Galaxies, stars and planets

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Introduction

For millennia, people have speculated about our place in the cosmos, with many traditions placing humans literally in a central position. Only in the last few centuries have observations and experiments gradually led us to the humbling conclusion that our position in the wider Universe is unremarkable. This course will describe our position in the cosmos, zooming out into our solar system and to larger scales, and also zooming the other way into microscopic scales. Throughout the journey, the course introduces some of the processes that are seen when viewing the Universe at these sizes.

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This OpenLearn course provides a sample of level 1 study in Science.

Learning Outcomes

After studying this course, you should be able to:

- understand the scale of items within the Universe
- appreciate the wide variety of objects contained in the Universe
- understand the relative sizes of the planets within the Solar System
- calculate how long it takes for light to reach the Earth from the Sun.

1 The Universe today

Astronomy is the study of all celestial bodies and the regions of space that separate them. It is a vast subject: quite literally as big as the Universe. It encompasses objects ranging in size from the incredibly small (the atoms from which planets and stars form) to the unbelievably vast (superclusters of thousands of galaxies, with each galaxy containing many billions of stars). The distances of these objects are also so enormous that the units of measurement, such as kilometres (km), that are familiar to many people on the Earth can't be used. The Universe is around 14 billion years old and contains materials with a range of properties that far exceeds anything that can be replicated in laboratories on the Earth. Temperatures range from close to absolute zero (−273.15 ºC) in dense clouds of gas and dust from which stars form, up to many millions of degrees in the interiors of stars. Although interstellar space is not empty, its density is far lower than that found in the best vacuum chambers on the Earth. In some stellar remnants, material the size of a cube of sugar would have a mass of 100 million tonnes! How can anyone know so much about the Universe when no-one has ever explored or directly measured any of it except the tiny part very close to a rather ordinary star in one of many billions of galaxies, and for only a tiny fraction of the time the Universe has existed?

The 'scientific method' involves the observation or measurement of a phenomenon or property, followed by the formulation of a hypothesis (proposed idea) to explain it, which is testable by an experiment. The results of the experiment may confirm or support the hypothesis or may prove it to be incorrect, in both cases advancing our understanding and leading to further testable hypotheses. This objective approach allows different scientists to repeat experiments to confirm the results, and build on the knowledge and understanding obtained. It has underpinned the development of modern science. However, it cannot be applied to the study of most of the Universe because it's generally not possible to conduct experiments to test a hypothesis. It's only possible to observe the Universe and attempt to explain what can be seen. A hypothesis can only be tested by predicting what else might be seen if the hypothesis is valid, and then attempting to observe it. An observation which matches the prediction provides further evidence (but not necessarily proof) that the hypothesis is valid.

When astronomers make observations, this creates a snapshot of the Universe as it *appears* now. From this, astronomers must try to discover or deduce the properties of the different objects in the Universe, how they formed, and how they have evolved, over a 14 billion year time span! Many astronomical objects take millions or even billions of years to evolve. We cannot hope to record any process that takes more than a few thousand years to occur (the length of recorded history) or directly observe it for more than a few decades (the working lifetime of a scientist or the time since many modern astronomical methods were developed). Stellar evolutionary processes generally take far too long for anyone to see a noticeable change in their properties (although there are exceptions). It's possible, however, to observe many different stars, all at different stages of their evolution, and try to build a picture of how they relate to each other in order to understand that evolution, in much the same way as attempting to work out the life cycle of a tree by walking through a forest.

The sheer scale of the Universe can help in this process. Objects can be seen from the light they emit. This light travels at a very high but finite speed of about three hundred thousand kilometres per second. The distances to stars are so vast that even at this speed it takes several years for light to reach us from the nearest stars. This is the origin of the use of 'light-years' as a measure of distance.

- Why is a unit of time (years) used to measure distance?
- Because a 'light-year' is the distance that light travels in one year.

Answering in-text questions

Throughout this course there are in-text questions (marked by a filled-in square), which are immediately followed by their answers (which are hidden until you click on 'Reveal answer'). To gain maximum benefit from these questions you should avoid reading the answer until you have thought of your own response. You will probably find it helpful to write down your answer, in note form at least, before reading the answer in the text.

The light from other galaxies can take many millions or even billions of years to reach us. This means that more distant galaxies can be seen as they were billions of years ago. More powerful telescopes, that allow us to see ever more distant objects, allow us to effectively observe further back in time and develop a better understanding of how the Universe and galaxies formed and evolved. This course summarises the scale of the Universe and the wide variety of objects it contains (Figure 1).

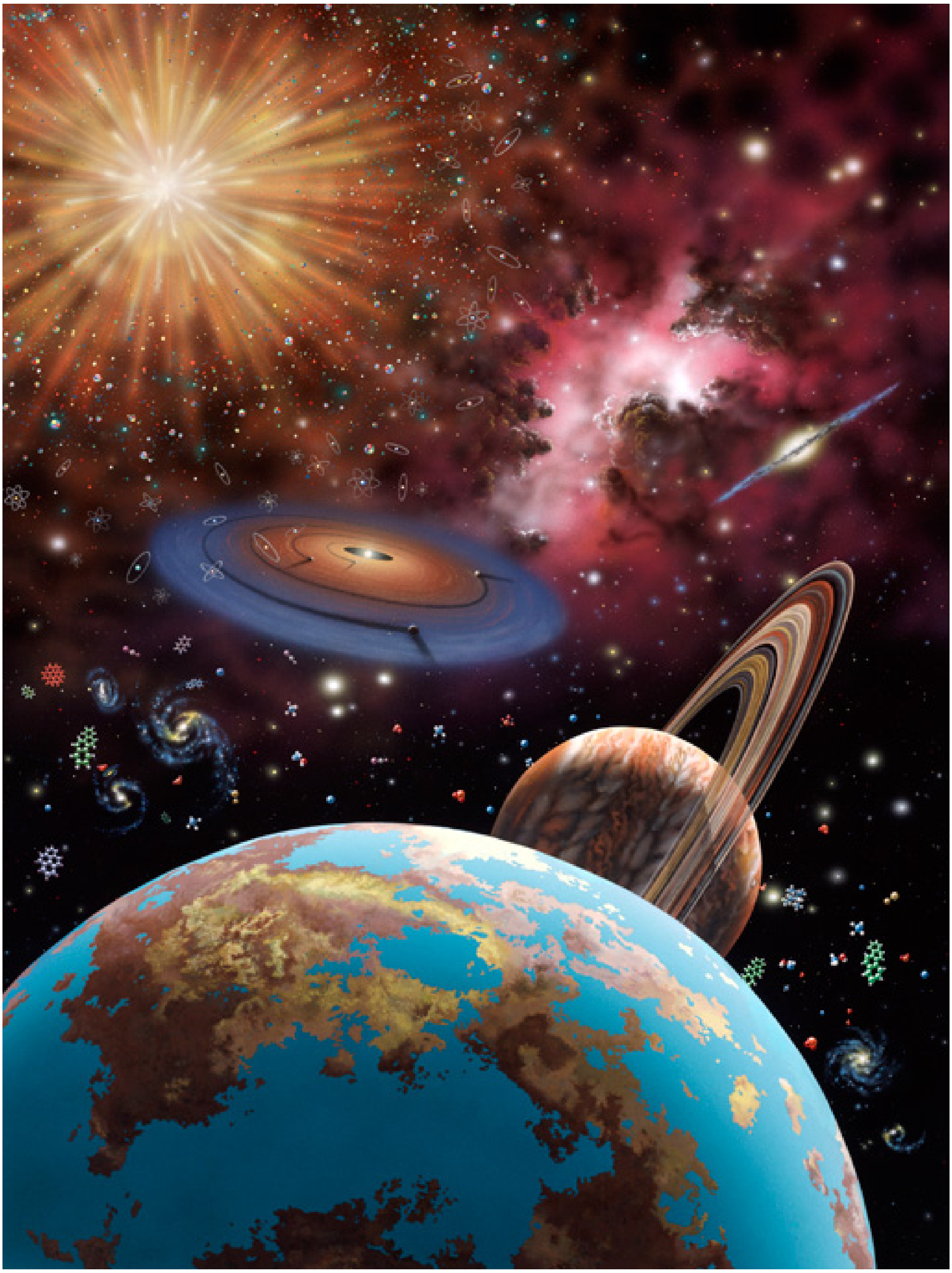

Figure 1 The image above illustrates some of the events that eventually led to life on Earth including the Big Bang, galaxies, the formation of stars and planets and the chemistry of life.

2 Scale of the Universe

Our bodies, in common with all material on the Earth, the planets of our Solar System, the Sun, stars and galaxies are composed of what we call matter. Much of the matter in and among the stars is composed of atoms and molecules that are familiar here on Earth. An atom is made up of particles called *electrons* which occupy a cloud-like structure around a central nucleus composed of *protons* and *neutrons*. The electrical attraction between negatively charged electrons and positively charged protons holds the atom together. A chemical *element* is defined by the number of protons in the nucleus. Hydrogen has one proton, helium has two and so on. A *molecule* is a group of two or more atoms (see Figure 2).

Many of the molecules in the human body are extremely complex combinations of atoms of different elements, but the simplest atom, hydrogen is the most common chemical element in the Universe, and helium is the second most common.

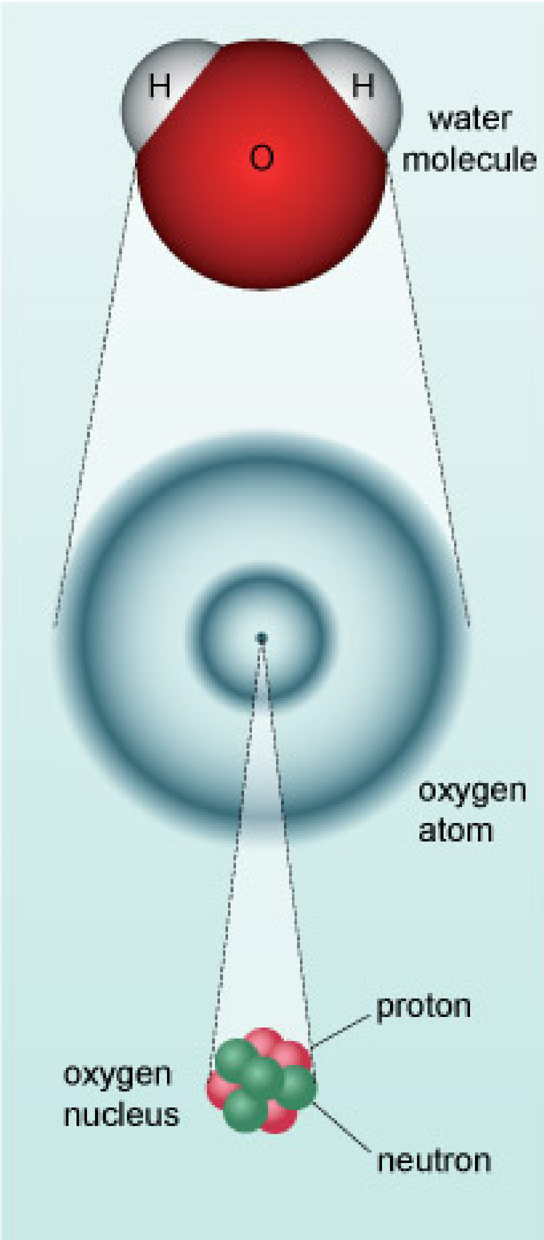

Figure 2 The structure of a water molecule which consists of two atoms of hydrogen and one of oxygen. The structure of the oxygen atom is also shown.

Atoms are among the smallest objects that are found in the Universe (individual hydrogen atoms are abundant in the interstellar medium - the space between the stars). Everyday units for length (such as metres) are just as inappropriate for these tiny objects as they are for defining the vast distances between stars.

When measuring the scale of the Universe it's necessary to consider the smallest and largest objects and distances and how they're defined. The physical quantity of interest is length (it may be the diameter of an object or its distance from us).

Units, numbers and physical quantities

Much of astronomy concerns quantities such as distances, masses, temperatures, etc. In all of these cases, units of measurement are important. Physical quantities are generally the result of multiplying together a number and a unit of measurement. Thus a distance such as 5.2 metres is really the result of multiplying the number 5.2 by the unit of distance known as the metre. There are many units of measurement in common use, so, whenever you quote the value of a physical quantity, you should always take care to include the unit as well as the number multiplying that unit. It is no use being told that a distance is 5.2 if you don't know whether that means 5.2 centimetres or 5.2 metres. The unit is just as important as the number.

In scientific work there are several internationally agreed conventions for the definition of units and the way in which units should be used and represented when writing down the values of physical quantities. The most widely adopted system of units is known as SI, which stands for Système International. This is based on seven carefully defined units that include the metre (for length), the second (for time) and the kilogram (for mass). The other four base units relate to luminous intensity (i.e. brightness), quantity of matter, electric current and temperature.

The SI unit of temperature is called the kelvin (signified by the abbreviation K and not °K). A difference of 1 K is the same as a difference of 1 °C but the Kelvin scale starts from a different zero point. 0 °C corresponds to the temperature at which water freezes (at the Earth's atmospheric pressure). 0 K, which is equal to −273.15 °C, corresponds to *absolute zero* where, in the classical theory of matter, all motion of atoms ceases. Both scales are used in scientific literature. The Celsius scale, which is generally used in everyday life, is more commonly used for biological environments, whereas the Kelvin scale is used for the wider temperature ranges found in astronomy.

The recognised abbreviations for the metre, the second and the kilogram are m, s and kg, respectively. Abbreviated units should always be written in the singular form, i.e. 5.2 m, rather than 5.2 ms, since that might be misinterpreted as 5.2 × 1 m × 1 s or as 5.2 milliseconds, which is abbreviated to 5.2 ms. When writing units in full, for example as the result of a calculation, the singular should also be used (e.g. 5.2 metre rather than 5.2 metres). It is, however, acceptable to use the plural when expressing quantities in text to maintain correct grammar, as in the following paragraph.

In calculations, units should be treated in the same way as numbers. For example, speed is distance travelled divided by time taken, so the unit of speed is the unit of distance (metre) divided by the unit of time (second). For example, the result of dividing 6.0 m by 3.0 s is 2.0 m/s, which can be read as 2.0 metres per second.

Units that result from combining the *base units* are called *derived units*. The most common derived units are sometimes given their own names and symbols. Examples are the joule (J; unit of energy) and the watt (W; unit of power, which is energy per unit time or J/s).

The size of an atom is about one-ten-billionth of a metre, and the nucleus of that atom is around a hundred thousand times smaller still! Clearly some different units for distance are needed that are more appropriate for the very small and very large. One way to do this is to use units that are appropriate for a given scale. For example, the size of an atom is better described by a unit that is one-ten-billionth of a metre in size called an ångström (Å), whereas distances to stars can be measured in light-years (ly).

You have already been introduced to the light-year.

- If light travels at 300 million metres in one second, how many metres are there in a light-year?
- The number of seconds in a year is about (365.25 days) × (24 hours in a day) × (60 minutes in an hour) × (60 seconds in a minute), which equals over 30 million seconds

(31 557 600 to be precise). So light will travel 300 000 000 × 31 557 600 = 9467 280 000 000 000 metres in a year.

You can see that 1 ly is easier to write than 9467 280 000 000 000 m! In fact professional astronomers use a different unit to measure the distance of stars, the parsec (pc), which is about 3.26 ly.

Ångströms, metres and parsecs cover an enormous range of sizes, and are ideal for measuring at atomic, human and stellar distance scales respectively. However, an even smaller unit than an ångström is needed to describe the sizes of atomic nuclei, and an even larger unit than the parsec for distances to other galaxies. Rather than invent new units every time we need to describe a certain scale, the SI unit of length, the metre, can be used. But how?

Very large and very small numbers

The SI unit of length is the metre. If you want to measure something that is typically 1000 times smaller or larger then you can use the familiar units the millimetre and kilometre respectively. So, using the same process, you could have units that are progressively 1000 times smaller or larger to reach any scale that's needed. The lists below show how:

Units larger than 1 metre:			
1 kilometre	1 km	is 1000 times larger than 1 m	
1 megametre	1 Mm	is 1000 times larger than 1 km	and 1000 000 × 1 metre
1 gigametre	1 Gm	is 1000 times larger than 1 Mm	and 1000 000 000 × 1 metre
1 terametre	1 Tm	is 1000 times larger than 1 Gm	and 1000 000 000 000 × 1 metre
1 petametre	1 Pm	is 1000 times larger than 1 Tm	and 1000 000 000 000 000 × 1 metre
1 exametre	1 Em	is 1000 times larger than 1 Pm	and 1000 000 000 000 000 000 × 1 metre
1 zetametre	1 Zm	is 1000 times larger than 1 Em	and 1000 000 000 000 000 000 000 × 1 metre
1 yotametre	1 Ym	is 1000 times larger than 1 Zm	and 1000 000 000 000 000 000 000 000 × 1 metre
Units smaller than 1 metre:			
1 millimetre	1 mm	is 1000 times smaller than 1 m	
1 micrometre	1 μm	is 1000 times smaller than 1 mm	and equals 1 m/1000 000
1 nanometre	1 nm	is 1000 times smaller than 1 μm	and equals 1 m/1000 000 000
1 picometre	1 pm	is 1000 times smaller than 1 nm	and equals 1 m/1000 000 000 000
1 femtometre	1 fm	is 1000 times smaller than 1 pm	and equals 1 m/1000 000 000 000 000
1 attometre	1 am	is 1000 times smaller than 1 fm	and equals 1 m/1000 000 000 000 000 000

A table

So attometres would be useful for measuring atomic nuclei and petametres for measuring the distances to nearby stars. Figure 3 shows how these units relate to the scale of the Universe.

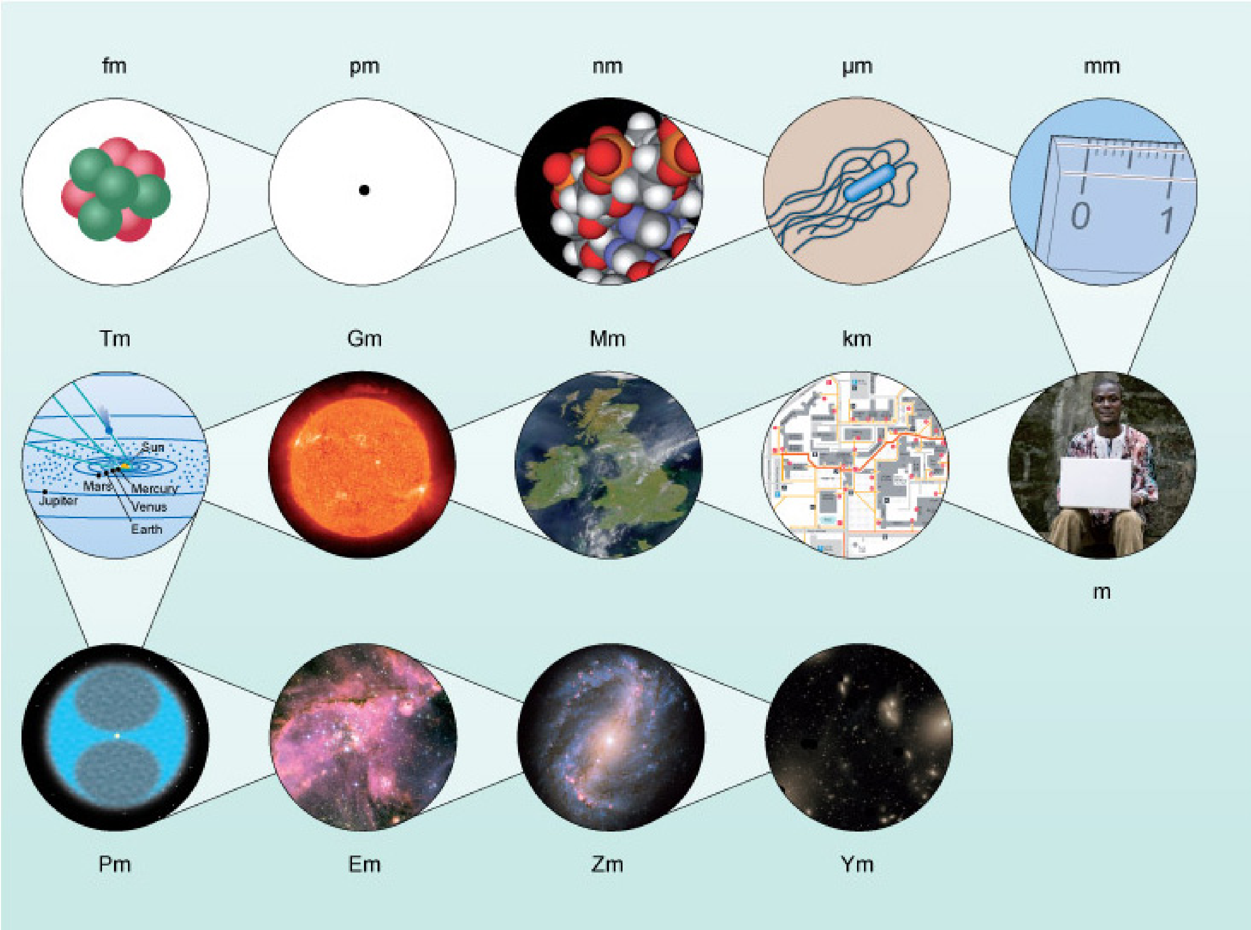

Figure 3 The scale of the Universe from atoms to galaxies. Each image is representative of the unit indicated. Each stage is 1000 times larger than the previous one. The smallest shown, femtometres (fm), is depicted by the nucleus of an oxygen atom. The next microscopic scale (pm) is still too small to show a whole atom. The next two scales (nm and µm) are represented by the diameter of deoxyribonucleic acid (DNA) and a bacterial cell respectively. You will be familiar with the scales millimetres (mm) to megametres (Mm). The Sun is at the scale of a gigametre (Gm). Moving outwards are the inner Solar System (Tm), Oort cloud (Pm), a nebula (Em), galaxy (Zm) and cluster of galaxies (Ym).

Most of these units will sound unfamiliar, not just because they refer to scales that we do not come across in our daily lives. Astronomy is an ancient science and certain non-SI units are commonly used instead, such as the ångström and parsec. Within our Solar System, distances are measured in units of the average distance of the Earth from the Sun, called the astronomical unit (AU). The rest of this course looks at the objects that can be observed in the Universe, starting with our own planetary system and the star that supports life on Earth, and then moving out to stars and galaxies.

3 Orbits and gravity

An understanding of orbital motion is fundamental to astronomy. It is crucial in the design of space missions and it enables astronomers to deduce the existence of planets associated with other stars. Stars can orbit one another and they also move in orbit around the centre of a galaxy. This section introduces some key ideas about orbital motion.

People sometimes wonder what keeps the Moon in orbit and stops it crashing to the Earth. This is a perfectly reasonable question to ask. If you lift an object above the Earth's surface and let it go, it falls to the ground, pulled down by the force of gravity. Why doesn't this happen to the Moon? Indeed, why don't the Earth and other planets fall into the Sun? To answer that question, and to see the role that gravity plays in the story, first requires an examination of circular motion.

If you set an object in motion it will move in a straight line, unless there is something pushing or pulling it into a curved path. To keep an object moving in a circular path, it needs constantly to be nudged sideways - there needs to be some force (that is, a push or a pull) directed towards the centre of the circle. The technical name for a force directed towards the centre of a circle is a centripetal force (centripetal means 'centre-seeking'). You can demonstrate this for yourself in the next activity.

Activity 1 Creating circular motion

The estimated time for this activity is 20 minutes.

For this activity you will need a table-tennis ball or large marble (or a similar smooth, smallish ball), a smooth table-top or floor, and about 1 metre of string (or wool) attached to a cork or a lump of plasticine (or other object of similar size and weight that can easily be fixed to your string). The second part of the activity (whirling the cork) needs to be done somewhere well away from people or objects that might be hit by a flying cork, ideally outdoors. Do not use a heavy object in this part of the activity.

First, roll the table-tennis ball (without spinning it) along the smooth surface. Note that it moves in a straight line.

Next, try to make it follow a curved path (again, without spinning it). You will find that, left to itself, it always follows a straight line. To get a curved path, you need to keep nudging it sideways, as shown in Figure 4. If you could exert a steady force rather than a series of taps, you could make the ball move in a smooth curve because you would be supplying the necessary centripetal force.

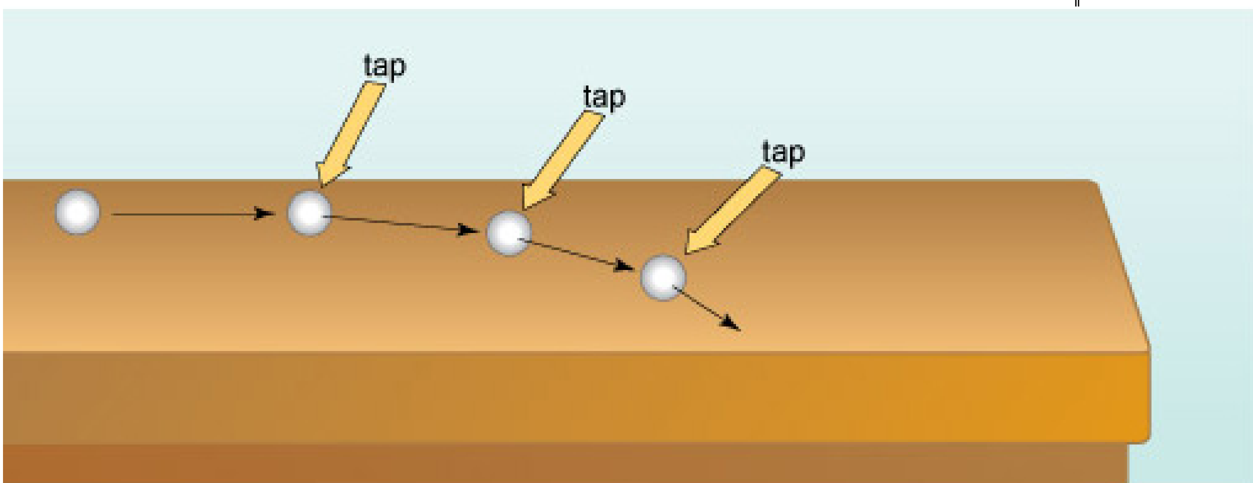

Figure 4 Making a table-tennis ball travel in a curve.

One way to supply a steady centripetal force is to pull on a piece of string attached to the moving object. Try whirling your cork or plasticine in a horizontal circle - you will feel that you need to keep pulling on the string as you do so.

Finally, let go of the string while whirling the cork and note the way it moves. You should be able to see that it continues to move in the direction it was heading at the time of release, as shown in Figure 5.

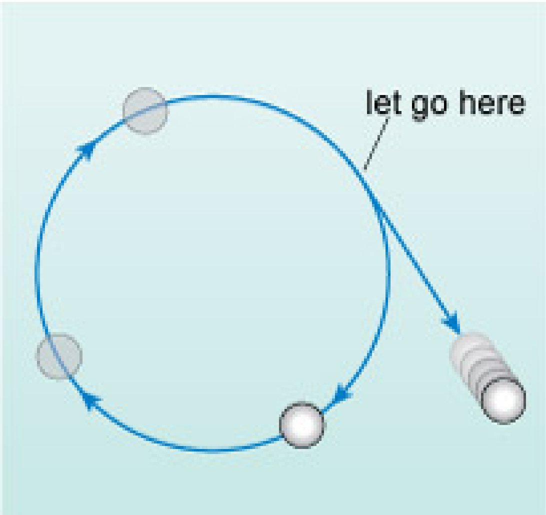

Figure 5 Letting go of a whirling object.

The need for a centripetal force applies to *all* cases of circular motion. In the example of the whirling cork, the force providing the inward pull is easy to see, but sometimes it is less so. For example, when a car is rounding a bend, the thrust of the engine and the grip of the tyres on the road combine to produce the necessary centripetal force.

What about the Moon? The Moon orbits the Earth in a (nearly) circular orbit.

- What must be providing the centripetal force for the Moon's orbit?
- The force of gravity acting between the Earth and the Moon keeps the Moon moving in its nearly circular path.

- What would happen to the Moon if gravity suddenly stopped acting?
- The Moon would drift off into space since there would be nothing to hold it in orbit around the Earth.

Gravity is familiar to us as the force that pulls objects towards the Earth, but our planet is not special in exerting this force. In fact, gravity acts between *all* objects. The strength of this attractive force increases in proportion to the product of the masses of the two bodies and decreases in proportion to the square of the distance between the centres of the two bodies. Thus, the more massive the bodies and the closer they are, the stronger the force. Just as the Earth and the Moon are attracted towards each other by gravity, so too are all bodies. (Example: if you increase the distance by a factor of 3, the force of gravity decreases by a factor of three squared, written as 3^2 = 3 by 3 = 9.) Even you and your cup of coffee are attracted to one another by gravity, but the force between small objects is so weak that it is normally unnoticed. We are usually only aware of gravity when at least one object is almost planet-sized.

If the Moon was simply suspended above the Earth and dropped, rather than moving in orbit, it would indeed move directly towards the Earth, pulled by gravity. In fact, it also has 'sideways' motion, and the overall effect is an orbit around the Earth. So, in wondering why the Moon does *not* fall towards the Earth, perhaps we should ask what gives it its sideways motion. Astronomers believe that the Moon formed from material ejected from the Earth in a giant impact. Some of this material would have ended up swirling around the Earth, where it gathered to form the Moon. The swirling motion is preserved in the form of the Moon's orbital motion.

So, in summary, it's possible to explain the Moon's orbital motion. It was acquired from the swirling material from which the Moon formed, and the Moon is kept in an almost circular orbit by the force of gravity acting between it and the Earth. Having explained the Moon's orbital motion, the same principles can be extended to other orbiting bodies.

4 Our neighbourhood

The Solar System consists of the Sun, eight major planets, some with one or more natural satellites and ring systems, and other minor bodies (dwarf planets, asteroids and comets).

Figure 6 shows the layout of the Solar System. All the planets orbit the Sun in the same prograde direction: anticlockwise when viewed from above the North Pole. Their orbits lie roughly in the same plane and, except for Mercury, are almost circular. In Figure 6 the orbits are viewed from an oblique angle, which distorts their shapes.

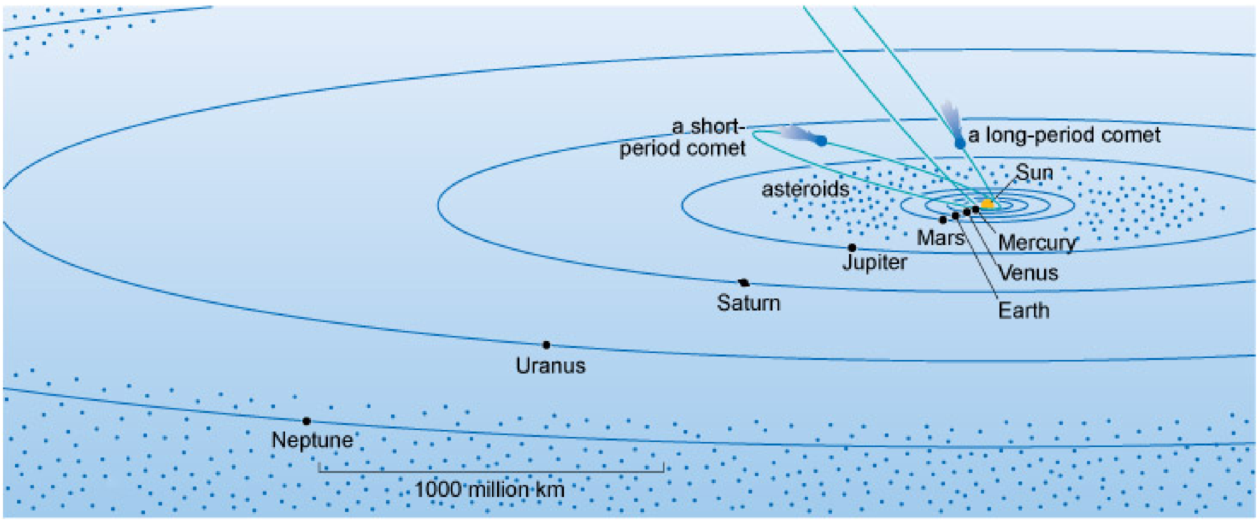

Figure 6 Schematic view of the Solar System showing the orbits of the eight major planets, looking obliquely southwards from outside the Solar System. Minor bodies are shown schematically: asteroids between Jupiter and Mars; trans-Neptunian objects in the outer Solar System; and the orbits of two typical comets. Note the scale bar showing a distance of 1000 million kilometres or 1 terametre.

Most of the planets spin on their axes with the same anticlockwise (prograde) sense of rotation. The exceptions are Venus, which spins very slowly backwards (retrograde), and Uranus, which is tipped on its side.

Figure 7 indicates the relative sizes of the major planets. Note the scale bar compared with that in Figure 6. The orbits of the planets cover distances of thousands of millions of kilometres, whereas Jupiter, the largest planet, is only 140 000 kilometres in diameter.

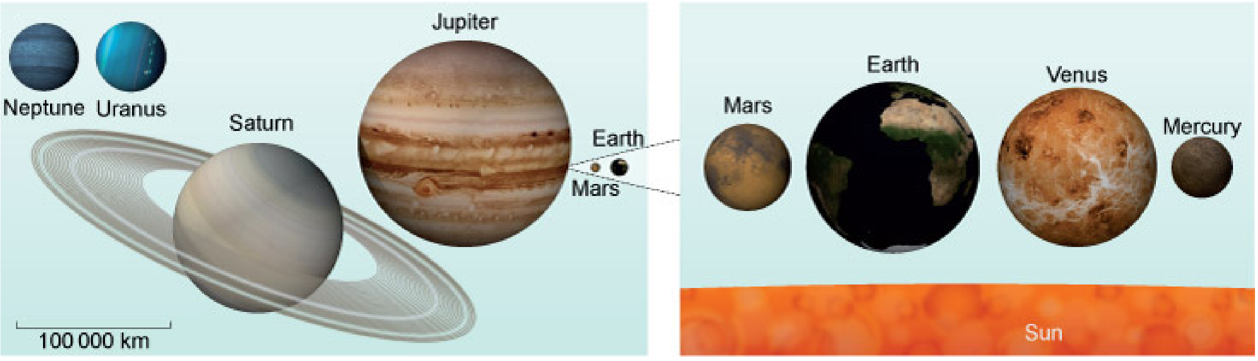

Figure 7 The Sun and the eight major planets showing their true relative sizes. Note the change in scale between the right and left panels.

Table 1 lists the relative sizes of the planets on a scale of 1 cm to 5000 km. On this scale, a model Sun has a diameter of more than 2 m. You can get a feel for the relative sizes of the major bodies in the Solar System by representing each planet as a fruit. Note that an orange (Uranus) is about ten times the diameter of a redcurrant (Mercury), but the volume ratio is much larger - you could fit about 1000 redcurrants into the volume occupied by an orange.

Table 1 also shows the distances to the planets on the same scale. If you made a scale model of the Solar System you would not want to arrange the model planets at these relative distances! This illustrates the vast distances between the planets compared with their sizes.

Table 1 The sizes and distances of the planets on a scale of 1 cm to 5000 km.

Planet	Approx. diameter/ km	Approx. model diameter/cm	Representative fruit	Approx. distance from Sun/ million km	Approx. model distance/m
Mercury	5 000	1.0	redcurrant	58	116
Venus	12 000	2.4	cherry tomato	108	216
Earth	13 000	2.6	cherry tomato	150	300
Mars	7 000	1.4	blueberry	228	456
Jupiter	140 000	28	water melon	778	1600
Saturn	120 000	24	pumpkin	1430	2900
Uranus	51 000	10	orange	2870	5700
Neptune	49 000	9.8	orange	4500	9000

- The data in Table 1 are for a model on a scale of 1 cm to 5000 km. How much bigger is the real Solar System than the model?
- One metre is 100 centimetres, and 1 kilometre is 1000 metres, so there are one hundred thousand centimetres in a kilometre (i.e. 1 km = 100 000 cm). In 5000 kilometres there are five hundred thousand thousand centimetres - in other words

five hundred million centimetres - so the actual Solar System is five hundred million (500 000 000) times bigger than the model.

The planets form two groups: the four closest to the Sun (the terrestrial planets) are similar in size to the Earth and have rocky surfaces, whereas the outer four planets (gas giants) are much larger with deep dense atmospheres.

The orbits of all planetary satellites lie close to the plane of their planet's equator and most travel in the same prograde direction as their planet's spin. The largest are comparable in size with the planet Mercury, whereas the smallest are little more than giant boulders. The largest of the minor bodies (asteroids, comets and trans-Neptunian objects) are more than 1000 km in diameter and are large enough to have their shapes (roughly spherical) determined by their own gravity - they are called *dwarf planets* and include the former planet Pluto as well as the largest asteroid Ceres.

For astronomers, the Sun is fascinating because it is our nearest star. By studying the Sun, they can gain an insight into the workings of the other millions of stars that are visible in the night sky. Learning that the Sun is a star can be a little surprising. After all, the Sun is a brightly glowing, yellow object - so bright that it is dangerous to look at it directly, and so hot that its radiation can be felt warming the whole Earth. Stars, on the other hand, are mere pinpoints of light that are visible only against the darkness of the night sky and with no discernible heating effect on Earth. How can they possibly be the same sort of object? The key to the answer lies in their *distances*.

In astronomical terms, the Sun is relatively close, being only about 150 million kilometres (1 astronomical unit) from Earth. As you have seen, the stars that are visible at night are so much further away that they appear as just faint points of light. Imagine looking at a glowing light bulb first from very close up and then from a much greater distance. Close up, you would see the shape of the bulb but, from far away, it would be just a point of light.

Although it is a very ordinary star, the Sun dominates the Solar System. With a diameter of 1.4 million km it is about ten times larger than Jupiter and more than a hundred times larger than the Earth. Its mass is over three hundred thousand times that of the Earth. The combined mass of the planets is less than 0.2% of the mass of the Sun. For this reason the Sun dominates the Solar System in several ways. The Sun's gravitational force controls the motion of bodies within the Solar System. It also distinguishes the Sun (as a star) from planets. The temperatures and pressures near the centre of this massive body are sufficiently high to sustain the nuclear reactions that power the Sun and result in its prodigious output of energy in the form of electromagnetic radiation. The planets, with their much smaller masses, cannot support these reactions. They are generally observed as a result of reflected or absorbed and re-emitted sunlight.

5 The Sun and stars

Safety warning

Never look directly at the Sun, either with the unaided eye or through spectacles, binoculars or a telescope. You risk permanently damaging your eyes if you do so.

The part of the Sun that you normally see is called the photosphere (meaning 'sphere of light'); this is best thought of as the 'surface' of the Sun, although it is very different from the surface of a planet such as Earth. The photosphere is not solid. Rather, it is a thin layer of hot gaseous material, about 500 kilometres deep, with an average temperature of about 5500 °C or 5800 K.

Figure 8a shows a visible light image of the Sun. Sunspots (Figure 8b) appear as small dark patches on the photosphere, which typically survive for a week or so, and sometimes for many weeks. The longer-lasting sunspots can be photographed repeatedly as they cross the face of the Sun so they can even be used to investigate the rate at which the Sun rotates. The number of sunspots changes with time, gradually increasing to a maximum every eleven years then decreasing to a minimum when no sunspots may be visible for some time - a cycle intimately linked to changes in the Sun's magnetic field. A close-up view of the visible surface of the Sun (Figure 8b) also reveals a seething pattern of granules seen all across the photosphere. Individual granules, resulting from upwelling hot gas due to convection (an important process in stellar energy transport) come and go in a few minutes, often to be replaced by other granules.

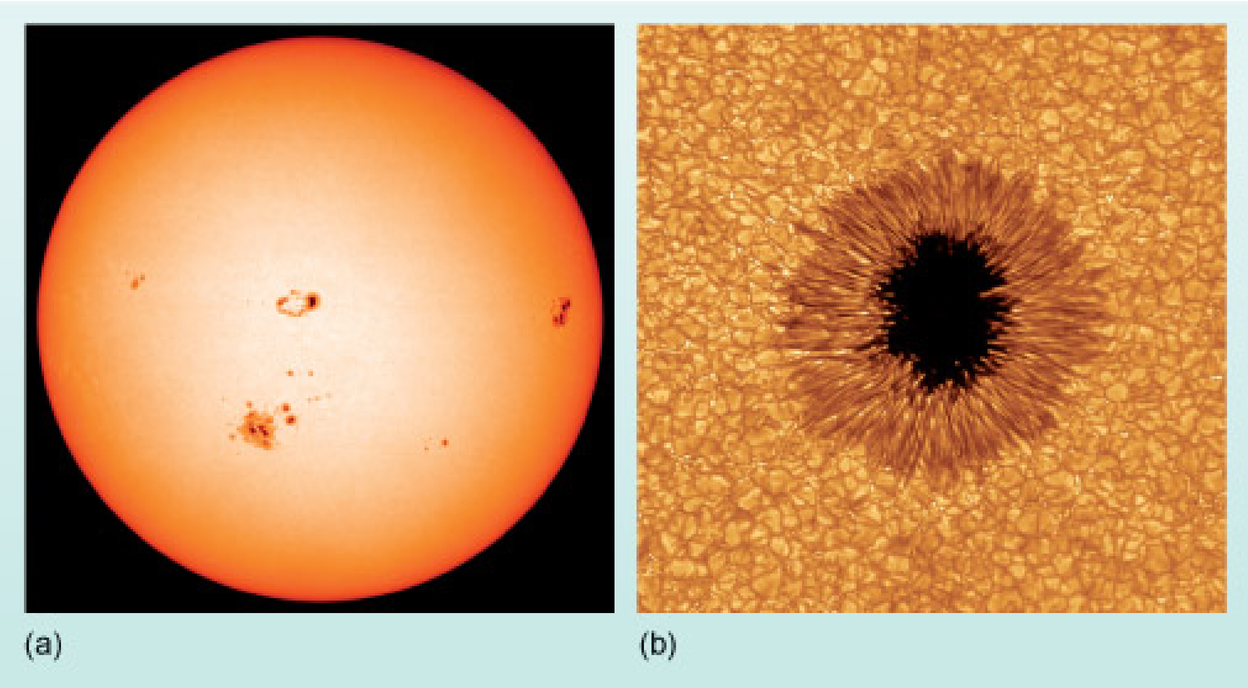

Figure 8 (a) A visible light image of the Sun. (b) A sunspot and granules on the Sun's surface.

Detailed studies of the body of the Sun usually require special equipment. However, the natural phenomenon known as a total eclipse of the Sun provides an opportunity to gain further insight into the nature of the Sun (see Figure 9). A total eclipse happens when the Moon passes in front of the Sun and blocks out the bright light from the photosphere.

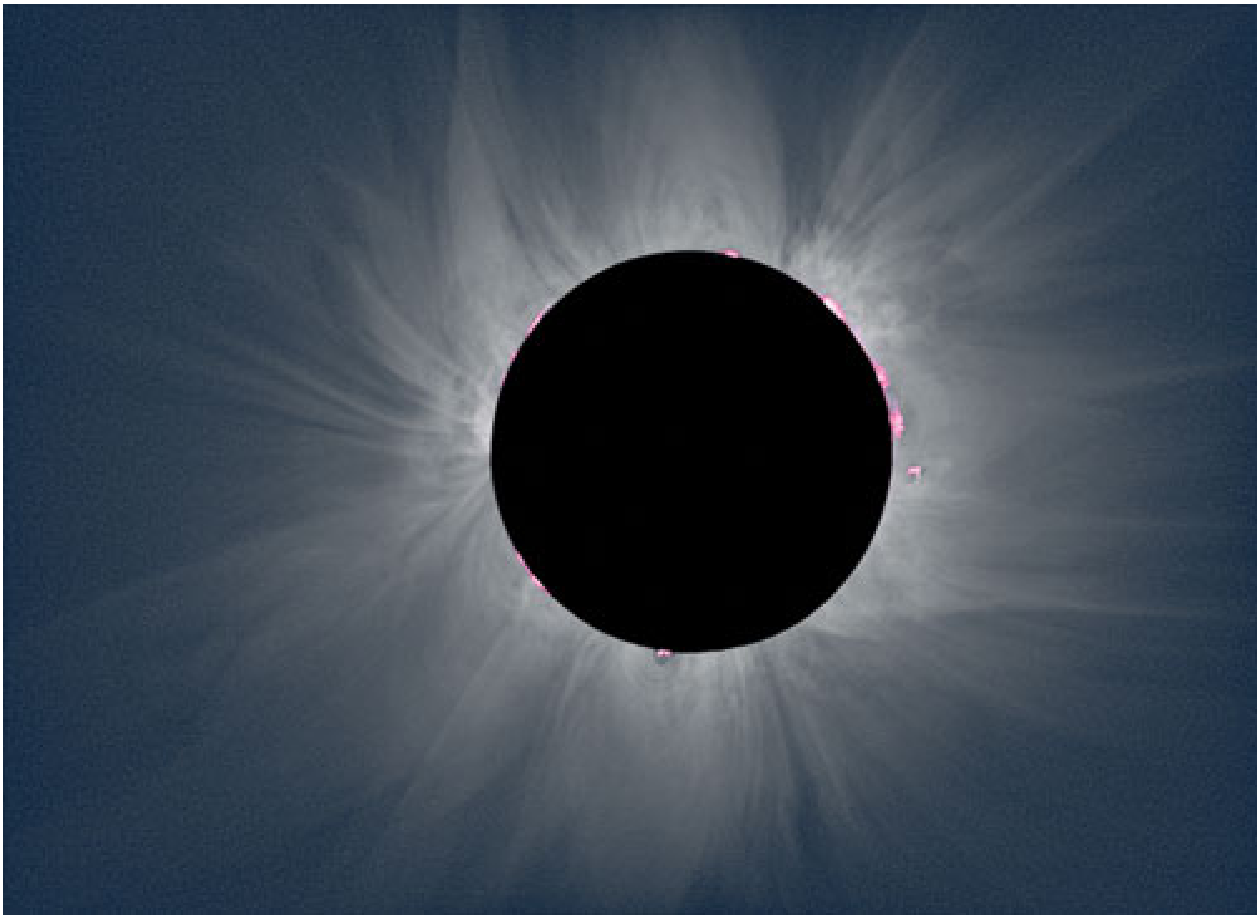

Figure 9 A total eclipse of the Sun, revealing the inner and outer parts of the Sun's atmosphere, the chromosphere and the corona.

When the Moon just eclipses the bright photosphere, it is often possible to see part of a narrow, pink-coloured ring that encircles the Sun. This is the chromosphere (meaning 'sphere of colour'), the lower or 'inner' part of the Sun's atmosphere. It is actually another layer of gaseous material, a few thousand kilometres thick, which sits on top of the photosphere. The lower parts of the chromosphere are cooler than the photosphere, while the higher parts are considerably hotter, but the chromospheric material is so thin that it emits relatively little light, and is therefore unseen under normal conditions.

As a total solar eclipse proceeds, a third part of the Sun is seen - the corona (meaning 'crown'). This is the extremely tenuous (i.e. thin) upper atmosphere of the Sun that extends to several times the Sun's photospheric radius. The corona sometimes looks like streamers or plumes, but its shape changes from eclipse to eclipse, although it will not usually show any changes during the few minutes of totality that characterise a typical total eclipse. The corona is very hot (temperatures of several million kelvin are not unusual) but it is so thin that its pearly white light is very faint compared with the light from the photosphere.

- The corona may be faint, but it does glow. Why are we not normally aware of the Sun's corona?
- The bright light from the Sun's photosphere is scattered by the Earth's atmosphere. This makes the sky blue and generally rather bright. As a result, the much fainter light from the corona can't be seen (rather as the light from a dim torch is unnoticeable on a bright sunny day).

Sometimes in eclipses observers also see prominences - great spurts of hot material at the edge of the Sun, extending outwards from the solar surface for many thousands of kilometres. Prominences and the changing shape of the corona indicate that the Sun is an active body, not just a quietly glowing source of light. When the Sun is observed with instruments that can detect electromagnetic radiation other than visible light, it is possible to see the full extent of the activity of the Sun.

Prominences, sunspots and other features of the Sun seen at different wavelengths are indicative of active regions, generally caused by the Sun's magnetic field, which influences the flow of hot gaseous material on the Sun. Sudden changes to the magnetic field in the corona are thought to be responsible for flares, one of the most energetic of all solar phenomena, which emit bursts of radiation of all wavelengths, from radio waves to gamma-rays as well as energetic particles (such as fast-moving protons and electrons).

The Sun is a typical star and only appears much brighter than other stars because they are so much further away. Astronomers can use this to deduce the actual distances to stars. One important observation makes this easier: namely, *stars that are the same size and colour give out the same amount of light*. So, if astronomers observe two stars of exactly the same colour, they can start by *assuming* they are the same size and therefore they must be giving out the same amount of light. If one looks fainter, it must be further away. By measuring the amount of light entering a telescope from each star, astronomers can work out just how much further away one star is than the other. Figure 10 shows the principle. Stars A and B give out the same amount of light, but B is at twice the distance of A, so its light is more spread out by the time it reaches an observer on Earth. Four (2 × 2) times as much light from A enters the telescope (or eye), so A appears four times brighter.

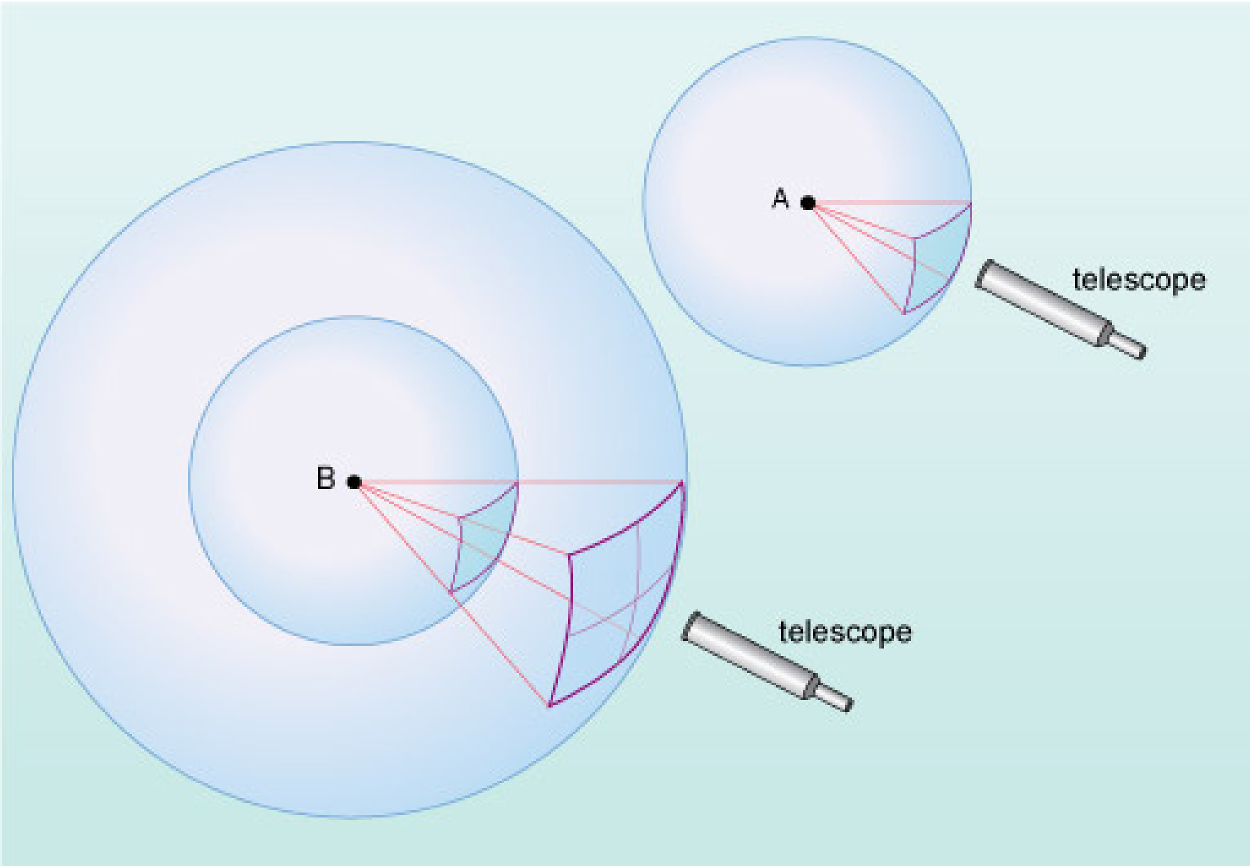

Figure 10 Light from a more distant star B is more spread out, so the star appears fainter than an identical star A nearby.

Powers

When a number is multiplied by itself, the result is called the *square* of that number. For example, multiplying three by three gives nine. Nine is said to be 'the square of three' or 'three squared'. This is expressed mathematically as 3^2, which means 3 × 3. The *cube* of a number is that number multiplied by itself three times, so three cubed = 3 × 3 × 3 = 3^3. Note that 3^3 can also be described as 'three to the power of three'.

- What is the general rule for describing how the apparent brightness of a star diminishes with distance?
- The general rule is that the apparent brightness diminishes with the *square* of the distance.

  So if the distance is multiplied by 2, the apparent brightness is reduced by $2^2 = 2 \times 2 = 4$. If the distance is multiplied by 5, the apparent brightness is reduced by $5^2 = 5 \times 5 = 25$, i.e. such a star has 1/25 of the apparent brightness of a similar star lying at 1/5 of its distance.

  Squares can also be worked out backwards so that as nine is three squared, three is the *square root* of nine, written $3 = \sqrt{9} = 9^{1/2}$, and as 27 is three cubed, three is the *cube root* of 27, thus $3 = \sqrt[3]{27} = 27^{1/3}$.

The apparent brightness of a star (or any other luminous object) is therefore said to obey an inverse square law.

- If star B is 10 times the distance of identical star A, how much brighter would A appear?
- Star A would appear 10 × 10 = 100 times brighter than star B.

In practice, it is not quite so easy to measure distance, because some stars are the same colour but different sizes and so give out different amounts of light - but the general principle of 'faint means far' underlies many of the techniques for measuring distances. Figure 11 shows that stars have different colours. These colours are related to the temperatures of the stars. The Sun is yellowish, with a photospheric temperature of about 5800 K. Bluish-white stars are hotter than the Sun and orange-red stars are cooler. Stellar temperatures range from less than 2000 K to over 40 000 K.

Figure 11 A region of sky visible from the Southern Hemisphere. The brightest star is Alpha Centauri, a faint companion of which is the closest star to our Sun. To the right is the famous constellation of the Southern Cross (Crux).

Stars come in a range of sizes, masses and luminosities. White dwarfs are only around the size of the Earth whereas some red giants are so large that if placed at the location of the Sun, they would engulf the Earth! The masses of stars, however, cover a much smaller range. The least massive are around ten percent of the mass of the Sun and the most massive around a hundred solar masses. The mass of the Sun, 1 solar mass, denoted $1 M_{\odot}$, provides another commonly used unit in astronomy. The subscript symbol $\odot$ represents the Sun, so the radius of the Sun is $1 R_{\odot}$ and the luminosity (the total power output) of the Sun is $1 L_{\odot}$. The luminosities of stars range from less than a thousandth of the solar luminosity to greater than $1 \text{ million } L_{\odot}$. Figure 12 shows examples of different types of stars. A wide variety of combinations of properties are found, such as small, cool, faint red dwarfs and large, hot, highly luminous supergiants. However, some types are more common than others and not all possible combinations of these properties are found among the stars that have been observed.

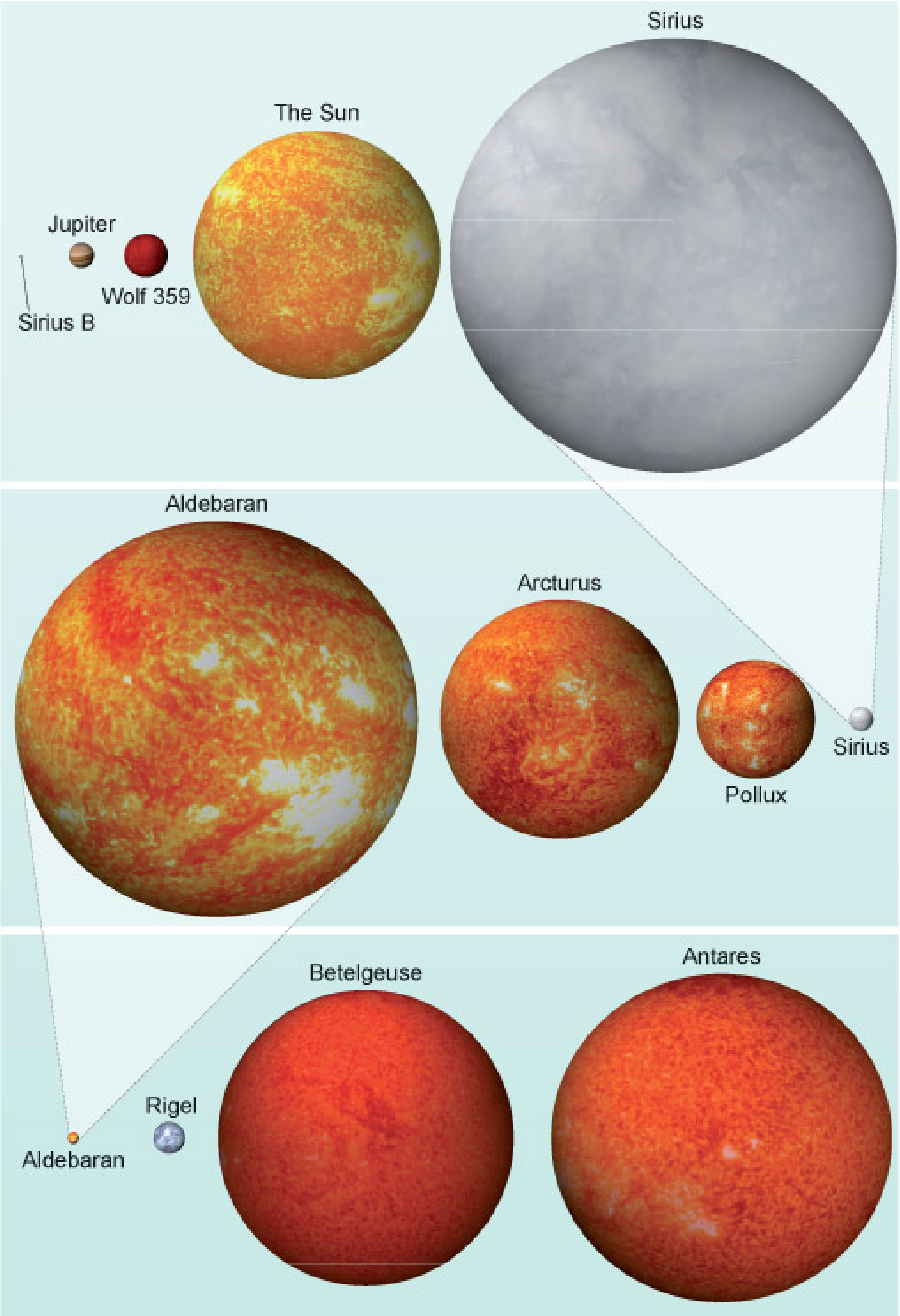

Figure 12 Sizes of stars compared. The colours are indicative of temperature; the bluish stars are hotter than the Sun whereas the orange-red stars are cooler. Jupiter, shown in the first panel, has too small a mass to support the nuclear reactions that power the stars.

6 Galaxies

The Sun is one of about a hundred billion (10^{11}) stars in our galaxy. It is difficult to determine the structure of the Galaxy as we are located inside it. As well as stars, it contains vast clouds of gas and dust, which can obscure our view in certain directions. However, if you observe the night sky from a dark site on a clear moonless night, you will see the Milky Way, a band of light circling the sky, that comes from many faint stars that cannot be individually distinguished (Figure 13). It reveals the most obvious characteristic of our galaxy, that it has a flattened shape. Careful analysis of the distances and motions of stars in space are required to reveal the true nature of our galaxy, called the Milky Way galaxy.

Figure 13 The night sky as seen from the Atacama Desert in Chile, showing the Milky Way in the direction of the centre of the Galaxy.

The human eye is extremely sensitive, but even with the aid of a telescope it is not ideal as an astronomical detector, because it does not record images. Until the use of photography in the late nineteenth century, astronomers recorded their observations with drawings made at the telescope. Despite the fact that photographic plates were much less sensitive than the human eye, they had one additional critical advantage - they could accumulate the light from a faint object for as long as a telescope could track it (the human eye retains an image for less than a tenth of a second). Photographs, and more recently electronic imaging detectors, reveal a huge variety of galaxies (Figure 14). They revealed that what appeared as faint smudges of light to the eye were in fact vast systems of stars like our own galaxy. (Our galaxy is sometimes referred to as 'the Galaxy' (with a capital 'G') to distinguish it.)

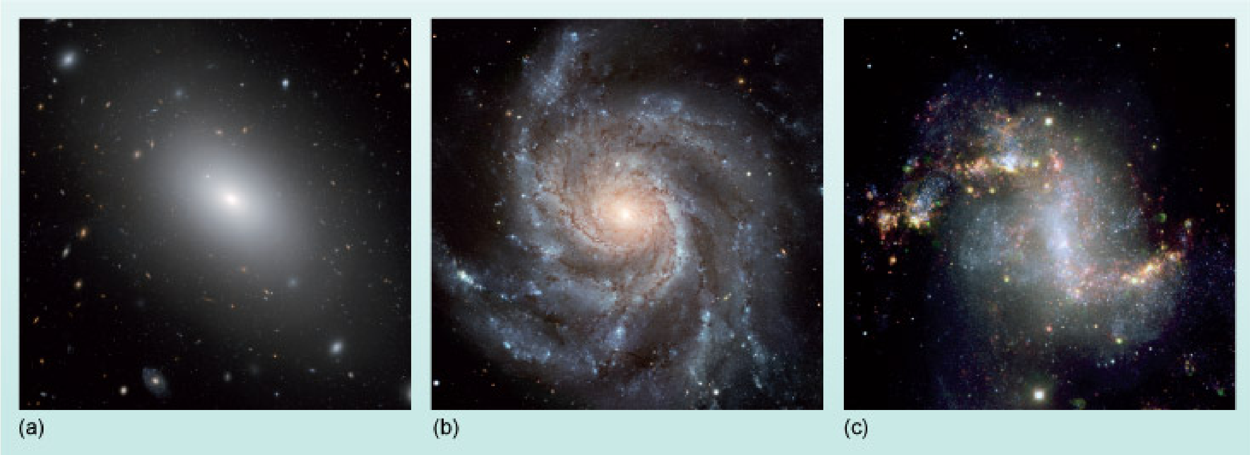

Figure 14 Examples of different types of galaxy. (a) An elliptical galaxy. (b) A spiral galaxy. (c) An irregular galaxy.

Galaxies are not distributed uniformly in space. Our own galaxy is a member of a small group of about 40 galaxies. Larger galaxy clusters may have more than a thousand members (see Figure 15) and these clusters themselves appear to be arranged into even larger structures.

Figure 15 The Virgo Cluster of galaxies. The dark spots indicate where bright foreground stars were removed from the image. Messier 87, which is visible through a small telescope, is the largest galaxy in the picture (lower left).

Our understanding of the Universe is, not surprisingly, derived largely from the light emitted by stars and galaxies. However, our understanding of the properties and evolution of these stars and galaxies comes from applying scientific principles and mathematical models. As new observational techniques developed and this understanding grew it became more apparent that the objects that can be seen represent only a fraction of the matter in the Universe. The majority of matter, called dark matter, is not visible but is required to understand the properties of the Universe. Some dark matter may simply be in the form of dead stars, but most appears not to be made up of the familiar elements but of some so far unknown constituents. This material is called non-baryonic dark matter. Figure 16 indicates what is currently thought to be the material composition of the Universe.

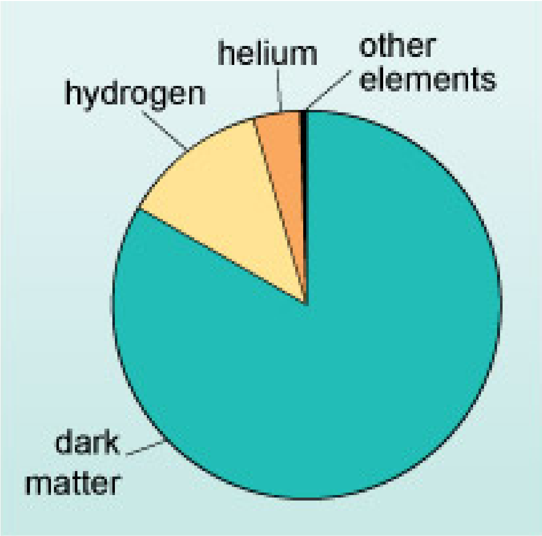

Figure 16 The matter in the Universe. Chemical elements account for less than about one-sixth of all matter. The majority is believed to consist of non-luminous 'dark matter', the nature of which is still uncertain.

7 'We are stardust'

How did the atoms in our bodies, the Earth, the Sun and other astronomical objects originate? This question is intimately tied with one of the most fundamental questions in science 'How was the Universe formed?'. Only the simplest atoms were present in the early stages of the Universe. Even now, the composition of normal matter in the Universe is dominated by hydrogen and helium. All the other heavier atoms, rather confusingly referred to as 'metals' by astronomers, amount to around 2% of normal matter. The heavier elements have been produced in nuclear reactions within stars.

If the nuclear reactions in stars occur close to the centre where the temperatures and pressures are highest, how can these heavy elements escape to make their way into the gas and dust clouds in the Galaxy and ultimately into planets and us? The answer lies in the details of the evolution of stars. The structure of stars changes as they age and some end their lives in catastrophic explosions that distribute much of their mass into the surrounding space and increase the fraction of heavier elements that can be incorporated into new stars.

- About 1% of the Sun's photosphere is composed of heavy elements. If the Sun formed from clouds of gas and dust in the Galaxy why does it contain only half the amount of heavy elements now present in the Galaxy?
- The Sun formed when the Galaxy was considerably younger (around 4.6 billion years ago). As time passes more and more stars complete their life cycles and so the proportion of heavy elements increases. The Sun therefore formed when there were fewer heavy elements in the Galaxy.

Table 2 lists the fraction by mass of the most common elements in the photosphere of the Sun compared with those in the Earth and a human body. As you would expect, the elements that are most common in the Sun are those that are most commonly produced in the nuclear reactions in stars. However, if the Earth formed at around the same time as the Sun why does it have such a different composition? The most abundant atoms in the Universe are only minor constituents of the Earth. The answer lies in the way in which these elements are combined in molecules that formed the building blocks of the planets.

Table 2 The approximate atomic composition of a human being compared with astronomical objects. The number preceding each element in the left-hand column is the number of protons in the nucleus.

		Abundance (% by mass)*			
	Element	**Sun (photosphere)**	**Whole Earth**	**Earth's crust**	**Human**
1	Hydrogen	**74**		0.1	**10**
2	Helium	**25**			
8	Oxygen	0.6	**30**	**47**	**61**
6	Carbon	0.2	0.1	0.1	**23**
26	Iron	0.1	**32**	5.1	
10	Neon	0.1			
12	Magnesium	0.1	**15**	2.1	
7	Nitrogen	0.1			2.6
14	Silicon	0.1	**16**	**28**	
16	Sulfur		0.6	0.1	0.2
28	Nickel		1.8		
20	Calcium		1.7	3.7	1.4
13	Aluminium		1.6	**8.1**	
11	Sodium		0.2	2.8	0.1
24	Chromium		0.5		
15	Phosphorus		0.1	0.1	1.1
25	Manganese		0.2	0.1	
17	Chlorine			0.1	0.1
27	Cobalt		0.1		
19	Potassium			2.6	0.2
22	Titanium		0.1	0.6	

* Abundances of less than 0.1% are not shown. The biggest contributors are in **bold**. Totals do not add up to 100% because of rounding and missing elements.

The Earth is a rocky body, so elements that form minerals and rocks (oxygen, silicon and metals such as iron and magnesium) are the most common. Helium is an inert gas (as are neon and argon), which means that it does not react with other atoms to form molecules, and therefore does not contribute significantly to the rocky material of the Earth. The gas giant planet Jupiter has a composition much closer to that of the Sun; its vast atmosphere is composed of mainly hydrogen and helium.

The elemental composition of the human body is dominated by hydrogen, carbon and oxygen, three of the four most abundant atoms in the Sun. Water is formed from hydrogen and oxygen, and carbon is the key to forming highly complex molecules. These organic (carbon containing) molecules provide the framework for constructing the complex structures present in the human body and for carrying the information that allows humans to grow and reproduce (one of the definitions of life).

- Helium is the second most abundant element in the Universe but is not a significant component of the human body. Why is this?
- Because helium is an inert gas it does not form into molecules that are present in the human body.

It is beyond the scope of this short discussion to investigate the requirements for these complex molecules that are essential for life (as we know it) to exist. Nevertheless understanding how those conditions are satisfied on the Earth is the first step in attempting to find environments elsewhere where life may exist.

Current views of different parts of the Universe offer a wonderful spectacle, but all astronomers know that, as they peer across vast cosmic spaces, they also look back over great reaches of cosmic time. This is an unavoidable consequence of the finite speed of light. The light seen today from the most distant observable galaxies was emitted over 12 billion years ago. The earliest signals of any kind that can be detected (a particular kind of microwave radiation that is the remnant of the Big Bang that is believed to have formed the Universe) originated over 13 billion years ago. The Sun and Earth were formed around 4.6 billion years ago, and life has developed on Earth within the last 3 billion years. Only in the last million years of this vast timescale, did humans evolve on Earth (Figure 17), and only in the last century have they been able, in theory, to communicate their presence to other possible inhabitants of our galaxy. One of the most exciting recent developments in astronomy has been the detection of planetary systems around other stars. Many astronomers believe firm evidence for the presence of extraterrestrial life, either on another planet in our Solar System or orbiting a different star, will be found during our lifetimes. The prospects for finding extraterrestrial intelligent life appear to be much more remote.

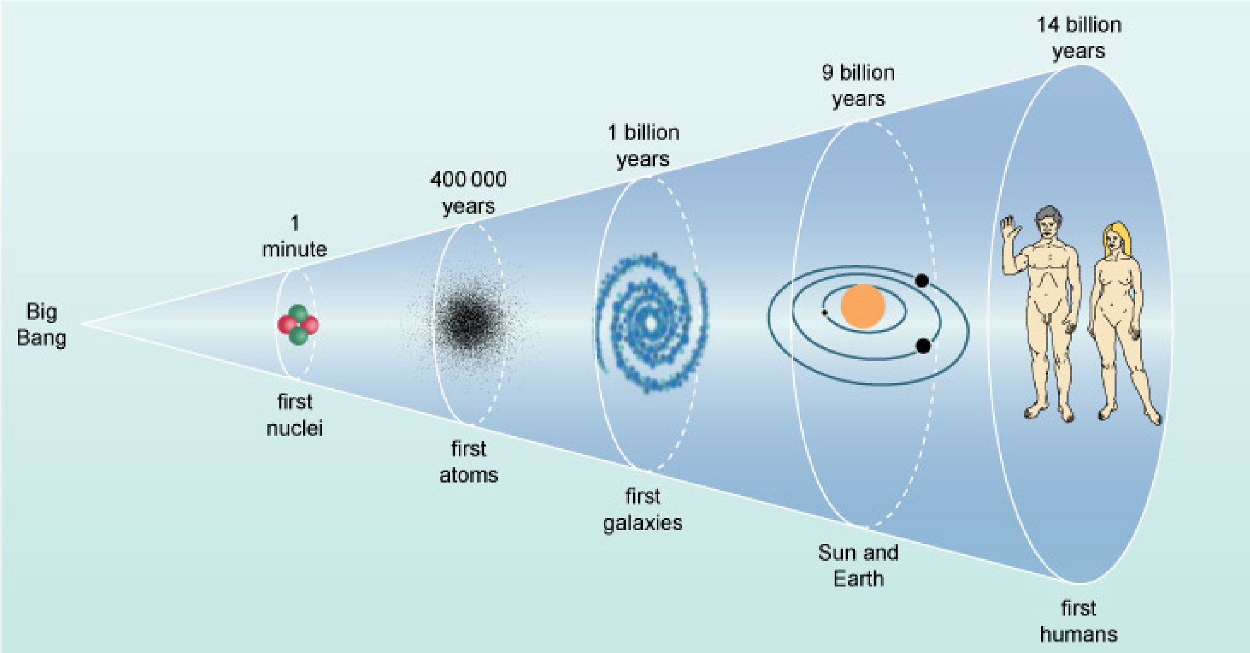

Figure 17 Cosmic time, from the Big Bang, about 13.7 billion years ago, to the present. The first galaxies may have formed less than one billion years after the Big Bang. The Sun and the Earth formed about 4.6 billion years ago, when the Universe was about 9 billion years old.

End-of-course questions

Question 1 What would be the diameter of the Sun if it was represented in the model of the Solar System described in Table 1?

Question 2 Distances to nearby stars are a few light-years. Calculate how long it takes light to reach the Earth from the Sun and hence explain why the light-year is not a useful unit for measuring the distance to the very nearest star, the Sun.

Question 3 Two stars, X and Y, have the same size and colour but X is four times further away from an observer on Earth than Y. How will the apparent brightness of the stars compare to the observer?

Question 4 The majority of the Earth's rocky surface is comprised of silicate rocks (compounds containing silicon and oxygen together with metals such as aluminium, calcium, magnesium and iron). The core of the Earth is believed to be predominantly composed of iron. What evidence is there in Table 2 to support this?

Answers to questions

Question 1 The Sun has a diameter of 1.4 million km which is 1400 000 km. The scale of the model is 1 cm to 5000 km. The diameter of the Sun in the model will therefore be 1400 000/5000 = 280 cm = 2.8 m. There is no fruit large enough to represent it in the model!

Question 2 The distance from the Sun to the Earth is 150 million km = 150 000 000 km = 150 000 000 000 m. Light travels at 300 million metres per second so it will take 150 000 000 000/300 000 000 = 500 seconds to travel from the Sun to the Earth. This is a tiny fraction of a year (which is over 30 million seconds) so a light-year is not an appropriate unit to measure distances within the Solar System.

Question 3 Star X is four times further away than star Y, so it will appear to be $4^2 = 4 \times 4 =$ 16 times fainter than star Y.

Question 4 The composition of the crust is dominated by silicon and oxygen whereas the whole Earth has a smaller proportion of these elements indicating that the proportion of rocky material is lower overall. The proportion of iron is much higher in the whole Earth than in the crust, indicating that the iron is concentrated towards the centre.

Comments on activity

Activity 1

In the first part, you might have found that the table-tennis ball did not move exactly in a straight line. This might happen if the surface was not level, or if either the ball or the table were not completely smooth. If you inadvertently spun the ball, and there was some friction between the ball and table, that would also drive it into a curved path.

In the second part, the cork flies off in the direction it was heading, and falls in a curved path towards the Earth. It is being pulled downward by gravity. If there was no gravity it would move horizontally in a straight line.

Conclusion

This free course provided an introduction to studying Learn about galaxies, stars and planets. It took you through a series of exercises designed to develop your approach to study and learning at a distance, and helped to improve your confidence as an independent learner.

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