs of space that separate the planets as we move out from the Sun. We come to Uranus, a good deal smaller than Saturn, and with a smaller proportion of hydrogen and helium and a large icy–rocky core. In spite of its size it was unknown until 1781 when it was discovered accidentally by the Germano-British astronomer William Herschel (1738–1822) during a systematic survey of the stars. This was the first planet to be discovered in recorded history. It had escaped earlier detection because it is at the very threshold of unaided eye visibility, owing to its great distance from us. Its bands are generally not as strong as those of Jupiter and Saturn (Plate 19).

Neptune, like Uranus, was discovered in recorded history, but the circumstances were very different. Whereas Uranus was discovered accidentally, Neptune was discovered as a result of predictions made by two astronomers in order to explain slight departures of Uranus from its expected orbit. The British astronomer John Couch Adams (1819–1892) and the French astronomer Urbain Jean Joseph Le Verrier (1811–1877) independently predicted that the cause was a previously unknown planet orbiting beyond Uranus, and in 1846 Neptune was discovered by the German astronomer Johann Gottfried Galle (1812–1910) close to its predicted positions. Neptune, the last of the giants, is not so very different from Uranus (Plate 20), and so in the spirit of this quick tour we shall say no more here about the planet itself.

Uranus and Neptune have many satellites. The largest among them by far, Neptune's satellite Triton, is a rocky–icy body slightly larger than Pluto, and it is the only satellite other than Titan that has a significant atmosphere, though it is fairly tenuous, and allows the icy surface of Triton to be seen (Plate 21). Among Neptune's other satellites, Nereid has a huge and extraordinarily eccentric orbit (Table 1.2). The orbit of Triton is curious in a different way – though it is nearly circular it is **retrograde**, which is the opposite direction to the prograde orbital motion of the planets and all other large satellites.

1.2.3 Pluto and Beyond

Beyond Neptune lies Pluto, in an orbit where sunlight is 1600 times weaker than at the Earth. Pluto was discovered in 1930 by the American astronomer Clyde William Tombaugh (1906–1997) during a systematic search of a band of sky straddling the orbital planes of the known planets. It is a small world (Figure 1.4) and has not yet been visited by a spacecraft. Consequently we know rather little about Pluto and its comparatively large satellite Charon. Pluto is an icy world, with about half of its volume consisting of frozen water and other icy substances, and the remainder consisting of rock. Charon probably has a broadly similar composition. Pluto also has two tiny satellites, Nix and Hydra, of unknown composition.

Beyond Pluto space is not empty, and we have certainly not come to the edge of the Solar System. One type of body abundant beyond Pluto is the **comets**. These are small icy–rocky bodies that, through the effect of the Sun, develop huge fuzzy heads and spectacular tails when their orbits carry them into the inner Solar System (Plate 22). In the outer Solar System they have no heads and tails, and are not called comets there. There are two main populations. One of these has bodies in prograde orbits concentrated towards the ecliptic plane, and occupying orbits ranging from around the size of Pluto's orbit (39.8 AU from the Sun, on average) to far larger. This is the **Edgeworth–Kuiper belt**, and its occupants are called E–K objects (EKOs). Over 1000 have been seen, the largest at present being Eris, which Hubble Space Telescope

(HST) images have shown to have a radius about 20% larger than Pluto. It is currently (2006) 97 AU from the Sun, and when closest to the Sun lies at a distance of 38 AU. It is estimated that more than 10^5 EKOs are larger than 100 km across, and lie in orbits out to about 50 AU. There are more EKOs further away, Eris among them, and there are certainly many more that are smaller than 100 km.

The Edgeworth–Kuiper belt might blend into the second population of icy–rocky bodies, a swarm of 10^{12}–10^{13} in a thick spherical shell surrounding the Solar System, extending from about 10^3 to 10^5 AU. This is the **Oort cloud** (also called the Öpik–Oort cloud). Its outer boundary is at the extremities of the Solar System, where passing stars can exert a gravitational force comparable with that of the Sun. The Oort cloud has not been observed directly, but its existence is inferred from the comets that we see in the inner Solar System. These are a small sample of the Oort cloud and also of the Edgeworth–Kuiper belt, but in orbits that have been greatly modified. Table 1.4 lists some properties of selected comets.

Definition of a planet

That Eris, and several other EKOs, are larger or comparable in size with Pluto, has raised the issue of whether there are several more planets in the Solar System, or whether large EKOs, including Pluto, should not be regarded as planets.

At its triennial meeting in Prague in 2006, the International Astronomical Union faced this issue, and passed resolutions defining what, in the Solar System, determines whether a body is a planet. You might be surprised that previously there was no formal definition. The least controversial parts of the definition are that a planet is in its own orbit around the Sun and is large enough for its own gravity to overcome the strength of its materials, which, for a non-rotating, isolated body, would make it spherical. On this basis, Pluto, Eris, and Ceres would be planets. But the IAU added a further criterion, that to be a planet a body has to have cleared material in the neighbourhood of its orbit. This is a tricky concept. The important point is that Pluto, Eris, and Ceres do not meet it, and are therefore to be regarded as **dwarf planets**.

However, the debate is not over. Many astronomers are unhappy with the IAU resolutions, and therefore the definition of what is a planet might well be revised in the near future. Consequently, in this book, Pluto will continue to be regarded as a planet and also as a large EKO. Eris, and other large EKOs, will not, for now, be labelled as (dwarf) planets, and Ceres will continue to be regarded as the largest asteroid.

Question 1.2

In about 100 words, discuss whether there is any correlation between the size of a planet and its distance from the Sun.

1.3 Chemical Elements in the Solar System

With most of the mass in the Solar System in the Sun, and the Sun composed almost entirely of hydrogen and helium, the chemical composition of the Solar System is dominated by these two elements. Hydrogen is the lightest element. Its most common isotope (by far) has a nucleus consisting of a single proton. You saw in Section 1.1.3 that this isotope is represented as ^{1}H.

Helium is the next lightest element, with the nucleus of its most common isotope (again by far) consisting of two protons and two neutrons. Recall that an element is defined by the number of protons in its nucleus – this is the atomic number – and that the isotopes are distinguished by different numbers of neutrons. To denote a particular isotope the number of neutrons plus protons is included with the chemical symbol, as you have seen for helium's common isotope, ^4He (Section 1.1.3).

The Solar System contains all 92 naturally occurring chemical elements with atomic numbers from 1 (hydrogen) to 92 (uranium). The relative abundances of these elements have been determined through observations of the Sun and through analyses of primitive meteorites (Section 3.3.2).

Most of the mass outside the Sun is in Jupiter and Saturn, and these are also composed largely of hydrogen and helium, though they contain larger proportions of the other elements – the so-called **heavy elements**. For the Solar System as a whole, Table 1.5 gives the relative abundances of the 15 most abundant of the chemical elements. Note that the value for helium is for the Sun outside its fusion core. This region has not been depleted in helium by its conversion into hydrogen by nuclear fusion, such as occurs in the core of the Sun.

Except in very high-temperature regions, most of the atoms of most elements are combined with one or more other atoms, either of the same element, or of other elements. The important exceptions are helium, neon, argon, krypton, and xenon, which are so chemically unreactive that they remain monatomic and have been given the name **inert gases** or noble gases. If an element is combined with itself, as in H_2, then we have the element in molecular form, whereas if it is combined with other elements, then we have it as a chemical compound.

Water (H_2O) is the most abundant chemical compound of hydrogen in the Solar System. Table 1.5 suggests the reason.

❐ What is the reason?

It is because oxygen has a high abundance. But hydrogen is so overwhelmingly abundant that there is plenty left over after the formation of hydrogen compounds. Most of the uncompounded hydrogen outside of the Sun is in the giant planets, as H_2, or as a fluid of hydrogen with metallic properties. Water is the main repository of hydrogen in most of the other bodies.

1.4 Orbits of Solar System Bodies

1.4.1 Kepler's Laws of Planetary Motion

Each planet orbits the Sun as shown in plan view in Figure 1.5. As a crude approximation, the planetary orbits can be represented as circles centred on the Sun, with all the circles in the same plane, and each planet moving around its orbit at a constant speed; the larger the orbit, the slower the speed. A far better approximation is encapsulated in three empirical rules called **Kepler's laws of planetary motion**. These were announced by the German astronomer Johannes Kepler (1571–1630), the first two in 1609, the third in 1619.

Kepler's first law Each planet moves around the Sun in an ellipse, with the Sun at one focus of the ellipse.

Kepler's second law As the planet moves around its orbit, the straight line from the Sun to the planet sweeps out equal areas in equal intervals of time.

We shall come to the third law shortly.

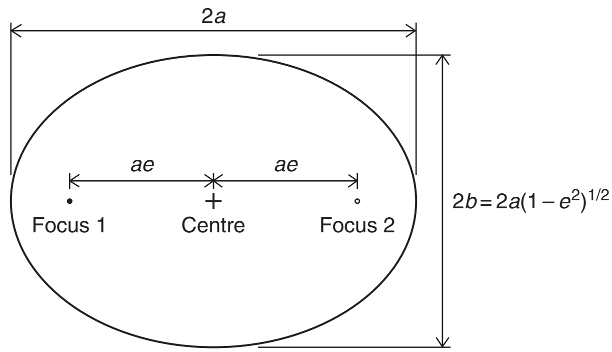

Figure 1.7 An ellipse, though far more eccentric than the orbit of any planet. This is the shape of the orbit of the comet 21P Giacobini–Zinner (Table 1.4).

Figure 1.7 shows an **ellipse**. The shape is that of a circle viewed obliquely: the more oblique the view, the greater the departure from circular form. The important features of an ellipse are marked in Figure 1.7, and are that

- it has a major axis of length $2a$ and a minor axis of length $2b$ – unsurprisingly, a and b are called, respectively, the **semimajor axis** and the semiminor axis;
- there are two foci that lie on the major axis, each a distance ae from the centre of the ellipse, where e is the **eccentricity** of the ellipse; note that the foci are in the plane of the ellipse, and that $e = \sqrt{1 - b^2/a^2}$.

The eccentricity is a measure of the departure from circular form. If e is zero, then the foci coalesce at the centre, a equals b, and the ellipse has become a circle of radius a. If e approaches one then the ellipse becomes extremely elongated.

Kepler's first law tells us that the shape of a planetary orbit is an ellipse, and that the Sun is at one focus. Figure 1.8 shows the orbit of Pluto, which among planetary orbits has the greatest eccentricity, $e = 0.254$. Note that whereas the shape is very close to a circle, the Sun, which

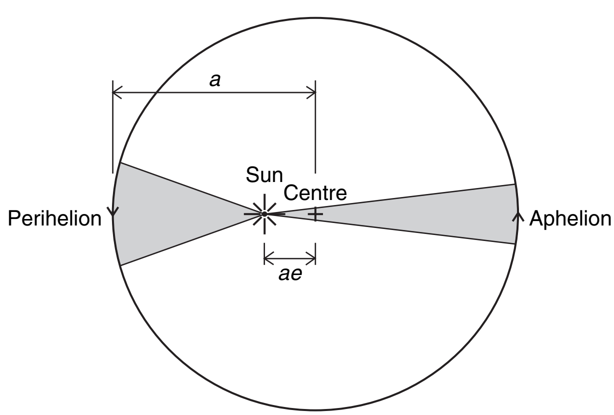

Figure 1.8 The orbit of Pluto.

is at one of the foci, is distinctly off centre. Note also that the semimajor axis is less than the maximum distance of a body from the Sun, but is greater than the minimum distance, and it is therefore some sort of average distance. At its greatest distance from the Sun the body is at a point in its orbit called **aphelion**; the closest point is called **perihelion**. These terms are derived from the Greek words *Helios* for the Sun, and *peri*- and *apo*- which in this context mean 'in the vicinity of' and 'away from' respectively. The length of the semimajor axis of the Earth's orbit is called the astronomical unit (AU), mentioned earlier.

Kepler's laws don't apply just to planets. Figure 1.7 is in fact the shape of the orbit of the comet 21P/Giacobini–Zinner (Table 1.4).

❐ Where should the Sun be marked in Figure 1.7?

The Sun should be shown at either one of the two foci. This is an orbit of fairly high eccentricity, $e = 0.7057$. The non-circular form is now very clear, and the foci are greatly displaced from the centre.

Kepler's *second* law tells us how a planet (or comet) moves around its orbit. For the case of Pluto the shaded areas within the orbit in Figure 1.8 are equal in area, and so by Kepler's second law these are swept out in equal intervals of time. Thus, around aphelion the body is moving slowest, and around perihelion it is moving fastest. The difference in these two speeds is larger, the greater the eccentricity.

❐ What are the speeds at different positions in a *circular* orbit?

In a circular orbit the equal areas correspond to equal length arcs around the circle, so the body moves at a constant speed around its orbit.

So far, Kepler's laws have described the orbital motion around the Sun of an *individual* body. The third and final law compares the motion of one body to another:

Kepler's third law If P is the time taken by a planet to orbit the Sun once, and a is the semimajor axis of the orbit, then

$$P = ka^{3/2} \tag{1.3}$$

where k has the same value for each planet.

P is called the orbital period or the period of revolution. It is the period as observed from a non-rotating viewpoint, which, for practical purposes, is any viewpoint fixed with respect to the distant stars. This leads to the term **sidereal** ('= star-related') **orbital period** for P. For the Earth this period is called the sidereal year. Therefore, with $P = 1$ (sidereal) year and $a = 1$ AU, $k = 1$ year AU$^{-3/2}$. According to Kepler's third law, this is the value of k for all the planets.

Equation (1.3) tells us that the larger the orbit, the longer the orbital period. This is partly because the planet has to travel further, and partly because the planet moves more slowly. We can see that the planet moves more slowly from the simple case of a circular orbit of radius a. The circumference of the orbit is $2\pi a$, so if the orbital speed were independent of a then P would be proportional to a, not, as observed, to $a^{3/2}$. Therefore, the orbital speed must be proportional to $a^{-1/2}$. In an elliptical orbit the circumference still increases as a increases, and now it is the *average* speed that decreases.

Kepler's third law enables us to obtain relative distances in the Solar System. If we measure the orbital periods of bodies A and B, then the ratio of the semimajor axes of their orbits is obtained from equation (1.3):

$$\frac{a_{\mathrm{A}}}{a_{\mathrm{B}}} = \left(\frac{P_{\mathrm{A}}}{P_{\mathrm{B}}}\right)^{2/3}$$

If one of the two bodies has a in AU, then we can express the other semimajor axis in astronomical units. This can be repeated for all orbits. Moreover, from the shape and orientation of the orbits, we can draw a scale plan of the Solar System, and at any instant we can show where the various planets lie. At any instant we can thus express in astronomical units the distance between any two bodies. If at the same instant we can measure the distance between any two bodies in metres, we can then obtain the value of the astronomical unit in metres.

Today, the astronomical unit is best measured using radar reflections. Radar pulses travel at the speed of light c, which is known very accurately (Table 1.6). Time intervals can also be measured very accurately, so if we measure the time interval Δt between sending a radar pulse from the Earth to a planet and receiving its echo, then the distance from the Earth to the planet is $c\Delta t/2$. Accurate measurements of distances in the Solar System have revealed that the semimajor axis of the Earth's orbit is subject to very slight variations. As a consequence the AU is now defined as *exactly* equal to $1.495\,978\,706\,9 \times 10^8$ km. The Earth's semimajor axis is currently (2006) 0.999 985 AU.

Question 1.3

The asteroid Fortuna is in an orbit with a period of 3.81 years. Show that the semimajor axis of its orbit is 2.44 AU.

Question 1.4

Suppose that when the Earth is at perihelion Venus lies on the straight line between the Earth and the Sun. The time interval between sending a radar pulse from the Earth to Venus and receiving its echo is 264 s. Taking the speed of light in space as $3.00 \times 10^5\ \mathrm{km\,s^{-1}}$, calculate to two significant figures the astronomical unit in metres. Proceed as follows.

For the instant of measurement

- from the orbital details calculate the distance between the Earth and Venus in AU;
- from the radar data calculate the distance in km between the Earth and Venus.

Hence calculate the number of metres in 1 AU.

Note: *For two-significant-figure accuracy Venus is sufficiently close to perihelion when the Earth is at perihelion for you to use the perihelion distance of Venus.*

1.4.2 Orbital Elements

The quantities a and e are two of the five quantities – of the five **orbital elements** – that are needed to specify the elliptical orbit of a body. P is *not* normally among the three remaining elements.

❐ Why is P (normally) redundant?

The orbital period is redundant because it can usually be obtained with sufficient accuracy from a via Kepler's third law. The need for three further elements is illustrated in Figure 1.9, which shows the plane of the Earth's orbit plus the orbit of another body. Note that, for clarity, the orbit of the Earth is not shown, though the direction of the Earth's orbital motion is indicated by an arrow. The plane of the Earth's orbit acts as a reference plane for all other orbits and, as noted earlier, is called the ecliptic plane. The position of the Earth in its orbit at a certain

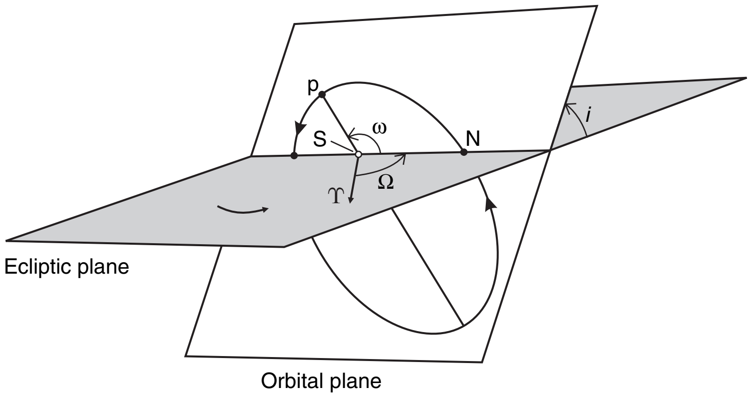

Figure 1.9 The three orbital elements i, ω, Ω, used to specify the orientation of an elliptical orbit with respect to the ecliptic plane.

moment in the year provides a reference direction. The direction chosen is that from the Earth to the Sun when the Earth is at the **vernal** (March) **equinox**. The direction points to the stars at a location called the **first point of Aries**. The direction (and the location) has the symbol ♈. The basis of these names will be given later.

For the other body in Figure 1.9, its orbital plane intersects the ecliptic plane to form a line. The Sun lies on this line at the point S – the Sun must lie in both orbital planes (Kepler's first law). Another point on the line is marked N, and this is where the body crosses the ecliptic plane in going from the south side to the north side, north and south referring to the sides of the ecliptic plane on which the Earth's North and South Poles lie. N is called the **ascending node** of the body's orbit. The angle Ω is measured in the direction of the Earth's motion, from ♈ to the line SN. This is the orbital element called the **longitude of the ascending node**. It can range from 0° to 360°. The orbital plane of the planet makes an angle i with respect to the ecliptic plane, and this is the element called the **orbital inclination**. It can range from 0° to 180° – values greater than 90° correspond to retrograde orbital motion.

❒ What is the inclination of the Earth's orbit, and why is the longitude of the ascending node an inapplicable notion?

The Earth's orbit lies in the ecliptic plane. With the ecliptic plane as the reference plane, the inclination of the Earth's orbit is therefore zero. An ascending node is one of the two points where an orbit intersects the ecliptic plane. The Earth's orbit lies in this plane and therefore the ascending node is undefined.

The last of the five elements that are needed to specify the elliptical orbit of a body is the angle ω, measured from SN to the line Sp, where p (Figure 1.9) is the perihelion position of the body. The angle ω is measured in the direction of motion of the body, and can range from 0° to 360°. It is called the **argument of perihelion**. However, it is somewhat more common to give as the fifth element the angle $(\Omega + \omega)$. This is called the **longitude of perihelion**. It is a curious angle, being the sum of two angles that are not in the same plane. Note that if the sum exceeds 360°, then 360° is subtracted.

To specify exactly where a body will be in its orbit at some instant we need to know when it was at some specified point at some earlier time. For example, we could specify one of the times at which the body was at perihelion. This sort of specification is a sixth orbital element.

Table 1.1 lists the values of the orbital elements for each planet and for the largest asteroid, Ceres. Note that

- the orbital inclinations are small: the planets' orbital planes are almost coincident, Pluto's inclination of 17.1° being by far the greatest;
- except for Pluto and Mercury, and to a lesser extent Mars, the orbital eccentricities are also small, and the exceptions are not dramatic.

Question 1.5

(a) Comet Kopff has the following orbital elements: inclination 4.7°, eccentricity 0.54, argument of perihelion 163°, longitude of the ascending node 121°. Sketch the orbit with respect to the ecliptic plane and the direction ♈. (An accurate drawing is *not* required.)

(b) The distance of Comet Kopff from the Sun at its perihelion on 2 July 1996 was 1.58 AU. Calculate the semimajor axis of the orbit, and hence calculate: its aphelion distance, its orbital period, and the month and year of the first perihelion in the twenty-first century (given that there are 365.24 days per year).

(c) The perihelion and aphelion distances of Mars are 1.38 AU and 1.67 AU, and yet the orbits of Mars and Comet Kopff do *not* intersect. In a few sentences, state why not. (A proof is *not* required.)

1.4.3 Asteroids and the Titius–Bode Rule

Nearly all of the asteroids are in a belt between Mars and Jupiter, and though their orbital inclinations and eccentricities are more diverse than for the planets (Table 1.3), the asteroids in the asteroid belt do, by and large, partake in the nearly circular swirl of prograde motion near to the ecliptic plane.

If we compare the semimajor axes of the planets, and include the asteroids, then something curious emerges. One way of making this comparison is shown in Figure 1.10. The planets have been numbered in order from the Sun: Mercury is numbered 1, Venus 2, Earth 3, Mars 4, the asteroids 5, Jupiter 6, and so on. The semimajor axes of the orbits have been plotted versus each planet's number. For the asteroids the dot is Ceres and the bar represents the range of semimajor axes in the main belt, a concentration within the broader asteroid belt. The curious thing is that, with a logarithmic scale on the 'vertical' axis, the data in Figure 1.10 lie close to a straight line. This means that the semimajor axes increase by about the same factor each time we go from one planet to the next one out. This is one of several ways of expressing the **Titius–Bode rule**, named after the German astronomers Johann Daniel Titius (1729–1796), who formulated a version of the rule in 1766, and Johann Elert Bode (1747–1826) who published it in 1772. Theories of the formation of the Solar System (Chapter 2) can give rise to an increase in spacing of planetary orbits as we go out from the Sun, so the Titius–Bode rule is an expression of this feature of the theories.

1.4.4 A Theory of Orbits

Kepler's laws are empirical rules that describe very well the motion of the planets around the Sun. One of the many achievements of the British scientist Isaac Newton (1642–1727) was that he was able to explain the rules in terms of two universal theories that he had developed. One

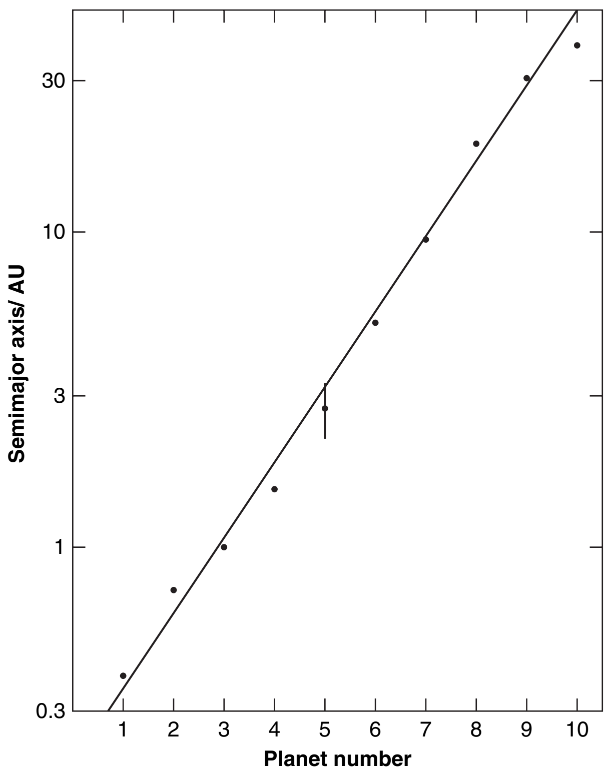

Figure 1.10 The semimajor axes of the planets versus the planets in order from the Sun: 1 = Mercury, 2 = Venus, etc., until 10 = Pluto. The vertical line at 5 is the asteroid belt.

theory is encapsulated in **Newton's laws of motion**, and the other in **Newton's law of gravity**. I state these laws here on the assumption that you have met them before, and will concentrate on using them to explore motion in the Solar System.

Newton's first law of motion An object remains at rest or moves at constant speed in a straight line unless it is acted on by an unbalanced force. (In other words, an unbalanced force causes acceleration, i.e. either a change of speed or a change of direction, or a change of both speed and direction.)

Newton's second law of motion If an unbalanced force of magnitude (size) F acts on a body of mass m, then the acceleration of the body has a magnitude given by

$$a = F/m \tag{1.4}$$

and the direction of the acceleration is in the direction of the unbalanced force.

Newton's third law of motion If body A exerts a force of size F on body B, then body B will exert a force of the same magnitude on body A but in the opposite direction.

Newton's law of gravity If two point masses M and m are separated by a distance r then there is a gravitational force of attraction between them with a magnitude given by

$$F = GMm/r^2 \tag{1.5}$$

where G is the universal gravitational constant (its value is given in Table 1.6).

A point mass has a spatial extent that is negligible compared with r. For extended bodies the net gravitational force is the sum of the gravitational forces between all the points in one body and all the points in the other.

To derive Kepler's laws from Newton's laws three conditions have to be met:

(1) The only force on a body is the gravitational force of the Sun.
(2) The Sun and the body are **spherically symmetrical**. This means that their densities vary only with radius from the centre to the (spherical) surface. In this case they interact gravitationally like point masses with all the mass of each body concentrated at its centre.
(3) The mass of the orbiting body is negligible compared with the Sun's mass.

The detailed derivation of Kepler's laws from Newton's laws can be found in books on celestial mechanics, and will not be repeated here, but we can illustrate some links between the two sets of laws.

Kepler's first and second laws

Take the first and second laws together and consider a body A in an elliptical orbit such as orbit 1 in Figure 1.11. Newton's law of gravity tells us that the Sun attracts A. Thus, from the second law of motion, A accelerates towards the Sun, its speed increasing as its distance from the Sun decreases. Because it has a component of motion other than towards the Sun, it does not fall directly towards the Sun. It therefore misses the Sun and swings through perihelion (p)

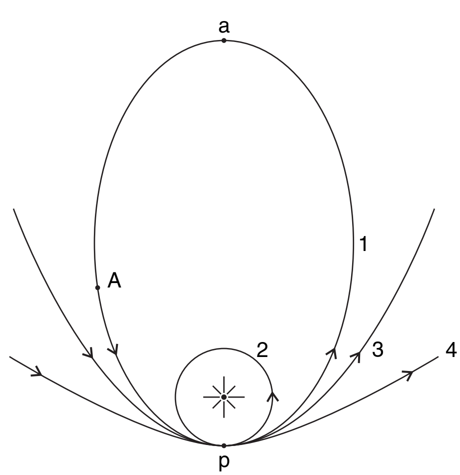

Figure 1.11 A body in a variety of orbits around the Sun.

at its maximum speed. It is then slowed down by the Sun's gravity as it climbs away from the Sun, and has its minimum speed as it passes through aphelion (a). The mathematical details show that under the three conditions the precise shape of the orbit is elliptical with the Sun at a focus (Kepler's first law) and that the increase in speed with decreasing solar distance gives the equal areas law (Kepler's second law).

Consider the body now in the circular orbit 2 in Figure 1.11. This orbit has the same perihelion distance as orbit 1, but the body is now moving more slowly at p than it was in orbit 2, and so it does not climb away from the Sun. It still accelerates towards the Sun in that its motion is always curving towards the Sun, but its overall motion is just right to keep it at the same distance from the Sun. Consequently its speed in its orbit is constant, and its acceleration is entirely in its change of direction. If a body had *no* sideways motion then it would accelerate straight into the Sun.

Parabolic and hyperbolic orbits

Now consider the body with a speed at the perihelion distance of p greater than that of the body in orbit 1 in Figure 1.11.

❐ What would be the orbit were the speed at p only slightly greater?

In this case the body would climb slightly further away at aphelion – the semimajor axis would be greater. If we increase the speed further then Newton's laws predict that we will reach a value at which the body climbs right away from the Sun, never to return. This threshold is met in orbit 3 in Figure 1.11. This is a parabolic orbit. It is not a closed curve – the two arms become parallel at infinity. Orbits with even greater perihelion speeds are even more opened out, and one example is orbit 4. These are **hyperbolic orbits**. At infinity, the two arms of a hyperbola become tangents to diverging straight lines; the greater the perihelion speed, the greater the angle between the lines. Parabolic and hyperbolic orbits are called unbound orbits, whereas an elliptical orbit is a bound orbit.

Are there any Solar System bodies in unbound orbits? Yes there are. Table 1.4 shows that the orbital eccentricities of two of the comets listed are indistinguishable from 1, a value that corresponds to a parabolic orbit. Two of those listed are in hyperbolic orbits. If a comet is in an unbound orbit then, unless its orbit is suitably modified to become bound, e.g. by a close encounter with a planet, it will leave the Solar System. Also, unless its orbit has been modified on its way inwards, it must have come from beyond the Solar System. Comets are a major topic in Chapter 3.

Kepler's third law

For Kepler's third law ($P = ka^{3/2}$) we have to consider bodies in orbits with different semimajor axes. You saw earlier that the $a^{3/2}$ dependence is the combined result of an increase in the distance around the larger orbit, and a lower orbital speed. This lower speed is explained by the decrease of gravitational force with distance (Newton's law of gravity, equation (1.5)) and the corresponding decrease in acceleration, a result derived in detail in standard texts. Such texts also show that, under the conditions 1 and 2 above, Newton's laws give

$$P = \left(\frac{4\pi^2}{G(M_\odot + m)}\right)^{1/2} a^{3/2} \quad (1.6)$$

where $M_\odot$ is the mass of the Sun and m is the mass of the other body. This is not quite Kepler's third law.

❒ What further condition is needed?

To get Kepler's third law $4\pi^2/G(M_\odot + m)$ must be a constant for the Solar System. With m being the property of the non-solar body, this condition is met if m is negligible compared with the Sun's mass. This is condition (3) above. In the Solar System Jupiter is by some way the most massive planet, but even so is only 0.1% the mass of the Sun. Therefore, condition (3) is met to a good approximation, and Kepler's third law is explained satisfactorily by Newton's laws.

Question 1.6

From the orbital data for the Earth in Table 1.1, calculate the mass of the Sun. Work in SI units, and note that 1 year $= 3.156 \times 10^7$ s. Repeat the calculation using the data for Jupiter's orbit. State any approximations you make, and whether your calculated masses seem to bear them out.

1.4.5 Orbital Complications

Conditions (1)–(3) in Section 1.4.4 are met only approximately in the Solar System, and because of this, complications arise, as follows.

The mass of the orbiting body is not *negligible compared with the Sun's mass*

Consider a single planet and the Sun, as in Figure 1.12(a). You can see that they each orbit a point on a line between them. This point is called the **centre of mass** of the system comprising the Sun and the planet. For any system of masses the centre of mass is the point that accelerates under the action of a force external to the system *as if* all the mass in the system were concentrated at that point. Thus if the external forces are negligible then the centre of mass is unaccelerated. By contrast both the Sun and the planet accelerate the whole time because of their orbital motions with respect to the centre of mass. In Figure 1.12(b) the same planet is shown in its orbit with respect to the Sun. This orbit is bigger than the two in Figure 1.12(a) but all three orbits have the same eccentricity and orbital period. Kepler's first two laws apply to the planetary orbit with respect to the Sun, as in Figure 1.12(b), and are *not* invalidated by the non-negligible planet's mass.

For two spherically symmetrical bodies, such as the Sun and planet in Figure 1.12, the centre of mass is at a position such that

$$r_\odot / r_p = m_p / M_\odot \qquad (1.7)$$

where $r_\odot$ and r_p are the *simultaneous* distances of the Sun and planet from the centre of mass at any point in the orbits, and m_p and $M_\odot$ are the masses. Though we shall not prove this equation, it has reasonable features. For example, the greater the value of $m_p/M_\odot$, the further the centre of mass is from the centre of the Sun. In Figure 1.12 $m_p/M_\odot = 1/4$, corresponding to a planet far more massive than any in the Solar System.

❒ Where is the centre of mass if the mass of the planet is negligible compared with the solar mass?

It is then at the centre of the Sun.

Jupiter, the most massive planet, has a mass 0.0955% of that of the Sun. Jupiter is in an approximately circular orbit with a semimajor axis of 7.78×10^8 km, and so, from equation (1.7),

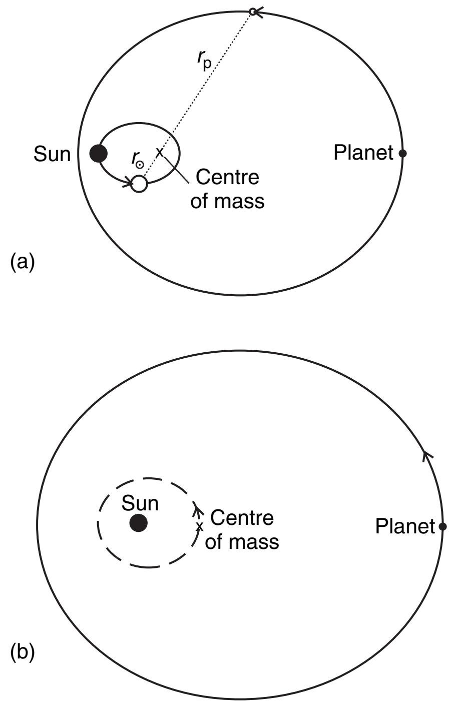

Figure 1.12 A planet in orbit around the Sun. (a) Motion with respect to the centre of mass. (b) Motion of the planet with respect to the Sun.

we can calculate that the centre of mass of the Jupiter–Sun system is 740 000 km from the Sun's centre. Thus, if Jupiter were the only planet in the Solar System the Sun's centre would move around a nearly circular orbit of radius 740 000 km – not much more than the solar radius. The effects of the other planets are to make the Sun's motion complicated, though the excursions of the Sun's centre are confined to within a radius of about 1.5×10^6 km.

The Sun and the body are not *spherically symmetrical*

Though the Sun and the planetary bodies are close to spherical symmetry, they are not perfectly so. One cause is the rotation of the body. No body is rigid and so the rotation causes the equatorial region to bulge, as in Figure 1.13(a), to give a tangerine shape. The rotational distortion of Saturn is clear in Plate 16. Another cause of departure from spherical symmetry is a gravitational force that varies in magnitude and/or direction across a body. From Newton's law of gravity (equation (1.5)) we can see that the parts of a planet closer to the Sun experience a slightly larger gravitational force than the parts further away, and so the planet stretches. An additional distortion arises from the change in direction to the Sun across the body perpendicular to the solar direction – this results in a 'squeeze'. The outcome (exaggerated) is shown in Figure 1.13(b) – a shape somewhat like a rugby ball, or an American football. The differential force (stretch and squeeze) is called a **tidal force**, and the distortion is called a tide. The Sun produces a tide in the body of the Earth, and a larger tide in the oceans. The Moon also produces tides in the Earth and actually raises greater tides than the Sun does, in spite of the Moon's far lower mass. This

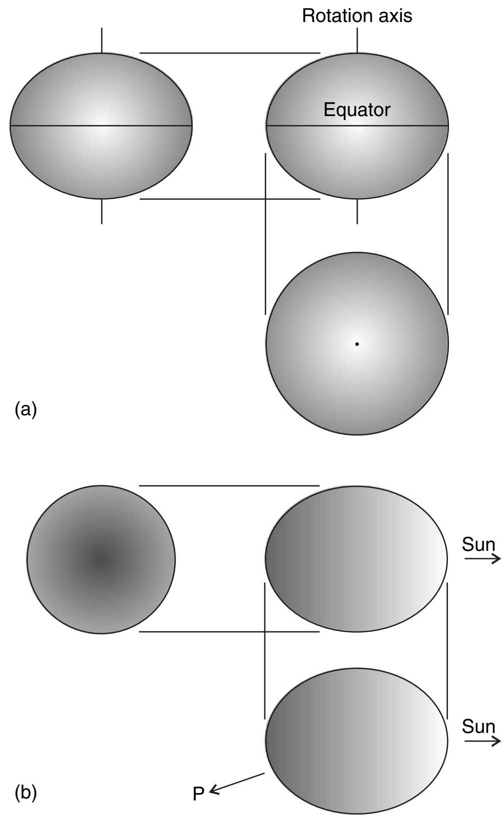

Figure 1.13 Departures from spherical symmetry in a planet due to (a) rotation and (b) the tidal force of the Sun.

is because it is so much closer than the Sun that the differential force it exerts across the Earth is greater than the differential force exerted by the Sun: the gravitational force of the Sun is almost uniform across the Earth, whereas that of the Moon is less so.

The importance of departures from spherical symmetry, however caused, is that they enable one body to exert a **torque** – a twisting – on another body. For example, a planet in Figure 1.13(b) in the direction P is slightly closer to the left end of the distorted planet than to the right end. It therefore exerts a greater overall gravitational force to the left than to the right, and so there is a torque. It can be shown that orbital changes result from such torques.

There are forces on a body additional *to the gravitational force of the Sun*

❐ List some gravitational forces on a planet other than the gravitational force of the Sun.

Most obviously there is the gravitational force exerted by the *other* planets. The planets have much smaller masses than the Sun, and are relatively well separated. Therefore, from Newton's law of gravity (equation (1.5)), it is clear that the combined gravitational force of the other planets is small, giving only slight effects on the planet's orbit. In contrast, a comet can approach a planet fairly closely, in which case the comet's orbit will be greatly modified. Planetary satellites also have an effect – it is the centre of mass of a planet–satellite system that follows an elliptical orbit around the Sun, in accord with Kepler's laws. The planet and each satellite thus follow a slightly wavy path.

As well as other *gravitational* forces there are non-gravitational forces. For example, when a comet approaches the Sun, icy materials are vaporised – it is these that give rise to the head and the tails. But they also exert forces on the comet, rather in the manner of rocket engines, and considerable orbital changes can result.

Because of additional forces and a lack of spherical symmetry the planetary orbits are therefore not quite as described by Kepler's three laws. However, the departures from the laws are usually sufficiently slight that we can regard the orbits as ellipses in which the orbital elements change, usually slowly, and often chaotically, i.e. without pattern, although the semimajor axes, eccentricities, and inclinations are usually confined to narrow ranges of values. The values given in Table 1.1 apply in 2006, but the values, almost to the precision given, will be unchanged for many decades. The values for a,e, and i in particular will not wander far from the values given, for millennia, except perhaps for the least massive planet Pluto.

The word 'usually' has been used several times in the preceding paragraph, which raises the question 'what about the exceptions?' In Section 1.4.6 we consider exceptions arising from the gravitational interaction between two bodies orbiting the Sun.

Question 1.7

Explain briefly why the orbital elements of Venus would be subject to greater variation than at present, if

(a) the Sun rotated more rapidly;
(b) the mass of Jupiter were doubled;
(c) the Sun entered a dense interstellar cloud of gas and dust.

1.4.6 Orbital Resonances

The gravitational interaction between two bodies orbiting the Sun gives rise to what are called orbital resonances. These can greatly affect the stability of an orbit. There are two types of resonance, mean motion resonances and secular resonances. Here we present a minimal account, sufficient to serve later needs.

A **mean motion resonance** (mmr) occurs when the ratio of the orbital periods P_J and P_A of bodies J and A is given by

$$\frac{P_J}{P_A} = \frac{p+q}{p} \tag{1.8}$$

where p and q are integers. Figure 1.14 illustrates the case of Jupiter J and an asteroid A when $P_J/P_A = 2$, i.e. for every one orbit of Jupiter the asteroid completes two orbits. This is called a 2:1 mmr. In Figure 1.14(a) the perihelion of the asteroid occurs when it is in line between the Sun and Jupiter (the eccentricity of Jupiter's orbit is small). Therefore, the asteroid is never very close to Jupiter, and its orbit is likely to be stable. In Figure 1.14(b) the asteroid's aphelion occurs when it is in line between the Sun and Jupiter. It therefore approaches Jupiter more closely and suffers a strong gravitational tug. Crucially, this is repeated in every Jovian orbit,

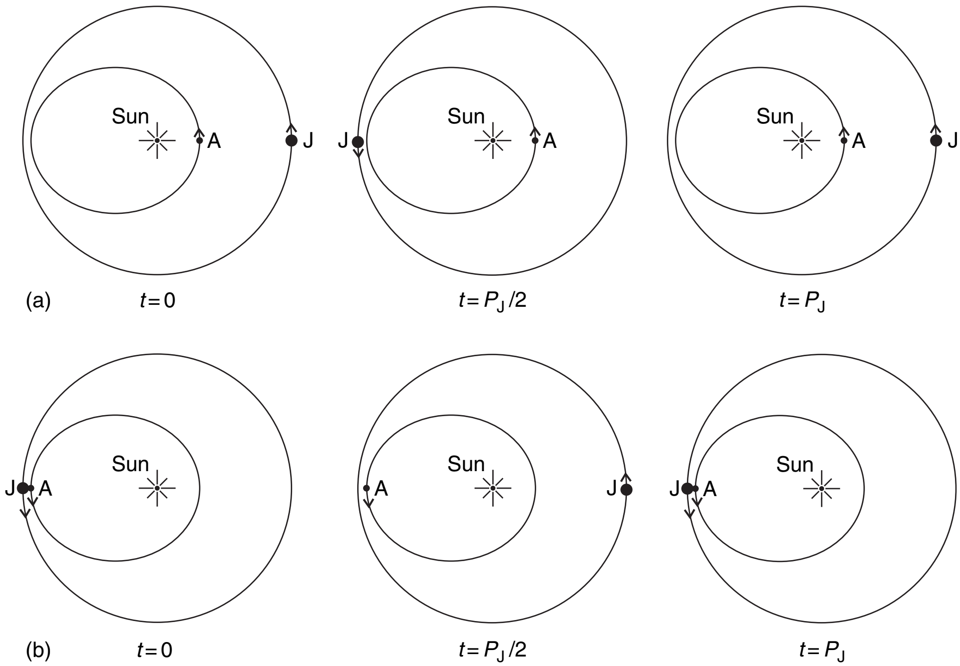

Figure 1.14 A 2:1 mean motion resonance (mmr) between Jupiter and an asteroid. (a) The perihelion of the asteroid occurs when it is in line between the Sun and Jupiter (probably stable). (b) The aphelion of the asteroid occurs when it is in line between the Sun and Jupiter (probably unstable).

so the effect of the tugs builds up, probably leading to ejection of the asteroid from its orbit. Many mmr effects are seen in the Solar System, as you will see in later chapters.

The other type of resonance is the **secular resonance**. ‘Secular’ in this context means a long-term interaction. Thus, rather than looking at the *instantaneous* interaction between two bodies in orbit around a star as in Figure 1.14, we consider the *averaged interaction* over a long period, In effect, it is as if each body has been smeared out along its orbit and the gravitational interaction is between these rings. There is a great variety of secular resonances.

Figure 1.15 illustrates just one type for the case of two bodies orbiting in the same plane. For the sake of clarity the orbit of each body has been replaced by its semimajor axis. Note that the interval between each configuration corresponds to many orbital periods. The gravitational interaction between the two bodies causes the semimajor axis of each of them to move around in the plane of the orbit (shown in grey). This means that the perihelion of each body also moves around – this is called **precession of the perihelion**. This is a general phenomenon when there are more than two bodies orbiting a star. But in this particular case you can see that the angle between the semimajor axes oscillates around zero, and that it never gets large. This confined difference is an example of a secular resonance. In this case it enhances the stability of the orbits. Other secular resonances lead to instability. Later chapters outline examples of secular resonances in the Solar System. Precession of the perihelion does not always correspond to a secular resonance, as you will see in the next section.

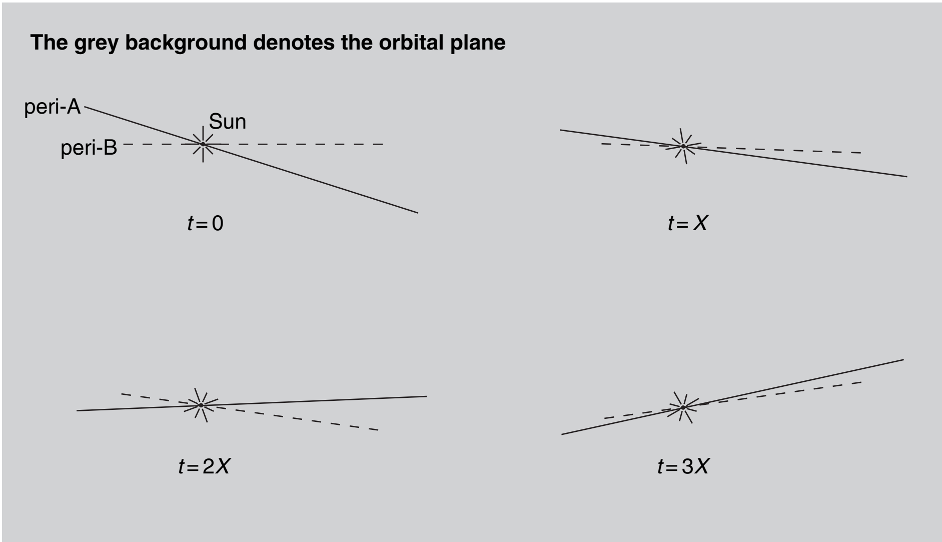

Figure 1.15 A secular resonance in which the angle between the semimajor axes never gets large.

Question 1.8

From the orbital periods of Neptune and Pluto in Table 1.1, deduce whether these two planets are in a resonance, and, if so, whether it is a secular resonance or a mean motion resonance.

1.4.7 The Orbit of Mercury

As for all the planetary orbits, the orbit of Mercury is not *quite* an ellipse fixed in space. An important departure is the precession of the perihelion that you encountered in Section 1.4.6. For Mercury it is illustrated in Figure 1.16. The actual precession (with respect to a coordinate

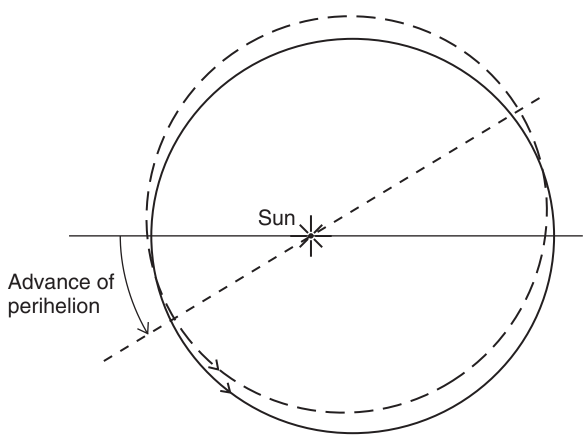

Figure 1.16 Precession of the perihelion of the orbit of Mercury. The two orbits are separated by 2000 years.

system fixed with respect to the distant stars) is through an angle of 574 arc seconds (arcsec) per century (3600 arcsec= 1°). The effect of all the other planets, and of the slight departure of the Sun from spherical symmetry, leaves a discrepancy of 43 arcsec per century. This discrepancy (at rather less precision) was a great puzzle when it was identified in the nineteenth century, and it was not accounted for until 1915 when the German–Swiss physicist Albert Einstein (1879–1955) applied his newly developed theory of **general relativity** to the problem. General relativity is *not* a modification of Newton's laws, but a very different sort of theory. Fortunately, for most purposes in the Solar System, the far simpler theory of Newton suffices. Einstein's theory accounts for the observed rate of precession of the perihelion of Mercury to within the measurement uncertainties.

1.5 Planetary Rotation

Each planet rotates around an axis that passes through its centre of mass. In the case of the Earth this rotation axis is shown in Figure 1.17. It intersects the Earth's surface at the North and South Poles, and the equator is the line half way between the Poles. You can see that the rotation axis is not perpendicular to the Earth's orbital plane (the ecliptic plane) but has an **axial inclination** of 23.4° from the perpendicular.

As the Earth moves around its orbit the rotation axis remains (very nearly) fixed with respect to the distant stars. This is shown (from an oblique viewpoint) in Figure 1.18. The axis is *not* fixed with respect to the Sun, and so the aspect varies around the orbit. At A the North Pole is maximally tilted towards the Sun. This is called the June **solstice**, and it occurs on or near 21 June each year. Six months later, at C, the North Pole is maximally tilted away from the Sun. This is the December solstice, which occurs around the 21st of the month. At B and D we have the only two moments in the year when the Earth's rotation axis is perpendicular to the line from the Earth to the Sun. Over the whole Earth, day and night are of equal length, which gives us the name for these two configurations – the **equinoxes**. The direction from the Earth

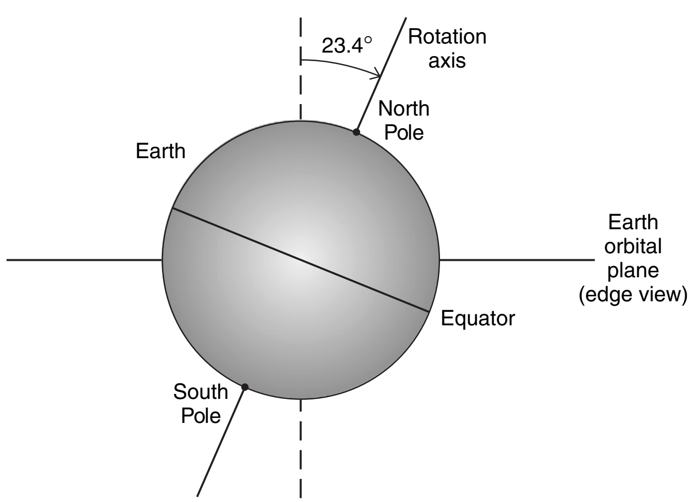

Figure 1.17 The axial inclination of the Earth.

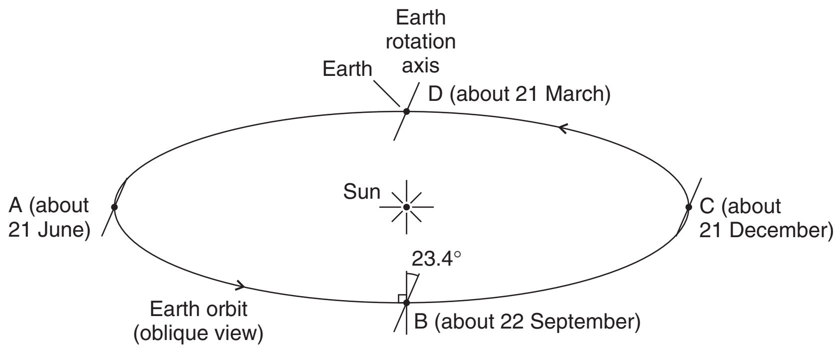

Figure 1.18 The Earth's rotation axis as the Earth orbits the Sun. This is an oblique view of the orbit, which is nearly circular.

to the Sun at the vernal (March) equinox is used as the reference direction ♈ in the ecliptic plane that you met in Section 1.4.2.

We now turn to the *period* of rotation. Figure 1.19 shows the Earth moving around a segment of its orbit. As it does so it also rotates, and the arrow extending from a fixed point on the Earth's surface enables us to monitor this rotation. Between positions 1 and 2 the Earth has rotated just once with respect to a distant star. This is the **sidereal rotation period**. The distant stars, to sufficient accuracy, provide a non-rotating frame of reference (just as for the sidereal orbital period in Section 1.4.1). For the Earth, the sidereal rotation period is actually called the mean rotation period – astronomical terminology can be perverse. However, the Earth has not yet rotated once with respect to the Sun. The Earth has to rotate further to complete this rotation, and in the extra time taken it moves further around its orbit, to position 3. The period of rotation of the Earth with respect to the Sun is called the **solar day**. It is clearly longer than the mean rotation period, though only by a few minutes.

❐ State in what way the motions in Figure 1.19 are *not* shown to scale.

In Figure 1.19 the Earth's motion around its orbit between positions 1, 2, and 3 has been exaggerated for clarity. As there are just over 365 days in a year, the Earth should only proceed about 1° around its orbit in the time it takes the Earth to rotate once.

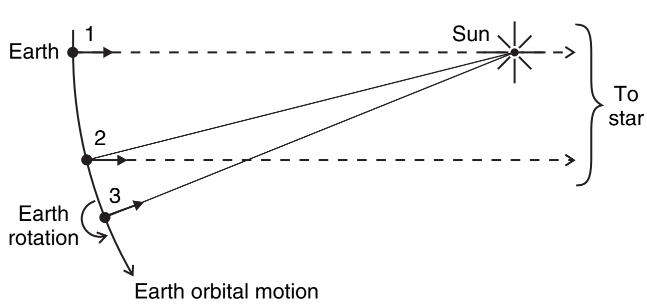

Figure 1.19 The rotation of the Earth with respect to the Sun and with respect to the distant stars (*not* to scale).

The mean rotation period does not vary significantly through the year, but the solar day does. This is a consequence of the eccentricity of the Earth's orbit and the inclination of its rotation axis (we shall not go into details). By contrast, the mean solar day is defined to be fixed in duration, and has the mean length of the solar days averaged over a year. If solar time and mean solar time coincide at some instant, they will coincide again a year later, but in between, differences develop, sometimes solar time being ahead of mean solar time and sometimes behind. The maximum differences are about 15 minutes ahead or behind. The day that we use in our everyday lives, as marked by our clocks, is the mean solar day. Even this varies in length, *very* slightly, and so for scientific purposes a standard day is defined, very nearly the same as the current length of the mean solar day. It is this standard **day** that appears in Tables 1.1–1.4 and elsewhere. It is exactly $24 \times 60 \times 60$ seconds in length, and thus consists of exactly 24 hours of 60 minutes, with each minute consisting of 60 seconds.

The mean rotation period is 23 h 56 min 4 s, i.e. 3 min 56 s shorter than the mean solar day. Over one sidereal year, this difference must add up to one extra rotation of the Earth with respect to the distant stars. You can convince yourself of this by considering a planet that is rotating as in Figure 1.20. In this case there are three rotations per orbit with respect to the Sun and four with respect to the stars. For the Earth, during the sidereal year there are 365.26 mean solar days and 366.26 mean rotation periods.

Table 1.1 gives the axial inclination and sidereal rotation period of each planet and also of the Sun. The inclination of each planet is with respect to the plane of its orbit, whereas in the case of the Sun it is with respect to the ecliptic plane. Note that, with three exceptions, the inclinations are fairly small. This means that the prograde swirl of motion of the orbits, almost in one plane, is shared by planetary and solar rotation. The exceptions are Venus, Uranus, and Pluto. The inclination of Venus is not far short of 180°.

❒ What is the difference between an axial inclination of 180° and 0°?

The difference is that 0° is prograde rotation whereas 180° is retrograde rotation, in each case with the rotation axis perpendicular to the orbital plane. Any inclination greater than 90° is retrograde, and so Pluto and Uranus are also in retrograde rotation, though Uranus's inclination

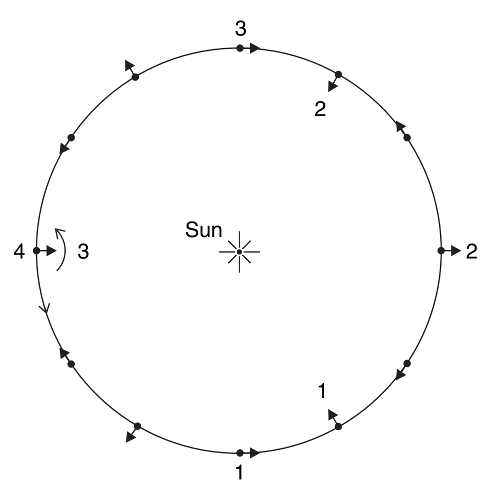

Figure 1.20 A fictitious planet rotating three times per orbit with respect to the Sun.

of 97.8° means that its rotation axis is almost in its orbital plane. We shall return to these oddities when we discuss the origin of the Solar System in Chapter 2.

As in the case of the orbital elements, the axial inclinations and rotation periods of a body are subject to changes, and for the same basic reason – the forces applied by the other bodies in the Solar System. For example, the sidereal rotation period of the Earth is currently increasing, somewhat erratically, by 1.4×10^{-3} seconds per century, largely because of the torque exerted by the Moon on the Earth's tidal distortion. The Earth has had a similar effect on the Moon, and has slowed down the Moon so that it is now locked into a rotation period that keeps it facing the Earth. When one body rotates so that it keeps one face to the body it orbits, it is said to be in **synchronous rotation**.

Seasons

Figure 1.21 is an edge view of the Earth's orbit with the positions A and C in Figure 1.18 marked, and the size of the Earth *greatly* exaggerated. When the North Pole of the Earth is maximally tilted towards the Sun, as at A, there is summer in the northern hemisphere because the surface there is receiving its greatest solar radiation. This is not only because the Sun reaches high in the sky, but also because of the long duration of daylight. By contrast, the southern hemisphere is maximally tilted *away* from the Sun.

❒ What season is this hemisphere experiencing?

It is winter in this hemisphere, because solar radiation is thinly spread over the surface and daylight is short. Six months later, at C, the December solstice, the seasons are reversed. It is thus the axial inclination that is responsible for seasonal changes. The eccentricity of the Earth's orbit has only a secondary effect. The Earth is at perihelion in early January, with the northern hemisphere in the depths of winter, and so, as a result of the orbital eccentricity, the seasonal contrasts are reduced in the northern hemisphere, and increased in the southern hemisphere.

Question 1.9

Discuss whether you would expect seasonal changes on Venus.

1.5.1 Precession of the Rotation Axis

So far, the direction of the Earth's rotation axis has been regarded as fixed with respect to the distant stars. This is not quite the case. In fact, it cones around in the manner of Figure 1.22, a

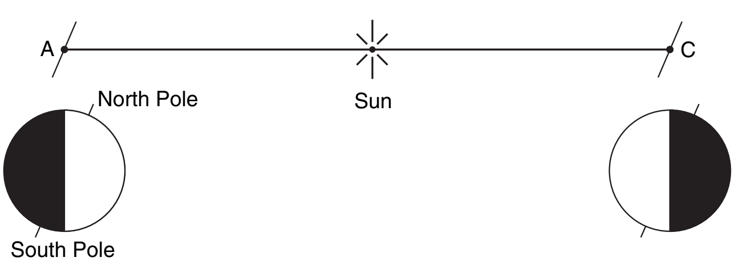

Figure 1.21 Seasonal changes in the solar radiation at the Earth's surface.

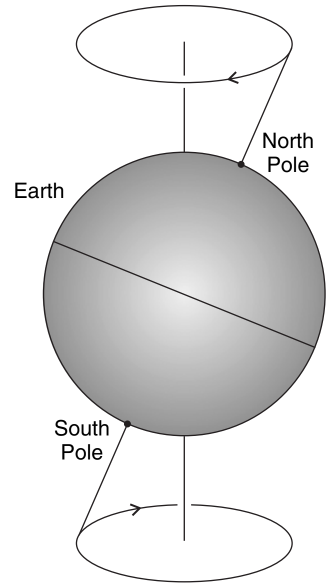

Figure 1.22 Precession of the Earth's rotation axis.

motion called the **precession of the rotation axis**. It is a result of the torques exerted by other bodies in the Solar System on the slightly non-spherical form of the Earth. The Moon and the Sun account for almost the whole effect. All planets are slightly non-spherical, so all of them are subject to precession. For the Earth, one complete coning takes 25 800 years, an interval called the precession period of the Earth.

One consequence of precession is that the positions of the equinoxes and solstices move around the orbit, giving rise to the term **precession of the equinoxes**. In the case of the Earth this motion is in a retrograde direction (taking 25 800 years to move around once). Figure 1.23 compares the present configuration (dashed lines) with the configuration 12 900 years from now (solid lines) – each equinox and solstice has moved half way around the orbit. Recall that the reference direction in the ecliptic plane is the line from the Earth to the Sun when the Earth is at the vernal equinox. Therefore, with respect to the distant stars, this reference direction has moved through 180° in Figure 1.23. At present, when the Earth is at the vernal equinox, the direction is to a point in the constellation Pisces, but about 2000 years ago, when precession became widely recognised, it was in the constellation Aries, when its location was called the first point of Aries. The name sticks, even though the point long ago moved into the constellation Pisces, and is now not far from the boundary with the constellation Aquarius.

The slow retrograde motion of the vernal equinox around the Earth's orbit means that the time taken for the Earth to traverse its orbit from one vernal equinox to the next is very slightly less than the sidereal year. The time interval between vernal equinoxes is called the tropical year, and it is the year on which our calendars are based. Its duration is 365.242 190 days, whereas the sidereal year is 365.256 363 days. From now on, the term **year** will mean the tropical year. It is this year that is the unit of time measurement in Tables 1.1, 1.3, and 1.4, and elsewhere. It is denoted by the symbol ‘a’, from the Latin word for year, *annus*.

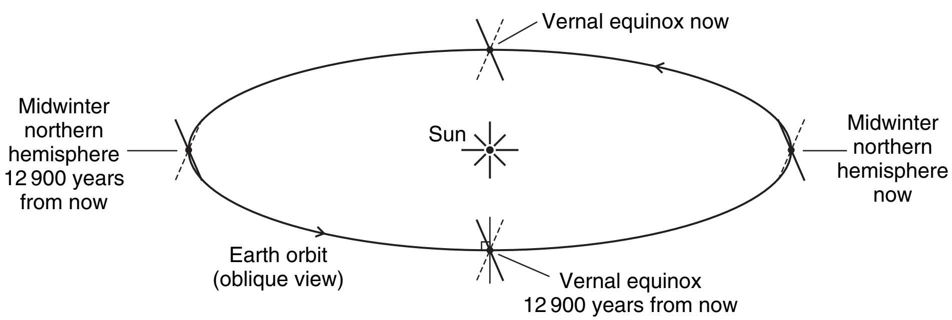

Figure 1.23 The effect of the precession of the Earth's rotation axis on the position of the equinoxes and solstices. The dashed line is the Earth's rotation axis now, and the solid line the axis 12 900 years from now.

Question 1.10

What would be the problem with basing our calendar on the *sidereal* year?

1.6 The View from the Earth

1.6.1 The Other Planets

The way that the planets appear in our skies depends on whether the orbit of the planet is larger or smaller than the orbit of the Earth. Figure 1.24 shows Venus representing the two planets (Venus and Mercury) with smaller orbits, and Mars representing those with larger orbits. The planets are shown at three instances. In position 1 all three planets are lined up with the Sun, a very rare occurrence but a useful one for describing the view from the Earth. The planets move at different rates around their orbits, so this alignment lasts only for an instant.

In position 1, Venus is between the Earth and the Sun. It is then at what is called inferior conjunction. The alignment is rarely exact, because of the inclination of the orbit of Venus. Exact or not, our view of Venus is drowned by the overwhelming light of the Sun. The greater angular speed of Venus in its orbit then causes it to draw ahead of the Earth and we start to see part of the hemisphere illuminated by the Sun as an ever-thickening crescent. At position 2, Venus has reached its greatest angle from the Sun and is at what is called its maximum western elongation. It is now relatively easy to see (before sunrise) and half of its illuminated hemisphere is visible. As it moves on we see even more of its sunlit hemisphere, but it is getting further away from the Earth, and closer in direction to the Sun, until at superior conjunction Venus is pretty well in the direction of the Sun again, but now on the far side of the Sun. Subsequently, it moves towards maximum eastern elongation, then again to inferior conjunction, and the whole cycle is repeated.

For planets beyond the Earth, such as Mars in Figure 1.24, the sequence of events is different. The line-up with Mars and Earth on the same side of the Sun does not result in an inferior conjunction, but in what is called an **opposition**, Mars being in the opposite direction in the sky from the Sun, as viewed from the Earth. Mars is then well seen, with the illuminated hemisphere facing us, and the separation between the planets being comparatively small – though this distance is different from opposition to opposition.

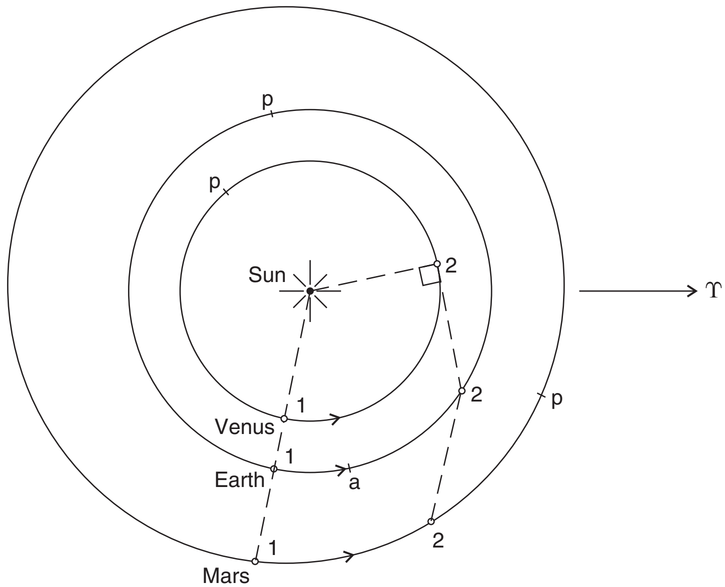

Figure 1.24 The motion of Venus and Mars with respect to the Earth. Perihelia are denoted by ‘p’, and Earth’s aphelion by ‘a’.

❒ When will the opposition distance between Mars and the Earth be a minimum?
It will be a minimum when opposition occurs with the Earth near aphelion, and Mars near perihelion. After opposition the greater angular orbital speed of the Earth causes it to overtake Mars ‘on the inside track’ as the configuration moves towards superior conjunction, with Mars on the far side of the Sun as seen from Earth.

The time interval between similar configurations of the Earth and another planet is called the **synodic period** of the planet. Opposition and inferior conjunction are important types of configuration. For any type of configuration the synodic period varies slightly, mainly because of the variations in the rate at which the Earth and the planet move around their respective orbits, as described by Kepler’s second law. It is thus the *mean* value of the synodic period that is normally quoted, as in Table 1.1. For a particular planet the mean synodic period is the same for all types of configuration. These mean periods are not simple multiples or simple fractions of the sidereal year, and so successive configurations have the Earth at different points in its orbit.

Question 1.11

Discuss why the opposition distance to Mars is least when oppositions occur in mid August.

1.6.2 Solar and Lunar Eclipses

Figure 1.25 shows an oblique view of the nearly circular orbit of the Moon around the Earth, and part of the orbit of the Earth around the Sun (strictly, the orbit of the centre of mass of the Earth–Moon system around the Sun). The size and inclination of the lunar orbit, and the sizes of the Sun, Earth, and Moon, have all been exaggerated. When the Moon is at A (Figure 1.25(a)) its

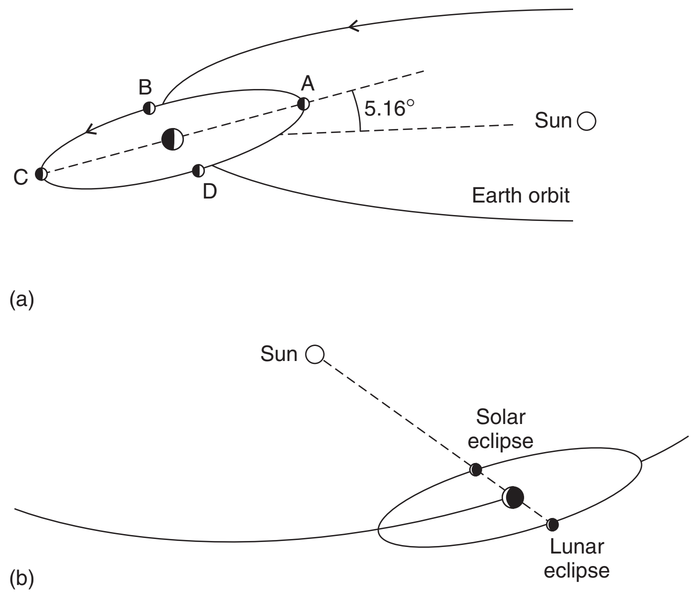

Figure 1.25 The Moon's motion around the Earth, as the Earth orbits the Sun (*not* to scale).

unilluminated hemisphere faces the Earth, and we have a new Moon. A quarter of an orbit later, at B, half of its illuminated hemisphere is facing us, and we see a half Moon, also called first quarter. At C the fully lit hemisphere faces the Earth, and the Moon is full. At D, three-quarters of the way around its orbit from A, we see another half Moon, the third quarter. We then get another new Moon at A, on average 29.53 days after the previous new Moon.

The plane of the Moon's orbit is inclined by 5.16° to the ecliptic plane, which it crosses at the two nodes labelled B and D in Figure 1.25(a). This orbital inclination means that for this configuration, the Moon, as seen from the Earth, cannot pass in front of the Sun, nor can the Moon be touched by the Earth's shadow. However, as the Earth moves around the Sun, the Moon's orbit stays (almost) fixed with respect to the distant stars, so that about a quarter of an Earth orbit later (3 months) the nodes lie on or near the line that joins the Earth and the Sun, as in Figure 1.25(b). If, at this time, the Moon is sufficiently near the node between the Earth and the Sun, then, as seen from the Earth, part or all of the Moon will pass in front of the Sun, and we get a **solar eclipse**. If the Moon is at or near the other node then the Earth's shadow will fall on part or all of the Moon, and we get a **lunar eclipse**. The nodes line up twice a year, and usually the Moon is sufficiently near a node for there to be an eclipse of some sort.

There are different types of solar eclipses. Figure 1.26(a) shows umbral and penumbral shadows of the Moon on the Earth. If we are at a point on the Earth's surface within the umbral shadow then the photosphere of the Sun is completely obscured and we see a **total solar eclipse**. With the photosphere obscured, we see the pearly white solar corona (Plate 2), the chromosphere, and prominences (Plate 3). It is worth making a considerable effort to see a total solar eclipse, which is a most magnificent spectacle. If we are in the penumbral shadow the Sun is only partly obscured and we see a partial solar eclipse. If the Moon is too far from the node, then the umbral shadow misses the Earth completely, and nowhere on Earth can we see a total solar eclipse.

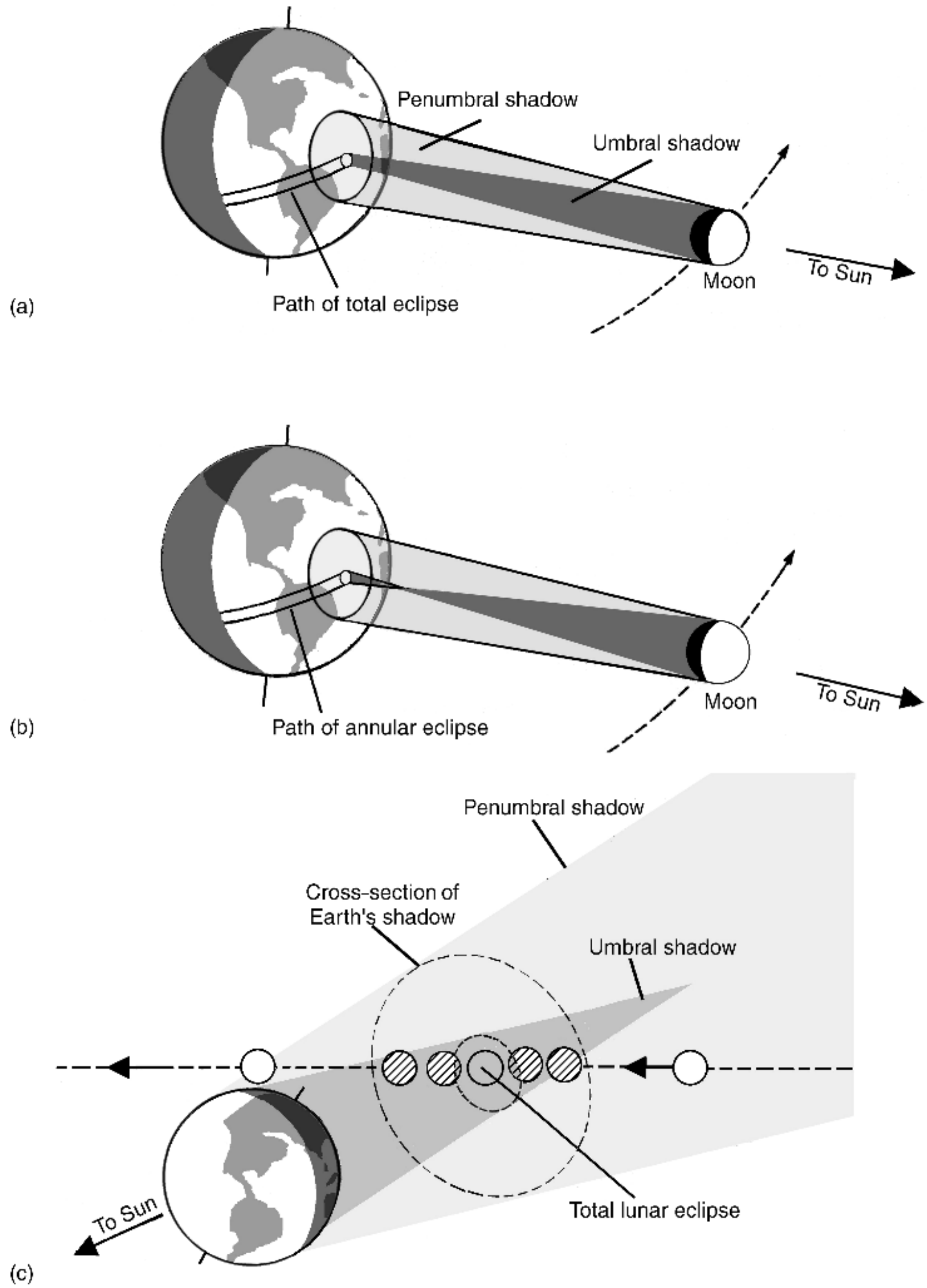

Figure 1.26 Different sorts of eclipses (*not* to scale). (a) Total and partial solar eclipses. (b) An annular solar eclipse. (c) A lunar eclipse. (From *Foundations of Astronomy* 3rd Edition, by Seeds, 1994. Reprinted with permission of Brooks/Cole, a division of Thomson Learning: www.thomsonrights.com, Fax 800 730–2215)

Even with the Moon at the node, not all solar eclipses are total. The Sun is about 400 times the diameter of the Moon, but it is also about 400 times further away, so the angular diameters of the two bodies are nearly the same, about 0.5°. Because of the eccentricity of the orbits of the Earth and the Moon, this coincidence means that sometimes an eclipse occurs with the Moon's angular diameter a bit smaller than that of the Sun, as in Figure 1.26(b). The umbral shadow does not reach the Earth, and from the Earth's surface, at the centre of the penumbral shadow, a thin ring of the photosphere is still exposed. This is called an annular solar eclipse. Largely because of tidal interactions with the Moon, the distance between the Moon and the Earth is currently increasing at a rate of about 25 mm per year, and so, from about 1000 Ma in the future, the Moon will never be close enough to the Earth to produce a total solar eclipse, and all solar eclipses will then be partial or annular.

Figure 1.27 shows the umbral shadow paths for the years 2001–2025. Within these narrow paths a total solar eclipse occurs. The paths are determined by the line-up of the Earth, Moon, and Sun, and by the combined effect of the orbital motion of the Moon and the rotation of the Earth, which together sweep the umbral shadow across the Earth. The duration of totality is longest at the centre of the path, and varies from eclipse to eclipse. The longest durations, approaching 7.5 minutes, occur when the Earth is at aphelion, and the Moon is closest to the Earth, at what is called perigee.

Figure 1.26(c) shows a total lunar eclipse, which occurs when the Moon is entirely within the umbral shadow of the Earth. Where the umbral shadow falls on the Moon, the lunar surface

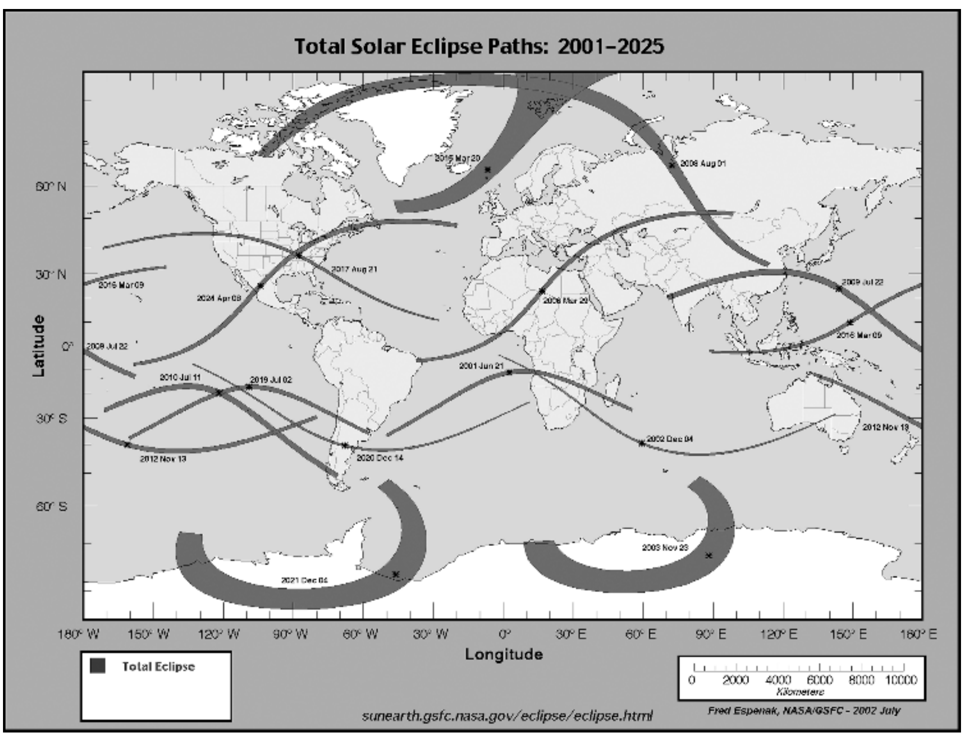

Figure 1.27 Total solar eclipse paths (umbral shadow paths) 2001–2025. (Eclipse map and calculations courtesy Fred Espenak, NASA-GSFC)

is not completely dark. Sunlight is refracted by the Earth's atmosphere, red light more than the other visible wavelengths, which can give the Moon a coppery tint. At any moment the eclipsed Moon can be seen from half the Earth's surface. The view *from* the Moon would be of the black, night side of the Earth, surrounded by a thin red ring of sunlight refracted by the Earth's atmosphere.

Question 1.12

The nodes of the lunar orbit are not quite fixed but move around the lunar orbit in the retrograde direction in 18.6 years. How does this explain why eclipses are not confined to particular months?

1.7 Summary of Chapter 1

The Solar System consists of the Sun, nine planets with their satellites and rings, many asteroids (about 10^9 greater than 1 km across), the Edgeworth–Kuiper belt (more than 10^5 objects larger than 100 km), 10^{12}–10^{13} small icy-rocky bodies in the Oort cloud, and an interplanetary medium of tenuous gas and small solid bodies ranging in size down to less than 10^{-6} m.

Meteoroids are small rocky bodies, and those that fall to Earth are called meteorites, These have provided much information about the origin, evolution, and composition of the Solar System and the ages of events within it.

The planets orbit the Sun in one direction – the prograde direction – in approximately circular, coplanar orbits with the Sun near the centre. The orbital planes of the asteroids have a wider range of inclinations and eccentricities. The rotation of the Sun is prograde, as is that of most of the planets. If the inclination of the rotation axis to the orbital plane is more than a few degrees then the surface of the planet will experience seasonal changes. Rotation axes are subject to precession.

Some comet orbits reach to within a few AU of the Sun, but the great majority spend most or all of their time at far greater distances, where they are dormant icy–rocky bodies. There are two reservoirs. The Edgeworth–Kuiper belt lies immediately beyond the planetary domain, and contains bodies (EKOs) in orbits that are predominantly prograde and that are concentrated towards the ecliptic plane. The Oort cloud is more far flung and consists of bodies in a spherical distribution around the Sun, reaching out to the edge of interstellar space, about 10^5 AU from the Sun.

The Sun is by far the largest, the most massive, and the most luminous body in the Solar System. It is fluid throughout, and consists largely of hydrogen and helium. Its luminosity is sustained by the nuclear fusion of hydrogen deep in its interior where temperatures reach 1.4×10^7 K.

The four planets closest to the Sun – Mercury, Venus, the Earth, and Mars – are the terrestrial planets. They are comparable with the Earth in size, and consist of iron-rich cores overlain by rocky materials. The Earth is the largest of these bodies. The asteroids are rocky bodies concentrated between Mars and Jupiter.

The giant planets – Jupiter, Saturn, Uranus, and Neptune – are considerably larger and more massive than the terrestrial planets, Jupiter by some margin being the most massive planet of all. The giants consist largely of hydrogen, helium, and icy–rocky materials, and (like the Sun) are fluid throughout. The giants have richly varied families of satellites, and all giants have rings, those of Saturn being by far the most substantial. Beyond Neptune we come to the outermost planet, Pluto, smaller in size than the terrestrial planets, and more icy in its composition. The comets are also icy–rocky bodies. Beyond Pluto there is at least one body somewhat larger than Pluto – Eris. Pluto and Eris are regarded as large members of the Edgeworth–Kuiper belt.

The orbits of the planets are described to a very good approximation by Kepler's laws of planetary motion.

First law Each planet moves around the Sun in an ellipse, with the Sun at one focus of the ellipse.

Second law As the planet moves around its orbit, the straight line from the Sun to the planet sweeps out equal areas in equal intervals of time.

Third law If P is the sidereal period of a planet, and a is the semimajor axis of the orbit, then

$$P = ka^{3/2} \tag{1.3}$$

where $k = 1$ year $\mathrm{AU}^{-3/2}$.

Elliptical orbits are characterised by five orbital elements: the semimajor axis a, the eccentricity e, the inclination i, the longitude of the ascending node Ω, and the longitude of perihelion $(\Omega + \omega)$. To calculate the position of a body in its orbit we need a sixth element – a single position at any known time.

Newton's laws of motion and law of gravity account for Kepler's laws, and go further by accounting for the motion of comets and of other bodies, and for slight departures from Kepler's laws that have various causes. Major effects on orbits are caused by mean motion resonances and secular resonances.

The precession of the perihelion of Mercury shows that at the highest level of precision Einstein's theory of general relativity is superior to Newton's laws.

Our view from the Earth of the apparent motion of a planet depends on whether it is in a smaller or larger orbit than our own. Solar and lunar eclipses result when the Moon, Sun, and Earth line up. Figure 1.27 shows the umbral tracks of forthcoming total solar eclipses.

Tables 1.1–1.6 list basic data on the Solar System.

Table 1.1 Orbital elements in 2006 and some physical properties of the Sun, the planets, and Ceres

Object	Mean orbital elements[a,b]							From the Earth		Physical properties				
	Semimajor axis/ AU	Semimajor axis/ 10^6 km	Sidereal period/ years	Eccentricity	Inclination/ °	Long. of ascending node/ °	Long. of perihelion/ °	Mean syn. period/ days	Date, oppn, or inf. conj.	Axial inclin-ation/ °[c]	Sid. rotn period/ days[d]	Equat. radius/ km[e]	Mass/ kg	Mean density/ kgm^{-3}
Sun	—	—	—	—	—	—	—	—	—	7.2	25.4	696 000	1.9891×10^{30}	1410
Mercury	0.387	57.9	0.2409	0.206	7.00	48.3	77.5	116	08 Nov 06	0.0	58.646	2 440	3.302×10^{23}	5430
Venus	0.723	108.2	0.6152	0.0068	3.39	76.7	131.2	584	20 Aug 07	177.4	243.019	6 052	4.869×10^{24}	5240
Earth	1.000	149.6	1.0000	0.017	0	—	103.0	—	—	23.4	0.9973	6 378	5.974×10^{24}	5520
Mars	1.524	227.9	1.8808	0.093	1.85	49.5	336.1	780	24 Dec 07	25.2	1.0260	3 396	6.419×10^{23}	3940
Ceres	2.766	413.8	4.5993	0.080	10.59	80.4	153.6	466	12 Sept 06	54	0.378	479	9.4×10^{20}	2100
Jupiter	5.202	778.2	11.859	0.049	1.31	100.5	14.7	399	4 May 06	3.1	0.4135	71 490	1.8988×10^{27}	1330
Saturn	9.552	1430.0	29.521	0.055	2.49	113.6	93.8	378	27 Jan 06	26.7	0.4440	60 270	5.684×10^{26}	690
Uranus	19.173	2868.3	83.957	0.048	0.77	74.0	172.4	370	5 Sept 06	97.8	0.7183	25 560	8.684×10^{25}	1270
Neptune	30.091	4501.6	165.07	0.0069	1.77	131.8	48.0	367	11 Aug 06	28.3	0.6712	24 765	1.0245×10^{26}	1640
Pluto	39.777	5950.6	250.88	0.254	17.1	110.3	224.5	367	16 June 06	123	6.3872	1153	1.30×10^{22}	2030

[a] For all bodies except Ceres, the orbital data are for August 2006. For Ceres, the data are for September 2006.

[b] Another orbital element is the time of any perihelion passage. For the Earth in 2006 this was at 15:00 UT on 4 January.

[c] The Sun's axial inclination is with respect to the ecliptic plane.

[d] The rotation period of the Sun is at the equator: it increases with latitude, reaching about 36 days near the poles of the Sun. For Jupiter and Saturn it is for the deep interior.

[e] For the giant planets the equatorial radius is to the atmospheric altitude where the pressure is 10^5 Pa (1 bar).

Table 1.2 Some properties of planetary satellites[a,b]

Object[c]	Some mean orbital elements				Size, mass, mean density		
	Semimajor axis/ 10^3 km	Sidereal period/days	Eccentricity	Inclination/ °[d]	Radius/km[e]	Mass/10^{18} kg	Mean density/kg m^{-3}
Earth							
Moon	384.4	27.322	0.0554	5.16	1738	73 490	3 340
Mars							
Phobos	9.38	0.319	0.0151	1.1	11	0.0107	1870
Deimos	23.46	1.262	0.0002	1.8 var	6	0.0022	2300
Jupiter							
Metis	128.0	0.295	0.0012	0.02	22	?	?
Adrastea	129.0	0.298	0.0018	0.39	8	?	?
Amalthea	181.4	0.498	0.0031	0.39	84	2.08	860
Thebe	221.9	0.675	0.0177	1.07	50	?	?
Io	421.8	1.769	0.0041	0.04	1822	89 330	3530
Europa	671.1	3.551	0.0094	0.47	1561	48 000	3010
Ganymede	1 070	7.155	0.0011	0.17	2631	148 200	1940
Callisto	1 883	16.689	0.0074	0.19	2410	107 600	1830
Leda	11 165	241	0.16	27	~ 10	?	?
Himalia	11 461	251	0.16	27	93	?	?
Lysithea	11 717	259	0.11	28	~ 18	?	?
Elara	11 741	260	0.22	26	43	?	?
Ananke	21 276	630	0.24	149	~ 15	?	?
Carme	23 404	734	0.25	165	~ 23	?	?
Pasiphae	23 624	744	0.41	151	~ 30	?	?
Sinope	23 939	759	0.25	158	~ 19	?	?
Saturn							
Pan	133.6	0.575	0.0002	0.007	13	?	?
Atlas	137.7	0.602	0.0012	0.01	10	?	?
Prometheus	139.4	0.613	0.002	0.006	50	?	?
Pandora	141.7	0.629	0.004	0.052	43	?	?
Epimetheus	151.4	0.694	0.010	0.35	60	0.5	610
Janus	151.5	0.695	0.007	0.17	90	1.9	660
Mimas	185.6	0.942	0.0206	1.57	199	38	1160
Enceladus	238.1	1.370	0.0001	0.01	253	84	1120
Tethys	294.7	1.888	0.0001	0.168	530	627	960
Telesto	294.7	1.888	~ 0	1.16	13	?	?
Calypso	294.7	1.888	~ 0	1.47	10	?	?
Dione	377.4	2.737	0.0002	0.002	560	1097	1480
Helene	377.4	2.737	~ 0	0.21	15	?	?
Rhea	527.1	4.518	0.0009	0.327	765	2 308	1230
Titan	1 221.9	15.945	0.0288	1.634	2575	134 570	1880
Hyperion	1 464.1	21.276	0.0175	0.57	142	?	?
Iapetus	3 560.8	79.331	0.028	14.7	718	1 590	1090
Kiviuq	11 365	449	0.33	46	7	?	?
Ijiraq	11 442	451	0.32	47	5	?	?
Phoebe	12 944	548	0.1644	175	~ 110	?	?
Paaliaq	15 198	687	0.36	45	10	?	?
Albiorix	16 394	783	0.48	34	13	?	?
Siarnaq	18 195	896	0.30	46	16	?	?
Tarvos	18 239	926	0.54	33	7	?	?

(continued)

Table 1.2 (Continued)

Object[c]	Some mean orbital elements				Size, mass, mean density		
	Semimajor axis/ 10^3 km	Sidereal period/days	Eccentricity	Inclination/ °[d]	Radius/km[e]	Mass/10^{18} kg	Mean density/kg m^{-3}
Uranus							
Cordelia	49.8	0.335	~0	0.08	13	?	?
Ophelia	53.8	0.376	0.01	0.10	15	?	?
Bianca	59.2	0.435	0.001	0.19	23	?	?
Cressida	61.8	0.464	~0	0.01	33	?	?
Desdemona	62.7	0.474	~0	0.11	30	?	?
Juliet	64.4	0.493	0.001	0.06	43	?	?
Portia	66.1	0.513	~0	0.06	55	?	?
Rosalind	69.9	0.558	~0	0.28	30	?	?
2003 U2	74.8	0.618	~0	~0	6	?	?
Belinda	75.3	0.624	~0	0.03	34	?	?
1986 U10	76.4	0.638	~0	~0	~20		
Puck	86.0	0.762	~0	0.32	78	?	?
Mab	97.7	0.923	~0	~0	8	?	?
Miranda	129.9	1.413	0.0013	4.34	236	66	1200
Ariel	190.9	2.520	0.0012	0.04	579	1 350	1700
Umbriel	266.0	4.146	0.0035	0.0	585	1 170	1400
Titania	436.3	8.704	0.0024	0.0	789	3 520	1700
Oberon	583.4	13.463	0.0007	0.0	762	3 010	1600
Caliban	7 231	580	0.16	141	30	?	?
Sycorax	12 179	1288	0.32	159	60	?	?
Neptune							
Naiad	48.2	0.294	~0	4.74	30	?	?
Thalassa	50.1	0.311	~0	0.21	40	?	?
Despina	52.5	0.335	~0	0.07	75	?	?
Galatea	62.0	0.429	~0	0.05	80	?	?
Larissa	73.5	0.555	0.001	0.20	95	?	?
Proteus	117.6	1.122	~0	0.039	210	?	?
Triton	354.8	5.877	~0	157	1353	21 400	2060
Nereid	5 513	360	0.75	7.23	170	?	?
2002 N1	15 686	1875	0.57	134	25	?	?
Pluto							
Charon	19.57	6.387	0.000	96.15	603	1 518	1660
Nix	48.68	24.856	~0.002	96.18	tiny	?	?
Hydra	64.78	38.207	0.0052	96.36	tiny	?	?

[a] These data are as published in 2006.

[b] The inclinations of the rotation axes of the satellites and the rotation periods are not given, but in most cases the inclinations are small. Many of the satellites, like the Moon, are in synchronous rotation around their planet.

[c] Very small satellites of the giant planets are not included. The excluded satellites are: Jupiter and Saturn, all are < 5 km mean radius; Uranus, all those beyond Oberon smaller than Caliban; Neptune, all those beyond Nereid smaller than 2002 N1.

[d] Note that in most cases the orbital inclination is with respect to the *equatorial* plane of the planet. The exceptions are the Moon and the outer satellites of the giant planets: Jupiter, beyond Callisto; Saturn, beyond Iapetus; Uranus, beyond Oberon; Neptune, beyond Triton. In these cases the inclination is with respect to the *orbital* plane of the planet. This is because the inclination with respect to the equatorial plane changes periodically through a fairly large range of values. Inclinations greater than 90° indicate retrograde orbital motion, i.e. opposite to the direction of rotation of the planet.

[e] Values less than a few hundred km are average radii of irregularly shaped bodies. For many of these satellites the size is based on an assumed albedo of 0.04.

Table 1.3 Some properties of the largest 15 asteroids

Object/number and name	Some orbital elements[a]					Rotation and size	
	Semimajor axis/ AU	10^6 km	Sidereal period/years	Eccentricity	Inclination/ °	Sid. rotn period/h	Radius/km[b]
1 Ceres	2.766	413.8	4.599	0.080	10.59	9.07	479
2 Pallas	2.772	414.7	4.615	0.231	34.84	7.81	262
4 Vesta	2.361	353.2	3.629	0.089	7.13	5.34	256
10 Hygiea	3.137	469.3	5.555	0.118	3.84	27.62	222
704 Interamnia	3.061	457.9	5.357	0.150	17.29	8.69	165
511 Davida	3.166	473.6	5.633	0.186	15.94	5.13	163
15 Eunomia	2.643	395.4	4.298	0.187	11.74	6.08	160
52 Europa	3.102	464.1	5.464	0.103	7.47	5.63	151
3 Juno	2.668	399.1	4.357	0.258	12.97	7.21	137
87 Sylvia	3.489	522.0	6.519	0.080	10.86	5.18	131
31 Euphrosyne	3.150	471.2	5.591	0.226	26.32	5.53	128
16 Psyche	2.920	436.8	4.989	0.139	3.10	4.20	120
88 Thisbe	2.768	414.1	4.605	0.165	5.22	6.04	116
65 Cybele	3.433	513.6	6.362	0.105	3.55	6.1	115
324 Bamberga	2.682	401.2	4.394	0.338	11.11	29.41	114

[a] In September 2006.
[b] The asteroids are in order of decreasing size. Values less than a few hundred km are average radii of irregularly shaped bodies.

Table 1.4 Some properties of selected comets

Name	Some orbital properties						Associated meteor shower(s)	
	Semimajor axis/ AU	Sidereal period/ years	Eccentricity	Inclination/ °	Perihelion distance/ AU	Date, last perihelion passage		
Short period								
21P/Giacobini–Zinner	3.53	6.62	0.7057	31.81	1.0337	July 2005	Giacobinids	Oct
3D/Biela[a]	3.53	6.62	0.756	12.55	0.861	1852 (lost)	Andromedids	Nov
1P/Halley	17.94	75.98	0.9673	162.24	0.5871	Feb 1986	Eta Aquarids	May
109P/Swift–Tuttle	26.32	135.01	0.9636	113.43	0.9582	Dec 1992	Perseids	July–Aug
2P/Encke	2.22	3.30	0.8473	11.77	0.3385	Dec 2003	Taurids	Oct–Nov
36P/Whipple	4.17	8.51	0.2590	9.93	3.0882	July 2003	—	
29P/Schwassmann–Wachmann 1	5.99	14.65	0.0442	9.39	5.7236	July 2004	—	
39P/Oterma	7.24	19.49	0.2446	1.94	5.4707	Dec 2002	—	
23P/Brorsen–Metcalfe	17.07	70.53	0.9720	19.33	0.4789	Sept 1989	—	
Long period (bright)								
C/1843 D1 Great Comet of 1843	640	16 000	0.99 99 914	114.35	0.005 527	1843	—	
C/1858 L1 Donati	~ 150	~ 1700	0.99 6	116.96	0.578	1858	—	
C/1956 R1 Arend–Roland	Large	Long	1.00 0	119.95	0.316	1957	—	
C/1957 P1 Mrkos	Large	Long	0.99 9	93.94	0.355	1957	—	
C/1962 C1 Seki–Lines	Large	Long	1.00 0	65.01	0.031 397	~ 1962/3	—	
C/1965 S1 Ikeya–Seki[b]	92	880	0.999 915	141.86	0.007 786	1965	—	
C/1969 Y1 Bennett	141.9	1690	0.996 210 6	90.04	0.537 606 3	1971	—	
C/1973 E1 Kohoutek	—	—	1.000 007 9	14.30	0.142	1973	—	
C/1975 V1 West[c]	—	—	> 1.000	43.07	0.197	1976	—	
C1996 B2 Hyakutake[d]	923.8	2808	0.999 750 8	124.92	0.230 220 7	1996	—	
C/1995 O1 Hale–Bopp[d]	185.3	2521	0.995 065 4	89.43	0.914 141 0	1997	—	

[a] Split into two in 1846, and not seen since 1852.
[b] Split into three. Orbital elements are for one of the two larger fragments. The other two fragments had similar elements.
[c] Split into four.
[d] The orbital elements apply after the last perihelion passage.

Table 1.5 Relative abundances of the 15 most abundant chemical elements in the Solar System

Chemical element			Relative atomic mass ($^{12}C \equiv 12$)	Relative abundance[a]	
Atomic number	Name	Symbol		By number of atoms	By mass
1	Hydrogen	H	1.0080	1 000 000	1 000 000
2	Helium[b]	He	4.0026	97 700	388 000
6	Carbon	C	12.0111	331	3 950
7	Nitrogen	N	14.0067	83.2	1 160
8	Oxygen	O	15.9994	676	10 730
10	Neon	Ne	20.179	120	2 410
11	Sodium	Na	22.9898	2.09	48
12	Magnesium	Mg	24.305	38.0	917
13	Aluminium	Al	26.9815	3.09	83
14	Silicon	Si	28.086	36.3	1 010
16	Sulphur	S	32.06	15.9	504
18	Argon	Ar	39.948	2.51	100
20	Calcium	Ca	40.08	2.24	89
26	Iron	Fe	55.847	31.6	1 750
28	Nickel	Ni	58.71	1.78	104

[a] Abundances are given to 3–4 significant figures. Many are known to better than this.
[b] The helium values correspond to those before the conversion of some of the hydrogen in the Sun's core to helium, i.e. to the Sun at its formation.

Table 1.6 Some important constants

Name	Symbol	Value
Speed of light (in a vacuum)[a]	c	$2.997\,924\,58 \times 10^{8}$ m s^{-1}
Gravitational constant[b]	G	6.672×10^{-11} N m^2 kg^{-2}
Boltzmann's constant	k	$1.380\,65 \times 10^{-23}$ JK^{-1}
Planck's constant	h	$6.626\,07 \times 10^{-34}$ Js
Stefan's constant	σ	5.6704×10^{-8} Wm^{-2} K^{-4}
Astronomical unit	AU	$1.495\,978\,706\,9 \times 10^{11}$ m
Light year[c]	ly	$9.460\,536 \times 10^{15}$ m
Parsec	pc	$3.085\,678 \times 10^{16}$ m
Solar luminosity	$L_{\odot}$	3.85×10^{26} W
Day[d]	d	86 400 s exactly
Tropical year	a	365.242 190 d
Pi	π	3.141 59. . .

[a] This is an exact value. The second (s) is now defined in terms of atomic vibrations, and the metre (m) as the distance travelled by light in a vacuum in $1/(2.997\,924\,58 \times 10^{8})$ s.
[b] The kilogram (kg) is still defined as the mass of a metal cylinder at the International Bureau of Weights and Measures, Sèvres, France.
[c] This is the distance travelled by light in a vacuum in 1 year of 365.2425 days.
[d] The mean solar day is presently (2006) 86 400.0004 s.