Option D

16 Astrophysics

ESSENTIAL IDEAS

- One of the most difficult problems in astronomy is coming to terms with the vast distances between stars and galaxies and devising accurate methods for measuring them.
- A simple diagram that plots the luminosity versus the surface temperature of stars reveals unusually detailed patterns that help understand the inner workings of stars. Stars follow well-defined patterns from the moment they are created to their eventual death.
- The Hot Big Bang model is a theory that describes the origin and expansion of the universe and is supported by extensive experimental evidence.
- The laws of nuclear physics applied to nuclear fusion processes inside stars determine the production of all the elements up to iron.
- The modern field of cosmology uses advanced experimental and observational techniques to collect data with an unprecedented degree of precision, and as a result very surprising and detailed conclusions about the structure of the universe have been reached.

16.1 (D1: Core) Stellar quantities *– one of the most difficult problems in astronomy is coming to terms with the vast distances between stars and galaxies and devising accurate methods for measuring them*

Nature of Science

A topic without practical investigations

Astronomy is an unusual topic within the study of physics because the standard 'scientific method' is not so obvious. There are no controlled experiments designed to investigate a theory. Instead astronomers make observations and collect data. One consequence of this is that the growth of knowledge in astronomy is very much dependent on the latest technology available to aid observations.

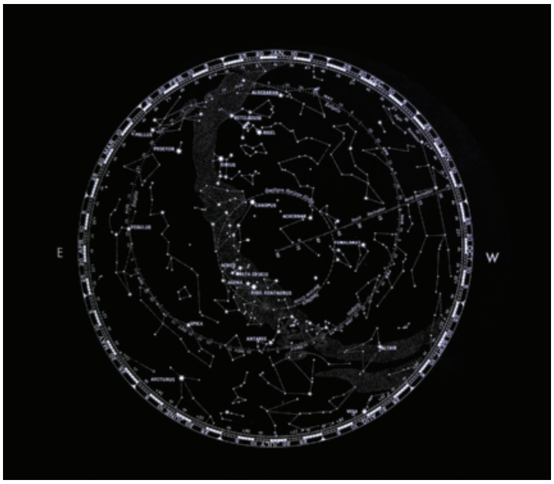
No student studying astronomy can fail to be impressed by the depth of knowledge about the universe that astronomers have gained from apparently so little evidence – just the radiation received from outer space!

In the first section of this chapter we will begin by summarising what we can see in the night sky and then outline the essential features of stars and stellar systems, before explaining the scale of the universe and the units astronomers use to measure such large distances. Finally we will establish the important relationship between the power emitted from a star and the intensity received here on Earth.

Observing the night sky

On a clear night, far away from the light pollution of towns, it may be possible to see hundreds of stars in the night sky with the unaided eye. A total of about 5000 stars are visible from Earth with the human eye, but not all can be seen at the same time, or from the same place. What we can see depends on our location, the time of night and the time of year. This variation happens because of the Earth's motion – its spin on its axis and its orbit around the Sun. In theory, at any one time, in any one place, we might be able to see about half of the visible stars.

Stars *seem* to stay in exactly the same positions/patterns (relative to other stars) over thousands of years and therefore we can locate the stars precisely on a **star map**, such as shown in Figure 16.1. Although stars are moving very fast, their motion is not usually noticeable from Earth, even over very long periods of time (in human terms) because they are such enormous distances away from us.

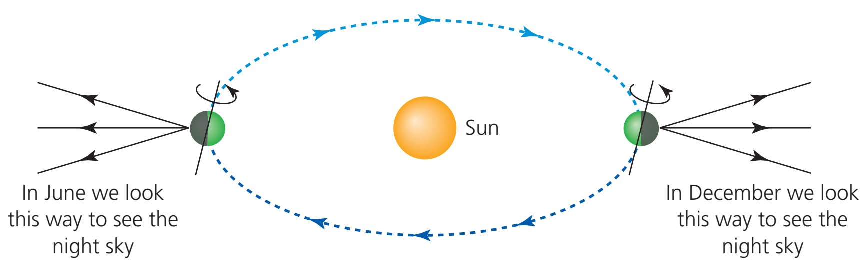


■ **Figure 16.1** A star map for the southern hemisphere

■ **Figure 16.2** The apparent rotation of the stars as the Earth spins

If you observe the stars over a period of hours on any one night you will notice that they appear to move across the sky from east to west – in exactly the same way as the Sun appears to move during the day. These apparent motions are actually produced because the Earth spins in the opposite direction. Time-lapse photography can be used to show the paths of stars across the sky during the night. Such photographs can even show the complete circular path of stars which are close to the Earth's extended axis (Figure 16.2).

In the course of one day, the Earth's rotation causes our view of the stars to revolve through 360° but, of course, during the day we are not able to see the stars because of the light from the Sun. (Radio astronomers do not have this problem.) Our night-time view changes slightly from one night to the next and after six months we are looking in exactly the opposite direction, as shown in Figure 16.3. The Sun, the Moon and the five planets that are visible with the unaided eye are all much, much closer to Earth than the stars. Their movements as seen from Earth can seem more complicated and they cannot be located in fixed positions on a star map. The Sun, the Earth, the Moon and the planets all move in approximately the same plane. This means that they follow similar paths across the sky as seen by us as the Earth rotates.



■ **Figure 16.3** How our view of the night sky changes during the year

The Sun and the Moon are the biggest and brightest objects in the sky. In comparison, all stars appear only as points of light. The closest planets may just appear as discs (rather than points) of light, especially Venus which is the brightest natural object in the night sky (other than the Moon).

There are a few other things we might see in the night sky. At certain times, if we are lucky, we may also be able to see a **comet**, an *artificial satellite* or a *meteor* – which causes the streak of light seen in the sky when a rock fragment enters the Earth's atmosphere and burns up due to friction. Occasionally, parts of meteors are not completely vaporized and they reach the Earth's surface. They are then called *meteorites* and are extremely valuable for scientific research, being a source of extra-terrestrial material.

Astrophysics internet sites

For many students astrophysics is a fascinating subject, but the opportunities for practical work are obviously limited. However, a considerable amount of very interesting information and stunning images are available on the internet and, without doubt, it will greatly enhance the study of this topic if you have easy and frequent access to the websites of prominent space organizations such as the European Space Agency (ESA), NASA and Hubble among others.

Objects in the universe

In this option we will concentrate our attention on (in order of size):

- planets and planetary systems (like the solar system), including comets
- stars (single and binary), stellar clusters (open and globular) and constellations
- nebulae
- galaxies, clusters of galaxies and super clusters of galaxies.

Nebulae

Nebulae are enormous diffuse 'clouds' of **interstellar matter**, mainly gases (mostly hydrogen and helium) and dust. Some of the matter may be ionized. A nebula forms over a very long time because of the gravitational attraction between the masses involved. ('Interstellar' means between the stars.)

There are several kinds of nebulae, with different origins and different sizes. Large nebulae are the principal location for the formation of stars and most nebulae already contain stars that are the source of the energy and light by which they can be observed.

It is possible to see some nebulae in our galaxy without a telescope, although they are diffuse and dim. They were probably first observed nearly 2000 years ago. Recent images of nebulae taken from the Hubble telescopes are truly spectacular. Figure 16.4 shows a telescope image of the Orion nebula. This can be seen without a telescope (close to Orion's belt in the Orion constellation) and it contains a number of 'young' stars. It is one of the closest nebulae to Earth and one of the brightest, so it has been much studied as a source of information about the formation of stars. It is about 1×10^{16} km from Earth and about 2×10^{14} km in diameter, so that it subtends an angle at the eye of approximately 0.02 rad ($\approx 1°$, which is large in terms of astronomy).

Figure 16.4 The Orion nebula (as pictured through a telescope)

Stars

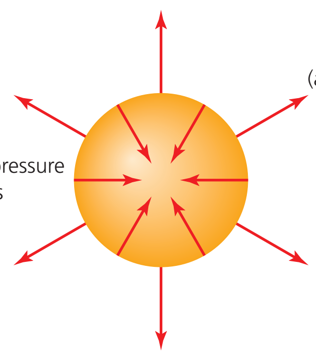
Within part of a nebula, over a very long period of time, gravity pulls atoms closer together and they can gain very high kinetic energies (that is, the temperature is extremely high – millions of kelvin) if the overall mass is large. The hydrogen nuclei (protons) can then have enough kinetic energy to overcome the very high electric forces of repulsion between them and fuse together to make helium nuclei. This process, known as **nuclear fusion**, can be simplified to:

$$4{}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + 2{}^{0}_{1}\mathrm{e} + \text{neutrinos and photons}$$

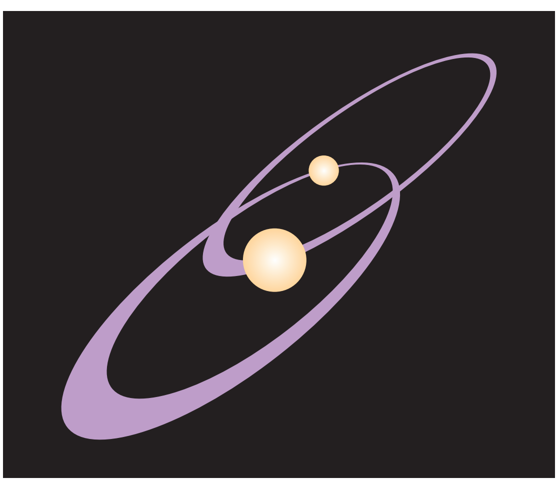
Nuclear fusion happens in all stars (until near the end of their 'lifetimes') and is their dominant energy transformation.

Each completed nuclear fusion of helium from four hydrogen nuclei (protons) is accompanied by a decrease in mass and an equivalent release of energy amounting to about 27 MeV (Chapter 12). The fusion of heavier elements occurs later in the lifetime of stars.

When nuclear fusion begins on a large scale it is commonly described as the *birth* of a star. The contraction of the material in the forming star creates a **thermal gas pressure** and the emitted radiation also creates a **radiation pressure** outwards in opposition to the **gravitational pressure** inwards. These pressures remain equal and opposite for a very long time, during which the star will remain the same size, stable and unchanging. It will be in **stellar equilibrium** (Figure 16.5). It may be helpful to compare this to a balloon in equilibrium under the action of the gas pressure outwards and the pull of the elastic inwards. There is also a balance between energy transferred from fusions and energy radiated from the surface.



■ **Figure 16.5** A stable star in equilibrium



■ **Figure 16.6** An artist's impression of a visual binary star system

During this period the star is known as a **main sequence** star. The only fundamental difference between these stars is their masses. Eventually the supply of hydrogen will be used up and the star will no longer be in equilibrium. This will be the beginning of the end of the 'lifetime' of a main sequence star. What happens then depends on the mass of the star (explained later in this chapter). Our Sun is approximately halfway through its lifetime as a main sequence star.

Binary stars

It is estimated that around half of all stars are in fact two (or more) stars orbiting around their common centre of mass with a constant period. Stars in a two-star system are described as **binary stars** (see Figure 16.6). Binary stars that are not too far away from Earth may be seen through a telescope as two separate stars, but most binary stars are further away and appear as a single point of light.

Binary star systems are important in astronomy because the period of their orbital motion is directly related to their mass. This means that if we can measure their period, we can calculate their mass. For non-visual binaries this may be possible using one of two observations:

- If one star passes regularly in front of the other as seen from Earth (an *eclipse*), the brightness will change periodically.
- If one star is momentarily moving towards the Earth, the other must be moving in the opposite direction. The frequency of the light received on Earth from each will be Doppler-shifted (Chapter 9) periodically.

Groups of stars

Galaxies

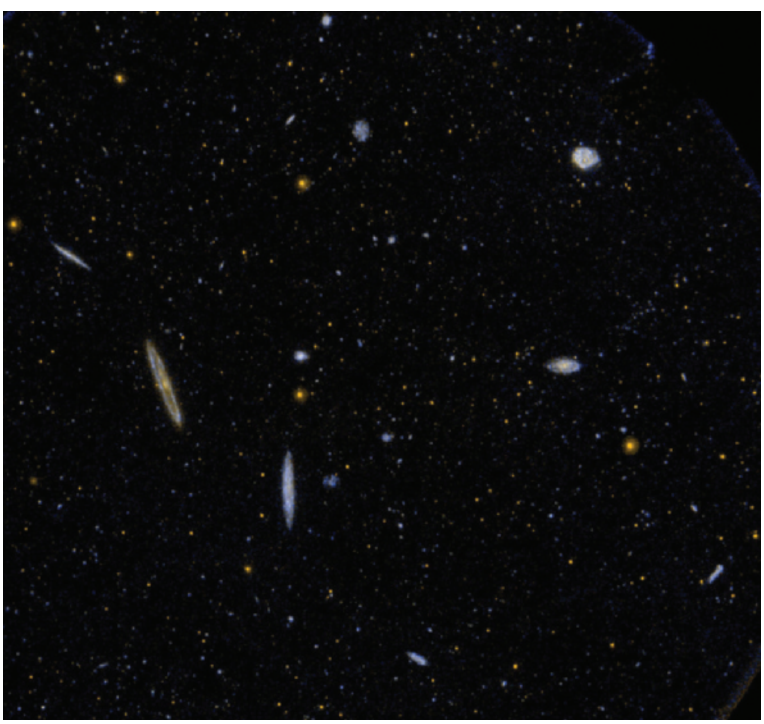
When we look at the stars in the night sky, they seem to be distributed almost randomly, but we are only looking at a tiny part of an enormous universe. The force of gravity causes billions of stars to collect into groups, all orbiting the same centre of mass. These groups are known as **galaxies**. Some of the spots of light we see in the night sky are distant galaxies (rather than individual stars). Billions of galaxies have been observed using astronomical telescopes. The Earth, the Sun and all the other stars that we can see with the unaided eye are in a galaxy called the **Milky Way**.

■ **Figure 16.7** Spiral galaxy M81

Galaxies are commonly described by their shape as being *spiral* (Figure 16.7), *elliptical* or *irregular*.

Galaxies are distributed throughout space, but not in a completely random way. For example, the Milky Way is one of a group of about 50 galaxies known as the 'Local group'. Larger groups of galaxies, called **clusters of galaxies**, are bound together by gravitational forces. (See Figure 16.8 for an example.) Clusters may contain thousands of galaxies and much intergalactic gas along with undetected 'dark matter'. (The term 'galactic cluster' is commonly used for a group of *stars* within a galaxy.)

Clusters of galaxies are not distributed evenly throughout space, but are themselves grouped together in what are known as **super clusters**. Super clusters of galaxies may be the largest 'structures' in the universe.



■ **Figure 16.8** Virgo cluster of galaxies

Stellar clusters

Some stars within a galaxy are close enough to each other that they become gravitationally bound together and rather than move independently, they move as a group called a **stellar cluster**. All the stars within a particular cluster were formed from the same nebula. There are two principal types of stellar cluster:

- **Globular clusters** are old and contain many thousands of stars in roughly spherical shapes that are typically about 10^{14} km in diameter.
- **Open clusters** are not as old as globular clusters. They are about the same size but contain much fewer stars (typically a few hundred). Because there are fewer stars in an open cluster, the overall shape is less well defined and the gravitational forces are weaker. Over time, an open stellar cluster may disperse because of the effects of other gravitational forces. The Pleiades (Figure 16.9) are an open cluster that is visible from Earth without a telescope.

■ **Figure 16.9** The Pleiades are an open stellar cluster.

It is important not to confuse stellar clusters, which are groups of stars relatively close to each other in space, with constellations.

Constellations

Ancient societies, such as Chinese, Indian and Greek civilizations, attempted to see some order in the apparent random scattering of the stars that we can see from Earth. They identified different parts of the night sky by distinguishing patterns of stars representing some aspect of their culture, such as the Greek hunter Orion (see Figure 16.10).

■ **Figure 16.10** The constellation of Orion: (a) the stars seen in the sky, (b) a representation from mythology

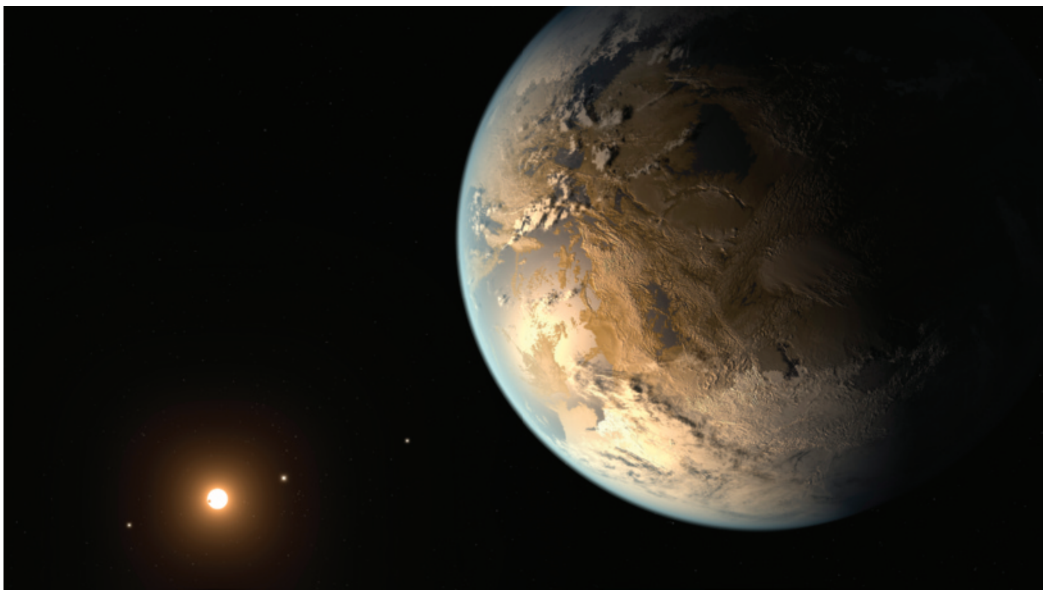
These two-dimensional patterns of visible stars are called **constellations**. It is important to understand that the stars within any given constellation do not necessarily have anything in common. They may not even be 'close together', despite the impression we have by viewing them from Earth. Although many constellations were first named thousands of years ago, their names are still widely used today to identify parts of the night sky.

Planetary systems around stars

A **planetary system** is a collection of (non-stellar) masses orbiting a star. Planetary systems are believed to be formed by the same processes as the formation of the stars.

Planets are objects of sufficient mass that gravitational forces have formed them into spherical shapes, but their mass is not large enough for nuclear fusion to occur. In other words, they are not massive enough to be stars. To distinguish planets from some smaller orbiting masses, it has been necessary for astronomers to specify that a planet has 'cleared its neighbourhood' of smaller masses close to its orbit.

The search for extraterrestrial intelligence (SETI) concentrates on planetary systems like our own solar system and new planetary systems are now discovered regularly. By the start of the year 2014 more than one thousand planetary systems had been identified. In April 2014 astronomers announced that they had discovered the 'most Earth-like planet', Kepler 186f, orbiting a small star at a distance of about 500 ly (light years) from Earth (see Figure 16.11).



■ **Figure 16.11** An artist's impression of Kepler 186f

The solar system

The **Sun** and all the objects orbiting it are collectively known as the **solar system**. Our Sun is a star and it is very similar to billions of other stars in the universe. It has many objects orbiting around it that are held in their orbits by gravity. The solar system is an example of a planetary system. Most of the planets have one or more objects orbiting around them. These are called **moons**. The Sun is the only large-scale object in our solar system which emits visible light; the others are only visible because they reflect the Sun's radiation towards Earth.

The Sun was formed about 4.6 billion years ago from the collapse of an enormous cloud of gas and dust. Evidence from radioisotopes in the Earth's surface suggests that the Earth was formed about the same time, 4.5 billion years ago.

Table 16.1 shows some details of the planets of our solar system (which do *not* need to be remembered). The distances given in the table are only averages because the planets are not perfect spheres and because their orbits are **elliptical** (oval) rather than circular. The Earth's orbit, however, is very close to being circular so the Earth is always about the same distance from the Sun. (The Earth is closest to the Sun in January but there is only about a 3% difference between the smallest and largest separations.) An ellipse has two *focuses* (foci) and the Sun is located at one of those two points. The **period** of the Earth's orbit is, of course, one year, but note that the further a planet is from the Sun, the longer its period. The link between orbital radius and period was discussed in Chapters 6 and 10.

Table 16.1 Planetary data (all data is correct to two significant figures)

Planet	Mass/10^{24} kg	Radius of planet/10^{6} m	Mean distance from Sun/10^{11} m	Period/y
Mercury	0.33	2.4	0.58	0.24
Venus	4.9	6.1	1.1	0.62
Earth	6.0	6.4	1.5	1.0
Mars	0.64	3.4	2.3	1.9
Jupiter	1900	69	7.8	12
Saturn	570	57	14	29
Uranus	87	25	29	84
Neptune	100	25	45	160

Compared with planets, **comets** are relatively small lumps of rock and ice that also orbit the Sun, but typically with very long periods and very elliptical paths (see Figure 16.12). They therefore spend relatively little of their time in the inner solar system close to the Sun and the inner planets, such as Earth. When they approach the Sun, radiation and the outflow of particles (solar wind) often cause a comet to develop a diffuse tail of dust and gas, which always points away from the Sun (Figure 16.13). This, together with the rarity of seeing them, has made comets a matter of great curiosity for many of the world's civilizations. Probably the most famous comet is named after the British astronomer and mathematician Edmund Halley (1656–1742). Halley correctly predicted that this comet would next be seen in 1758 (which was 16 years after his death). Halley's comet has a period of 75 years; it was last seen in 1986 and will be seen next in the year 2061.

In November 2014, after a 10-year mission, the European Space Agency's spacecraft *Rosetta* landed the first object on a comet. The Philae lander was able to identify organic molecules on comet 67P.

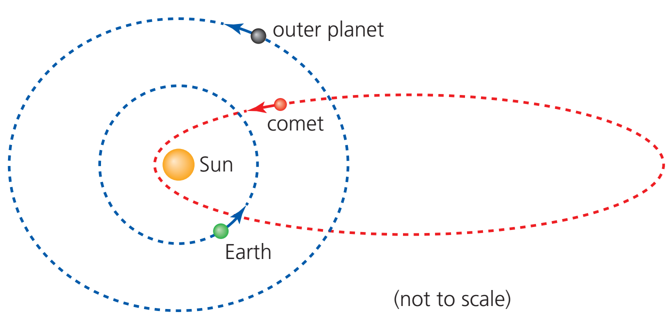


Figure 16.12 The eccentric ('flattened') path of a comet

Figure 16.13 A comet and its tail

1 a Calculate the average density of Earth and Jupiter.
  b Why are they so different?

2 a What is the average orbital speed of the Earth?
  b Compare the Earth's speed to that of Mercury.

3 a If there was a planet located at 35×10^{11} m from the Sun, suggest how long it might take to complete its orbit.
  b Would such a planet be visible to the unaided eye? Explain your answer.

4 a What is the smallest planet and what is its mass?
  b Why is Pluto not considered to be a planet?

5 What is the largest planet and what is its diameter?

Additional Perspectives

Asteroids colliding with the Earth

Asteroids are large rocks that are generally bigger than comets but much smaller than planets. They do not have 'tails' and most orbit the Sun in approximately circular orbits between Mars and Jupiter, in a zone called the *asteroid belt*. Because they are relatively small, the *trajectories* (paths) of asteroids and comets may be significantly altered if they pass 'close' to a planet (especially Jupiter) when they are subject to large gravitational forces.

Science-fiction authors and movie makers enjoy frightening us all with stories about asteroids or comets colliding with the Earth, but it is only in recent years that scientists have come to realise that such a major collision is not as unlikely as they had previously thought. In 1994 a large comet (Shoemaker–Levy 9) collided with Jupiter. The effect of the impact was seen easily with a telescope and was broadcast around the world on television (Figure 16.14). If a similar comet collided with Earth, the results would be catastrophic, although not quite on a scale comparable to the asteroid collision with Earth about 65 million years ago, which is thought to have led to the extinction of many species, including the dinosaurs.

Figure 16.14 Astronomers watch the impact of comet Shoemaker–Levy 9 with Jupiter.

We only need to look at the crater-covered surface of the Moon to become aware of the effects of collisions with asteroids and comets, but similar evidence is not so easy to find on the Earth's surface. Rocks of diameter 10 m or less usually break up in the Earth's atmosphere before impacting, so an asteroid would need to have a diameter of about 50 m or more before its impact would leave a noticeable and long-lasting crater. The effects of friction with the air might also cause an asteroid to explode before it impacted the Earth's surface. Of course, most of the Earth is covered with water and no craters would be formed after an impact with the oceans. Also, old craters may well have been eroded, weathered or just covered with vegetation over long periods of time.

Actual estimates about the size of possible asteroids that could collide with Earth and the probability of such events occurring are continually being refined. But, in general terms, we know that the probability of the Earth being struck by an asteroid is inversely related to its size.

For example, an asteroid 50 m in diameter may impact the Earth about every 1000 years; a 1 km asteroid about every 500 000 years and a 10 km asteroid once every 100 000 000 years. The chance of a catastrophic impact in an average human lifetime may be about 1 in 10 000.

There may be up to a million asteroids in our solar system capable of destroying civilization if they impacted with Earth, but it is not easy to observe all of them, nor track their movements. Much effort is now going into Near Earth Objects programs and researching what might be done if a dangerous impact was expected.

1 Calculate the kinetic energy of an asteroid of diameter 1 km and average density of $400\,\mathrm{kg\,m^{-3}}$ travelling at a speed of $20\,\mathrm{km\,s^{-1}}$. Compare your answer with 25 megatonnes of TNT, the energy that would be released from a 'large' nuclear bomb. (1 tonne of TNT is equivalent to 4.2×10^9 J.)

2 Use the internet to find out when the next large asteroid is expected to pass near to Earth. How close will it come and how dangerous would it be if it hit us?

Astronomical distances

The universe is enormous! Rather than use metres (or km) to measure distances, astronomers usually prefer to deal with smaller numbers and have introduced alternative units for distance.

The **light year**, **ly**, is defined as the *distance* travelled by light in a vacuum in one year.

At a light speed of $2.998 \times 10^8\,\mathrm{m\,s^{-1}}$ and 365.25 days, a light year is easily shown to be 9.46×10^{15} m. This value is provided in the *Physics data booklet*.

The **astronomical unit**, **AU**, is equivalent to the mean distance between the Earth and the Sun, 1.50×10^{11} m.

This value is provided in the *Physics data booklet*. (Although the actual distance varies, the value of 1 AU is *defined* to be $1.495\,978\,707 \times 10^{11}$ m.)

One **parsec**, **pc**, is equal to 3.26 ly. This value is provided in the *Physics data booklet*. The parsec is the preferred unit of measurement in astronomy because it is closely related to parallax angles – the way in which the distances to 'nearby' stars are measured (this will be explained later).

One parsec is defined as the distance to a star that has a parallax angle of one arc-second.

While distances to 'nearby' stars are commonly measured in parsecs, the more distant stars in a galaxy are kpc away and distances to the most distant galaxies will be recorded in Mpc and Gpc.

Table 16.2 Summary of distance units commonly used in astronomy

Unit	Metres/m	Astronomical units/AU	Light years/ly
1 AU =	1.50×10^{11}	–	–
1 ly =	9.46×10^{15}	6.30×10^4	–
1 pc =	3.09×10^{16}	2.06×10^5	3.26

The scale of the universe

The diameter of the **observable universe** is about 9×10^{10} ly. The speed of light limits the amount of the universe that we can, in principle, 'observe'. The distance to the edge of the observable universe is equal to the speed of light multiplied by the age of the universe (but the expansion of space itself must be considered, which will be discussed later in the chapter).

Distances between stars and between galaxies vary considerably. As a *very approximate* guide there might be 10^{12} stars in a big galaxy. A typical separation of stars within it may be about 1 ly, with a typical total diameter of a galaxy being about 10^4 ly (Figure 16.15). The billions of galaxies are separated from each other by vast distances, maybe 10^7 ly or more.

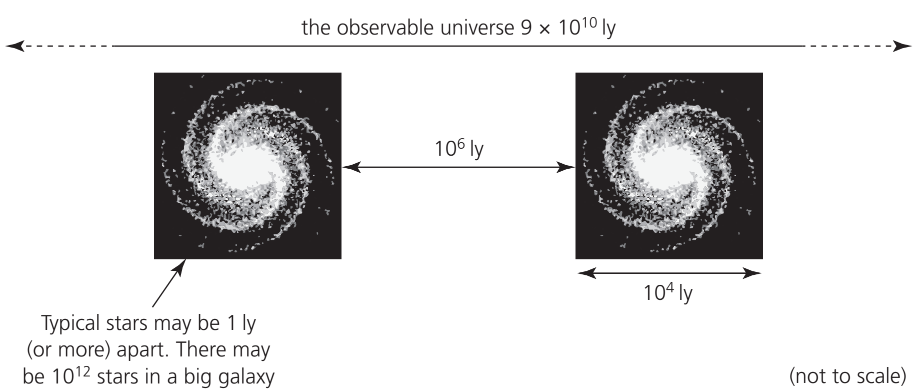


Figure 16.15 Very approximate dimensions of galaxies

6 Use Table 16.1 to determine the mean distance (in AU) from the Sun to the planets Mercury and Uranus.

7 What is the approximate size of the observable universe in:
a km
b pc?

8 Proxima Centauri is the nearest star to Earth at a distance of 4.0×10^{16} m.
a How many light years is this?
b If the Earth was scaled down from a diameter of 1.3×10^{7} m to the size of a pin head (1 mm diameter), how far away would this star be on the same scale?

9 Our solar system has an approximate size of at least 10^{11} km.
a How many light years is that?
b If you were making a model of our solar system using a ball of diameter 10 cm to represent the Sun, how far away would the 'edge' of the solar system be? (The Sun's diameter = 1.4×10^{6} km.)
c Research into how the edge of the solar system can be defined and what objects in the solar system are the most distant from the Sun.

10 Calculate the time for light to reach Earth from the Sun.

11 a Estimate how long would it take a spacecraft travelling away from Earth at an average speed of 4 km s^{-1} to reach:
i Mars
ii Proxima Centauri.
b Find out the highest recorded speed of a spacecraft.

12 Use the data from Figure 16.15 to make a very rough estimate of the number of stars in the observable universe.

13 Research the diameter of our galaxy, the Milky Way, in parsecs.

14 Explain why it would be unusual to quote a distance between stars in AU.

ToK Link

Imagination

The vast distances between stars and galaxies are difficult to comprehend or imagine. Are other ways of knowing more useful than imagination for gaining knowledge in astronomy?

Imagining the vast distances in the universe may be considered to be similar to imagining the number of molecules in a grain of salt – the numbers are so large that they are almost meaningless to us. There is no doubt that it does help us to make comparisons like 'it would take more than a billion years to walk to the nearest star', but then we realise that this is an incredibly *small* distance in the universe!

Determining the distances to the stars and distant galaxies

The measurement of astronomical distances is a key issue in the study of astronomy. However, determining the distance from Earth to a star or galaxy accurately is not easy and a variety of methods have been developed.

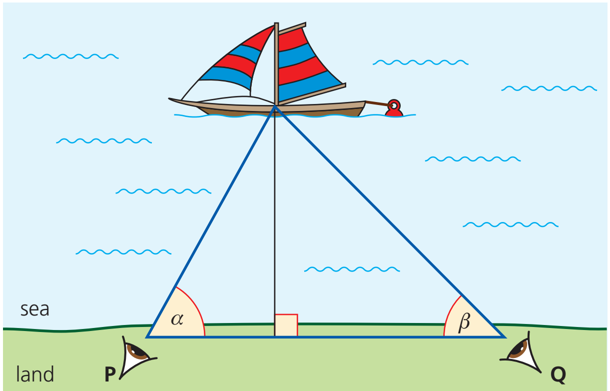
In this course we will consider three different ways in which the distance to a star or distant galaxy may be determined:

- stellar parallax
- use of Cepheid variable stars
- use of supernovae.

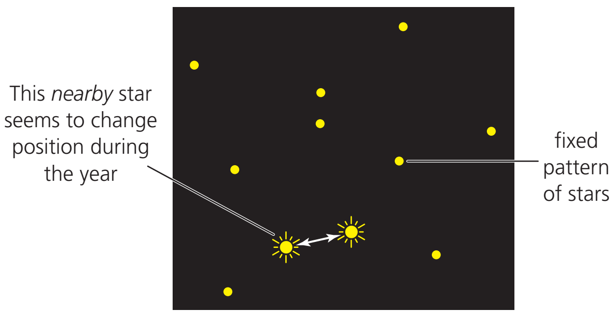
The use of **stellar parallax** for 'nearby' stars is the most direct and easily understood method. The other two methods are used for distant galaxies. They will be discussed later in the chapter.

Stellar parallax and its limitations

This method is similar in principle to one that we might use on Earth to determine the distance to an inaccessible object, such as a boat or a plane. If the object can be observed from two different places, then its distance away can be calculated using trigonometry. An example of this *triangulation* method is shown in Figure 16.16.



■ **Figure 16.16** Determining the distance to a ship at sea using triangulation



■ **Figure 16.17** A nearby star's apparent movement due to parallax

An observer on land sees the boat from position P and then moves to position Q. If the angles α and β are measured and the distance PQ is known, then the other distances can be calculated. When astronomers want to locate a star, they can try to observe it from two different places, but the distance between two different locations on Earth is far too small compared with the distance between the Earth and the star. Therefore, astronomers observe the star from the same telescope at the same location, but at two different places in the Earth's orbit; in other words, at different times of the year. To get the longest difference they usually take two measurements separated in time by six months.

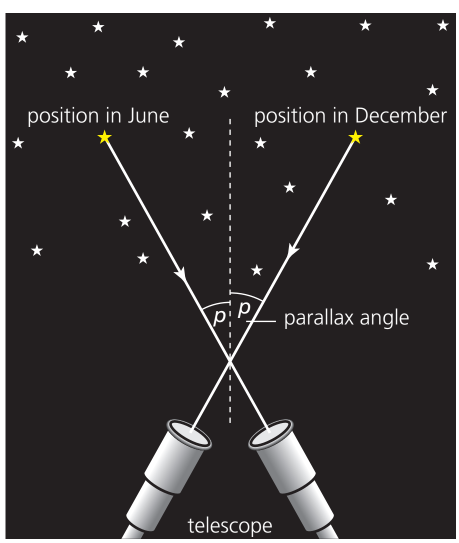
The triangulation method described above to locate a boat would be much more difficult if the observer was in a *moving* boat at sea and this is similar to the difficulty faced by astronomers locating stars from Earth. The problem can be overcome by comparing the position of the star to other stars much further away (in the 'background'). This is known as a **parallax** method.

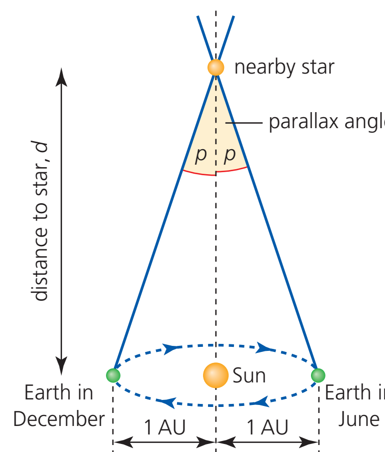
Parallax is the visual effect of a nearby object appearing to move its position, as compared to more distant objects (behind it), when viewed from different positions. A simple example is easily observed by looking at one finger held in front of your face and the background behind it, first with one eye and then the other. In the same way, a 'nearby' star can appear to *very slightly* change its position during the year compared to other stars much further away (although, as we have noted before, stars generally appear to remain in fixed patterns over very long periods of times).

Stellar parallax (Figure 16.17) was first confirmed in 1838. Many astronomers had tried to detect it before (without success) because the existence of stellar parallax provides evidence for the motion of the Earth around the Sun.

Using telescopes, astronomers measure the **parallax angle**, ***p***, between, for example, observations of the star made in December and June. Figure 16.18 shows the angular positions of a nearby star in December and June. (In Figures 16.18 and 16.19 the size of the parallax angle has been *much* exaggerated for the sake of clarity.)

■ **Figure 16.18** Measuring the parallax angle six months apart





■ **Figure 16.19** The geometry of the parallax angle

If the measurements are made exactly six months apart, the distance between the locations where the two measurements are taken is the diameter of the Earth's orbit around the Sun. We may assume that the orbit is circular, so that the radius is constant.

The parallax of even the closest stars is very small because of the long distances involved and this means that the parallax angles are so tiny that they are measured in **arc-seconds**. (There are 3600 arc-seconds in a degree.)

Once the parallax angle has been measured, simple geometry can be used to calculate the distance to the star (Figure 16.19):

$$\text{parallax angle, } p \text{ (rad)} = \frac{1.50 \times 10^{11}}{d} \text{ (m)}$$

Note that the distance from the Earth to the star and the distance from the Sun to the star can be considered to be equal for such very small angles, so: p (rad) = $\sin p = \tan p$.

Worked example

1 Calculate the distance, d, to a star if its parallax angle is 0.240 arc-seconds.

$$0.240 \text{ arc-seconds} = \left(\frac{0.240}{3600}\right) \times \left(\frac{2\pi}{360}\right) = 1.16 \times 10^{-6} \text{ rad}$$

$$p \text{ (rad)} = \frac{1.50 \times 10^{11}}{\text{d (m)}}$$

$$1.16 \times 10^{-6} = \frac{1.50 \times 10^{11}}{\text{d}}$$

$d = 1.29 \times 10^{17}$ m (= 13.7 ly)

If a parallax angle can be measured for a nearby star, calculations like this can be used to determine its distance away. Such calculations are common and it is much easier to use the angle directly as a measure of distance rather than making calculations in SI units.

We have already seen that the parsec is defined as the distance to a star that has a parallax angle of one arc-second. But there is an inverse relationship here – larger parallax angles mean smaller distances. So:

$$d \text{ (parsec)} = \frac{1}{p \text{ (arc-second)}}$$

This equation is given in the *Physics data booklet*. For example, a star with a parallax angle, p, of 0.25 arc-seconds will be from a star which is $\frac{1}{0.25}$ = 4 pc away etc. Table 16.3 shows the relationship between parallax angle and distance.

The stellar parallax method is limited by the inability of telescopes on Earth to observe very small shifts in apparent positions of stars or accurately measure very small angles less than 0.01 arc-seconds. This means that this method is usually limited to those stars that are relatively close to Earth, within about 100 pc, well within our own galaxy. The use of telescopes on satellites above the turbulence and distortions of the Earth's atmosphere can extend the range considerably, but it is still not suitable for the majority of stars, which are much further away.

Table 16.3 Parallax angles in arc-seconds and distances in parsecs

Parallax angle /arc-seconds	Distance away/pc
0.10	10.00
0.25	4.00
0.50	2.00
1.00	1.00

15 Convert an angle of 1 arc-second to:
a degrees
b radians.

16 The parallax angle for Barnard's star is measured to be 0.55 arc-seconds. How far away is it from Earth:
a in pc
b in m
c in ly?

17 What are the parallax angles for three stars at the following distances from Earth?
a 2.47×10^{15} km
b 7.9 ly
c 2.67 pc

Luminosity and apparent brightness

Every star (apart from our Sun) appears to us as a point in space. The only *direct* information that we can have about any particular star is its position (as might be displayed on a *two-dimensional* star map), the intensity of radiation received from it and the spectrum of its radiation. These are the only observable differences between all the stars that we can detect.

The **apparent brightness**, ***b***, of a star (including the Sun) is defined as the *intensity* (power/area) received (perpendicular to direction of propagation) at the Earth. The units are $W\,m^{-2}$.

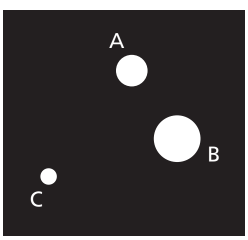


Figure 16.20 The apparent brightnesses of three stars (as indicated by the diameters of the dots)

The apparent brightness of the Sun is approximately $1360\,W\,m^{-2}$ above the Earth's atmosphere. This is also called the **solar constant** and was discussed in Chapter 8. Of course, the apparent brightnesses of all the other stars are much, much less. A typical value would be $10^{-12}\,W\,m^{-2}$. Astronomers have developed very accurate means of measuring apparent brightnesses using charge-coupled devices (CCDs), in which the charge produced in a semiconductor is proportional to the number of photons received, and hence the apparent brightness.

In Figure 16.20, stars A and B appear to be close together but in reality, in three-dimensional space, star A could be much closer to star C than star B. The situation may be further confused by differences in the brightness of the three stars. For example, it is feasible that star B could be the furthest away of these three stars and only appears brightest because it emits much more light than the other two.

The **luminosity**, ***L***, of a star is defined as the total power it radiates (in the form of electromagnetic waves). It is measured in watts, W.

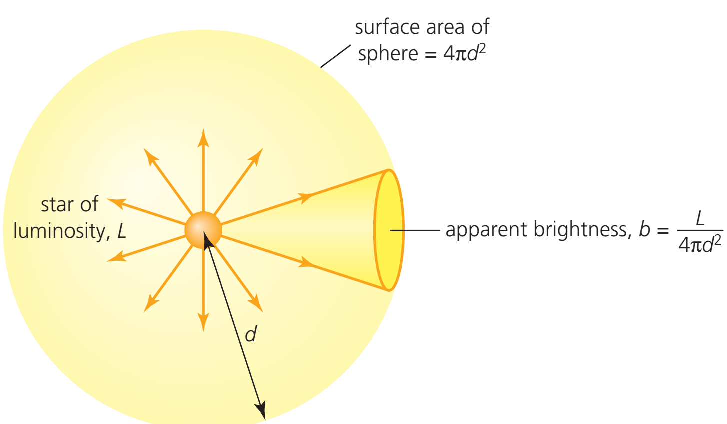


Figure 16.21 Relating apparent brightness to luminosity

For example, the luminosity of the Sun is 3.8×10^{26} W.

The apparent brightness of a star as observed on Earth will depend on its luminosity *and* its distance from Earth.

We would reasonably expect that the energy from any star spreads out equally in all directions, so the power arriving at a distant observer on Earth will be very considerably less than the power emitted. Assuming that none of the emitted energy is absorbed or scattered as it travels across space, the power received per square metre anywhere on a sphere of radius d will be equal to the emitted power (luminosity) divided by the 'surface' area of the sphere, as shown in Figure 16.21.

$$\text{apparent brightness, } b = \frac{L}{4\pi d^2}$$

This important equation is given in the *Physics data booklet*.

Nature of Science

The inverse square relationship

The importance of this equation for apparent brightness lies in the fact that once we have measured the apparent brightness of a star and *if* we know its distance from Earth, then it is a simple matter to calculate the luminosity of the star. Conversely, as we shall see later, if the luminosity of a star is known, measurement of its apparent brightness can lead to an estimate of its distance from Earth. The information provided by this simple equation is fundamental to an understanding of basic astronomy.

This is example of an **inverse square relationship**. If the distance from a star is multiplied by 2, then the apparent brightness is divided by 2^2; if the distance is multiplied by, for example, 37, then the apparent brightness will be divided by 37^2 (= 1369) etc. This is illustrated in Figure 16.22, which shows that at three times the distance, the same power is spread over nine (3^2) times the area.

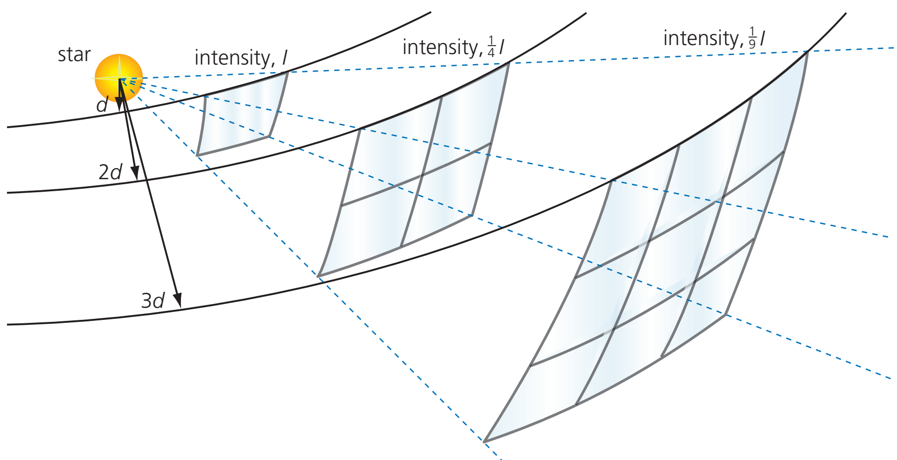


Figure 16.22 How intensity changes with the inverse square law

Not surprisingly, very little radiation is absorbed or scattered as it travels billions of kilometres through almost empty space, although the effects of the journey must be considered when studying the most distant galaxies. However, 100 km of the Earth's atmosphere does have a very significant effect, reducing brightness and resolution in many parts of the spectrum. That is why astronomers often prefer to use telescopes sited on mountain tops or on satellites above the Earth's atmosphere to gather data.

Utilizations

Telescopes on the ground and telescopes in orbit

Waves from all parts of the electromagnetic spectrum arrive at the Earth from outer space and it is truly impressive to consider just how much scientists have learned about the universe from studying these various radiations. Most of this option is about how that information is interpreted, but little has been included about how waves from the various parts of the electromagnetic spectrum provide different information about their sources. Figure 16.23 shows a telescope designed to focus and detect radio waves from outer space.

When radiation passes through the Earth's atmosphere some of it may be absorbed, refracted or scattered, and these effects will often depend on the wavelengths involved. For example,

■ **Figure 16.23** A telescope at the Very Large Array, New Mexico, USA receiving radio waves from space

■ **Figure 16.24** The telescopes at the Paranal Observatory on the top of Cerro Paranal, a mountain in the Atacama Desert in Chile

■ **Figure 16.25** The Hubble telescope

in visible light, the blue end of the spectrum is scattered more than red light and that helps to explain blue skies and red sunsets. We only have to look through the shifting haze above a hot surface to appreciate just how much convection currents in the air affect what we see.

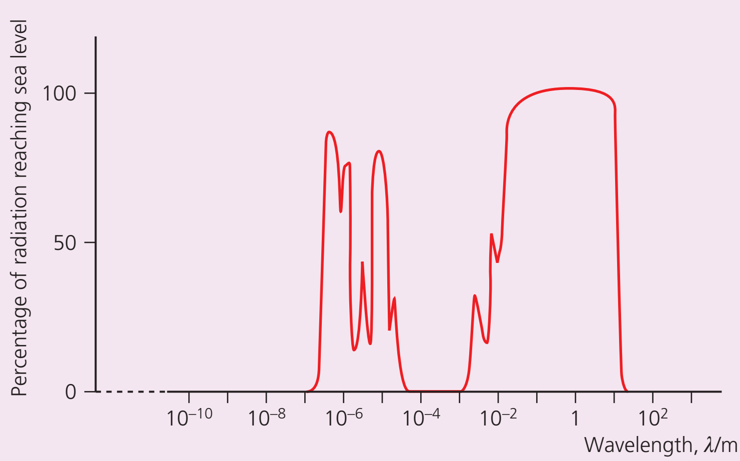
Astronomers have long understood the advantages of siting optical telescopes on the tops of mountains to reduce the adverse effects of the atmosphere on the images seen (Figure 16.24). The highest mountains are, of course, much lower than the height of the atmosphere, which is usually assumed to be approximately 100 km, although there is no distinct 'edge'.

The use of telescopes on orbiting satellites has greatly increased the *resolution* of images from space. (The resolution of images was discussed in detail in Chapter 9 and is needed by Higher Level students only.) The Hubble telescope (Figure 16.25) has been the focus of much attention, with many of its spectacular images well known around the world. The telescope was launched in 1990 and was named after the famous American astronomer, Edwin Hubble. It has a mass of about 11 tonnes and orbits approximately 560 km above the Earth's surface, taking 96 minutes for one complete orbit. One of the finest achievements of astronomers using the Hubble telescope has been determining the distances to very distant stars accurately, enabling a much improved estimate for the age of the universe.

The second major advantage of placing a satellite in orbit is that it can detect radiations that would otherwise be absorbed in the atmosphere before reaching any *terrestrial* telescopes (those on the Earth's surface). Figure 16.26 indicates (approximately) the effect that the Earth's atmosphere has on preventing radiations of different wavelengths from reaching the Earth's surface.

1 Make a sketch of Figure 16.26 and indicate and name the different sections of the electromagnetic spectrum.

2 Visit the Hubble website to look at the magnificent images from space and make a list of the important characteristics of the telescope.



■ **Figure 16.26** How the Earth's atmosphere affects incoming radiation

Worked example

2 A star of luminosity 6.3×10^{27} W is 7.9×10^{13} km from Earth. What is its apparent brightness?

$$b = \frac{L}{4\pi d^2}$$

$$b = \frac{6.3 \times 10^{27}}{4\pi \times (7.9 \times 10^{16})^2}$$

$$b = 8.0 \times 10^{-8}\,\mathrm{W\,m^{-2}}$$

18 How far away from Earth is a star that has a luminosity of 2.1×10^{28} W and an apparent brightness of $1.4 \times 10^{-8}\,\mathrm{W\,m^{-2}}$?

19 A star that is 12.4 ly from Earth has an apparent brightness of $2.2 \times 10^{-8}\,\mathrm{W\,m^{-2}}$. What is its luminosity?

20 Calculate the distance to the Sun using values for its luminosity and apparent brightness.

21 Star A is 14 ly away from Earth and star B is 70 ly away. If the apparent brightness of A is 3200 times higher than that of star B, calculate the ratio of their luminosities.

22 If the radiation from the star in Question 18 has an average visible wavelength of 5.5×10^{-7} m, estimate how many visible photons arrive every second at a human eye of pupil diameter 0.50 cm.

Relating the luminosity of a star to its surface temperature

We know from Chapter 8 that the power radiated from a surface in the form of electromagnetic waves can be calculated from $P = e\sigma AT^4$ where A is the surface area, T is the temperature (K) and σ is the Stefan Boltzmann constant. We may assume that stars behave as *perfect black bodies*, so that emissivity $e = 1$ and the power emitted by a star (its luminosity, L) is then given by:

$$L = \sigma AT^4$$

This equation is given in the *Physics data booklet*.

Remember that when a surface is described as a 'perfect black body' we mean that it emits the maximum possible radiation at any particular temperature and not that it appears black. This equation shows us that if we know the luminosity of a star and its surface temperature then we can calculate its surface area and radius ($A = 4\pi r^2$). This is shown in the following worked example and questions. In the next section we will review how Wien's displacement law (Chapter 8) can be used to determine the surface temperature of a star from its spectrum.

Worked example

3 What is the luminosity of a star of radius 2.70×10^6 km and surface temperature 7120 K?

$$L = \sigma AT^4$$

$$= (5.67 \times 10^{-8}) \times 4\pi \times (2.70 \times 10^6 \times 10^3)^2 \times (7120)^4$$

$$= 1.33 \times 10^{28}\,\mathrm{W}$$

23 A star has a surface area of $1.8 \times 10^{19}\,\mathrm{m^2}$ and a surface temperature of 4200 K. What is its luminosity?

24 If a star has a luminosity of 2.4×10^{28} W and a surface temperature of 8500 K, what is:
- **a** its surface area
- **b** its radius?

25 What is the surface temperature of a star that has an area of $6.0 \times 10^{20}\,\mathrm{m^2}$ and a luminosity of 3.6×10^{30} W?

26 If the star in question 23 is 17.3 ly away, what will its apparent brightness be when seen from Earth?

27 If the star in question 24 has an apparent brightness of $2.5 \times 10^{-8}\,\mathrm{W\,m^{-2}}$, how many kilometres is it from Earth?

28 Compare the luminosities of these two stars: star A has a surface temperature half that of star B, but its radius is forty times larger.

29 A star has eighty times the luminosity of our Sun and its surface temperature is twice that of the Sun. How much bigger is the star than our Sun?

16.2 (D2: Core) Stellar characteristics and stellar evolution

– a simple diagram that plots the luminosity versus the surface temperature of stars reveals unusually detailed patterns that help understand the inner workings of stars; stars follow well-defined patterns from the moment they are created to their eventual death

Stellar spectra

Nature of Science

Evidence provided by spectra

Astronomers have learnt a great deal about the universe from a limited range of evidence received from sources that are enormous distances from Earth. Apart from the location and luminosity of stars, a surprisingly large amount of information can be determined from close examination of the spectrum produced by a star.

- If we can measure the wavelength at which the emitted radiation has its maximum intensity, we can calculate the *surface temperature* of a star.
- If we can observe the absorption spectrum produced by the outer layers of a star, we can determine its *chemical composition*.
- If we compare the absorption spectrum received from a star to the spectrum from the same element observed on Earth, we can use the Doppler shift to determine the *velocity* of the star (or galaxy); this provides evidence for the expansion of the universe. (See section 16.3.)

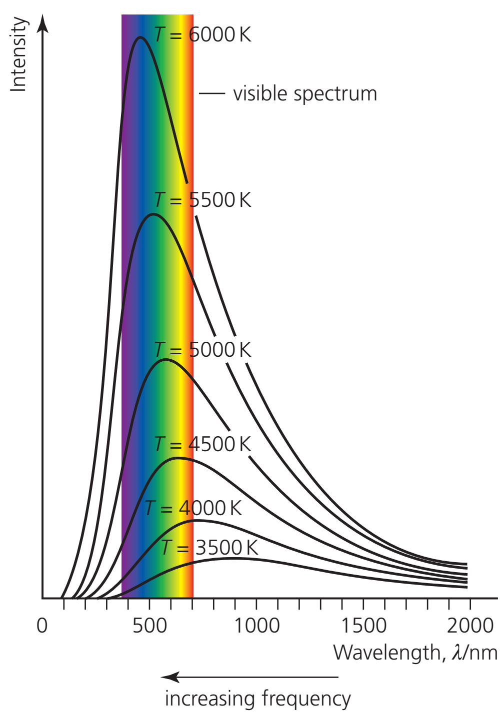


Figure 16.27 The black-body spectra emitted by stars with different surface temperatures

Surface temperature

Figure 16.27 shows that the spectra from stars with different surfaces temperatures differ, not only in overall intensity, but also in the spread of wavelengths emitted. This graph is similar to one previously seen in Chapter 8.

Wien's displacement law was also discussed in Chapter 8. It is an empirical law that represents how the wavelength at which the radiation intensity is highest becomes lower as the surface gets hotter:

$$\lambda_{max}T = 2.9 \times 10^{-3}\,\text{m K}$$

This equation is given in the *Physics data booklet*. It was also given in Chapter 8 in a slightly different form.

Worked example

4 What is the surface temperature of a star that emits radiation with a peak of intensity at a wavelength of 1.04×10^{-7} m?

$\lambda_{max}T = 2.9 \times 10^{-3}\,\text{m K}$

$(1.04 \times 10^{-7})T = 2.90 \times 10^{-3}$

$T = \dfrac{2.90 \times 10^{-3}}{1.04 \times 10^{-7}}$

$= 27\,900\,\text{K}$

30 If the surface temperature of the Sun is 5700 K, at what wavelength is the emitted radiation maximized? In what part of the visible spectrum is this wavelength?

31 A star emits radiation that has its maximum intensity at a wavelength of 6.5×10^{-7} m.
  a What is its surface temperature?
  b If it has a luminosity of 3.7×10^{29} W, what is the surface area of the star?
  c What is its radius?

32 **a** At what wavelength does a star with a surface temperature of 8200 K emit radiation with maximum intensity?
  b If this star has a radius of 1.8×10^{6} km, what is its luminosity?
  c If it is 36 ly from Earth, what is its apparent brightness?

33 The star Canopus has a luminosity of 5.8×10^{30} W and a radius of 4.5×10^{10} m. Use this data to estimate the wavelength at which it emits the most radiation.

34 Sketch graphs comparing the emission spectra from the stars Betelgeuse (3600 K) and Alkaid (20 000 K).

Utilizations

The classification of stars by the colours they emit

The surface temperatures of different stars may be as cool as a few thousand kelvin or as hot as 40 000+ K. Although Figure 16.27 only shows graphs for cooler stars, it should be clear that the range of visible colours present in the spectra from stars at different temperatures will be slightly different. For example, the light produced by a surface temperature of 4500 K has its highest intensity in the red end of the spectrum, whereas the light produced by 6000 K has more from the blue-violet end of the spectrum. Hotter stars are blue/white and cooler stars are yellow/red.

To observers on Earth this will be noticed as slight differences in colour and this has long been the way in which astronomers group and classify different stars. In general, cooler stars are slightly redder and hotter stars are slightly bluer.

Table 16.4 lists the eight spectral classes into which all visible stars are placed.

Table 16.4 Spectral classes, temperatures and colours

Spectral class	Surface temperature/K	Colour
O	30 000–50 000	blue
B	10 000–30 000	blue–white
A	7500–10 000	white
F	6000–7500	yellow–white
G	5000–6000	yellow
K	3500–5000	yellow–red (orange)
M	2000–3500	red

This apparently haphazard system of lettering stars according to their colour is an adaptation of an earlier alphabetical classification. A widely quoted mnemonic for remembering the order (from the hottest) is ‘Only Bad Astronomers Forget Generally Known Mnemonics’.

1 a What is the spectral class of our Sun?

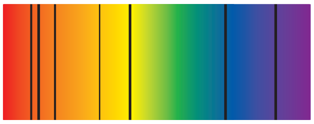
  b We often refer to the light from our Sun as ‘white’. Discuss whether or not this is an accurate description.

2 Two common types of star are called red giants and white dwarfs. What spectral class would you expect them to be?

3 What is the spectral class and colour of the star Alkaid (referred to in question 34)?

Chemical composition

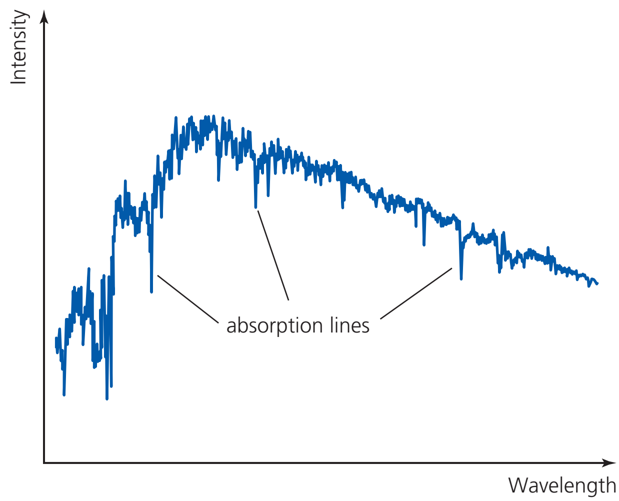
As the continuous black body spectrum emitted from a star passes through its cooler outer layers, some wavelengths will be absorbed by the atoms present. When the radiation is detected on Earth, an **absorption spectrum** (discussed in Chapter 7) will be observed.



■ **Figure 16.28** The absorption spectrum of helium

Because we know that every chemical element has its own unique spectrum, this information can be used to identify the elements present in the outer layers of a star. The element helium is the second most common in the universe (after hydrogen), but it was not detected on Earth until 1882. Fourteen years earlier, however, it had been identified as a new element in the Sun from its spectrum (see Figure 16.28).

Figure 16.29 shows a graphical representation of how a black-body spectrum emitted by the core of a star is modified by absorption of radiation in the outer layers.



■ **Figure 16.29** Graph of intensity against wavelength for a stellar absorption spectrum

ToK Link

The role of interpretation

The information revealed through spectra needs a trained mind to interpret it. What is the role of interpretation in gaining knowledge in the natural sciences? How does this differ from the role of interpretation in the other areas of knowledge?

Without detailed scientific knowledge and understanding, the observation of spectra would offer no obvious clues about the nature of stars. This is equally true of many other aspects of astronomy. Without scientific expertise, the information is of no use and may seem irrelevant, so that a non-expert would probably be unable to comment meaningfully. The same comments apply to advanced studies in other scientific disciplines.

■ The Hertzsprung–Russell (HR) diagram

The luminosity of a star depends on its surface temperature and its surface area ($L = \sigma AT^4$), so a star could be particularly luminous because it is hot or because it is big, or both.

In the early twentieth century two scientists, Hertzsprung and Russell, separately plotted similar diagrams of luminosity against temperature in order to determine whether or not there was any pattern in the way that the stars were distributed.

If there were no similarities in the composition of different stars, they could have many different combinations of temperature, size and luminosity. This would lead to them being randomly distributed on a luminosity–temperature diagram. But, more than about 90% of all stars are undergoing the same processes, fusing hydrogen into helium (as explained previously) and they are in a similar kind of equilibrium. These stars are called **main sequence stars** and their only essential difference is their mass.

Mass–luminosity relation for main sequence stars

Stars that are formed from *higher masses* will have stronger gravitational forces pulling them together. This will result in higher temperatures at their core and faster rates of nuclear fusion. More massive main sequence stars will have larger sizes, higher surface temperatures and *brighter luminosities*.

The relationship between luminosity, L, and mass, M, for main sequence stars is described by the following equation, which is given in the *Physics data booklet*. This is an approximate, generalized relationship and it may not be precise for any given star.

$$L \propto M^{3.5}$$

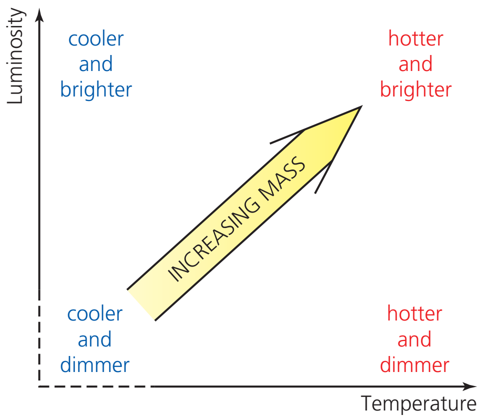


Figure 16.30 Linking mass, temperature and luminosity for main sequence stars

For example, if star A has twice the mass of star B, star A will have a luminosity approximately $2^{3.5}$ times greater than star B (≈ ×11). This means that the rate of nuclear fusion in the more massive star will be much higher and it will have a much shorter lifetime than a less massive star.

If the relationship between the mass and luminosity of a star is represented by this relationship, then we can be sure that it is a main sequence star.

Figure 16.30 suggests how we might expect a luminosity–temperature diagram to appear for main sequence stars of different masses.

Hertzsprung and Russell plotted data from a very large number of stars on luminosity–temperature diagrams, but the important HR diagram has two significant differences from Figure 16.30:

1 For historical reasons the temperature scale is reversed.
2 Because of the enormous differences in the luminosity of stars, the scale is logarithmic, rather than linear. (The temperature scale is also usually logarithmic.)

Figure 16.31 shows a large number of individual stars plotted on a Hertzsprung–Russell (HR) diagram, with all luminosities compared to the luminosity of our Sun ($L_\odot$). This figure also tries to give an impression of the colours of the stars.

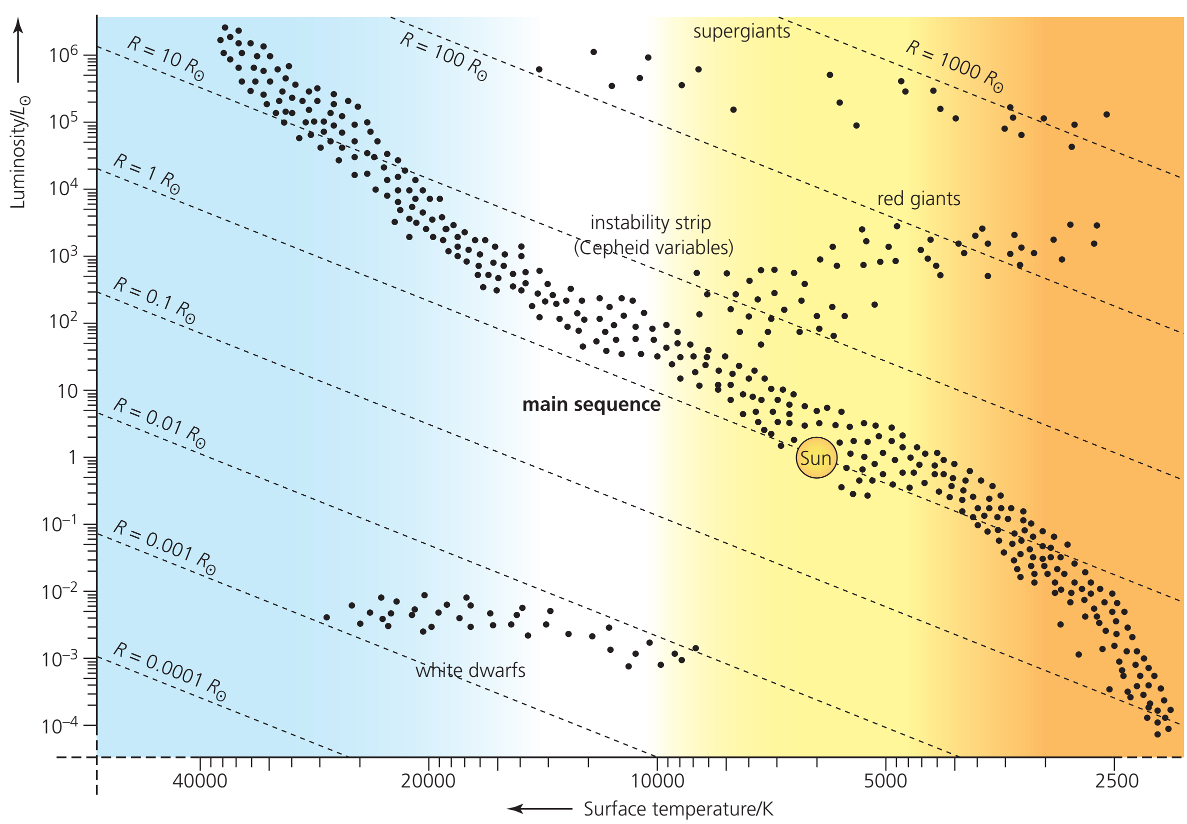


Figure 16.31 The Hertzsprung–Russell (HR) diagram

It should be apparent that the stars are *not* distributed at random in the HR diagram. The diagram can be used as a basis for classifying stars into certain types.

As already explained, most stars (about 90%) can be located in the central band, which runs from top left to bottom right in Figure 16.31. These are the main sequence stars. The 10% of stars which are *not* in the main sequence are important and they will be discussed in the next section. In general, we can say that any stars located vertically *above* the main sequence must be larger (than main sequence stars) in order to have higher luminosity at the same temperature. By similar reasoning, any stars vertically *below* the main sequence must be smaller than main sequence stars of the same temperature.

By considering $L = \sigma AT^4$ and $A = 4\pi R^2$ (leading to $L = \sigma 4\pi R^2 T^4$), it is possible to draw the lines of constant radius on the HR diagram (as shown in Figure 16.31).

Worked example

5 Use the HR diagram in Figure 16.31 to predict the surface temperature of a main sequence star that has ten times the radius of our Sun.

The band of main sequence stars crosses the $R = 10R_{\odot}$ line at about 30 000 K.

35 The radius of the Sun is 7×10^8 m and its surface temperature is 5800 K. Estimate the radius of a main sequence star that has a surface temperature five times that of our Sun.

36 The luminosities of two main sequence stars are in the ratio 10 : 1. What is the ratio of their masses?

37 **a** A star has a mass five times heavier than the mass of our Sun. Estimate its luminosity.
b What assumption did you make?
c Which star will have the longer lifetime?
d Use the HR diagram in Figure 16.31 to estimate the surface temperature of the star.
e Approximately how many times bigger is this star than our Sun?

38 Use the HR diagram to estimate the difference in diameter of a white dwarf star and a supergiant star if they both have the same surface temperature.

Utilizations

Using the HR diagram to estimate the distance to stars

Using Wien's law the surface temperature of a star can be determined from its spectrum and, assuming that it is a main sequence star, it is a relatively simple matter to use the HR diagram to estimate its luminosity, L, and hence calculate its distance, d, away from Earth using $b = L/4\pi d^2$ and a measurement of its apparent brightness, b.

This method assumes that the radiation, which has travelled vast distances from very distant stars, has not been altered in any way by the journey. For example, if any radiation is absorbed or scattered during the journey, the value of apparent brightness used in calculations will be less than it would have been without the absorption or scattering, leading to an over-estimate of the distance to the star.

Because the exact position of the star on the HR diagram may not be known with accuracy and because of unknown amounts of scattering/absorption, there is a significant uncertainty in this method of determining stellar distances.

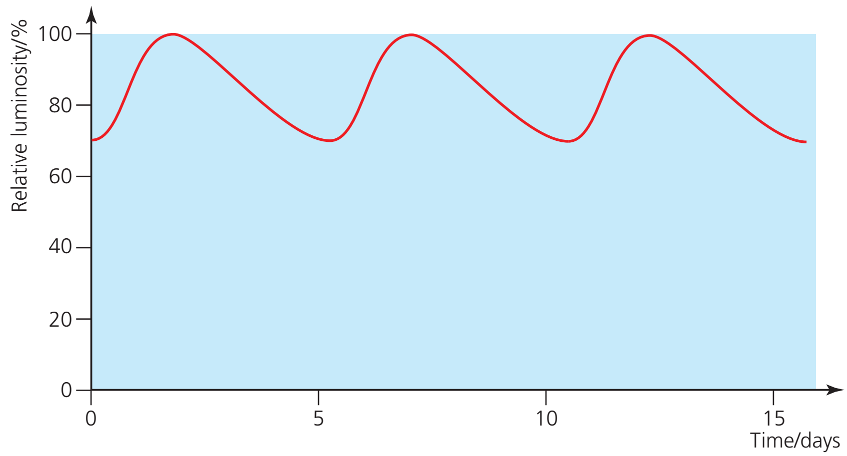
In fact, the use of this method (misleadingly called *spectroscopic parallax*) is mostly confined to our galaxy. The majority of stars are obviously further away in other galaxies, so to determine the distances to those galaxies we need other methods.

1 Estimate the distance from Earth (in pc) of a main sequence star that has a surface temperature of 7500 K and an apparent brightness of 4.6×10^{-13} W m^{-2}.

Types of star that are *not* on the main sequence

Cepheid variables

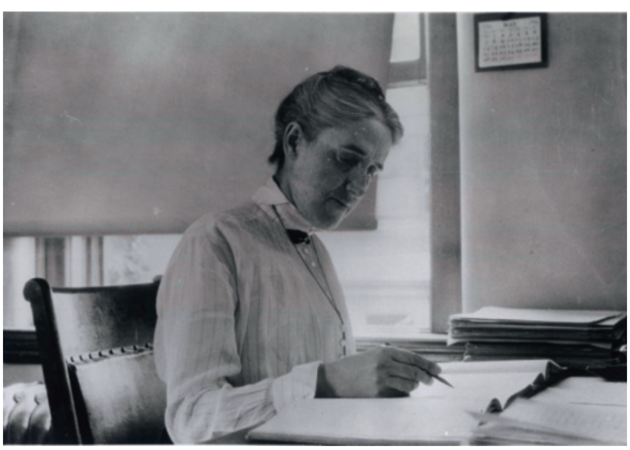
The **instability strip** on the HR diagram contains a number of different kinds of pulsating stars. Such stars have moved off the main sequence and are oscillating under the effects of the competing gravitational pressure, and radiation and thermal pressures. The most important stars in the instability strip are known as **Cepheid variables**.



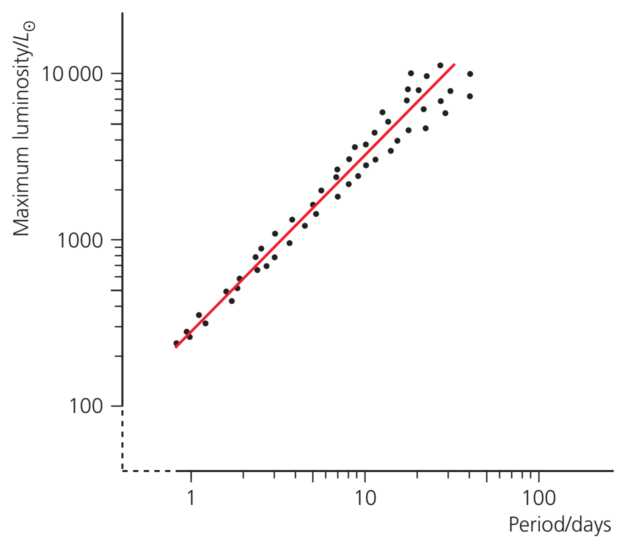
■ **Figure 16.32** Variation in luminosity of a Cepheid variable star

In a Cepheid variable the outer layers regularly expand and contract (typically by 30%) with surprisingly short periods (in astronomical terms), resulting in very regular and precise variations in luminosity (see Figure 16.32) – a typical period is a few weeks. If the surface temperature remains approximately constant then the increasing luminosity is explained by the larger surface area when the star expands.

Although Cepheid variables are not common stars, they are important and their behaviour has been studied in great depth. From observations of those Cepheid variables that are relatively close to Earth, it is known that there is a precise relationship between the time period of their pulses of luminosity (and hence their received apparent brightness on Earth) and the peak value of that luminosity. This was first discovered by Henrietta Leavitt (Figure 16.33) in 1908. This relationship is called the **period–luminosity relationship** and it is commonly presented in graphical form, as shown in Figure 16.34; the longer the period, the higher the luminosity of the Cepheid variable.



■ **Figure 16.33** Henrietta Leavitt discovered the periodicity of Cepheid variables in 1908.



■ **Figure 16.34** Period–luminosity relationship for a Cepheid variable

Note the logarithmic nature of both the scales on the graph in Figure 16.34. This is necessary to include the enormous range of values involved.

Using Cepheid variables to determine astronomical distances

If the luminosity of a Cepheid variable can be determined from its period, then its distance from Earth, d, can be calculated if its apparent brightness, b, is measured. Again we can use the equation:

$$b = \frac{L}{4\pi d^2}$$

Inaccuracies in the data involved mean that these estimates of distance, especially to the furthest galaxies, are uncertain. This uncertainty is a significant problem when estimating the age of the universe.

Astronomers often describe Cepheid variables as '**standard candles**' because if their distance from Earth is determined, it can then be taken as a good indication of the distance of the whole galaxy from Earth (since that distance is very much longer than the distances between stars within the galaxy, see Figure 16.15).

Worked example

6 A Cepheid variable in a distant galaxy is observed to vary in apparent brightness with a period of 8.0 days. If its maximum apparent brightness is $1.92 \times 10^{-9}\,\mathrm{W\,m^{-2}}$, how far away is the galaxy?

From a luminosity–period graph (similar to Figure 16.34), the maximum luminosity can be determined to be 2500 times the luminosity of the Sun.

$$\text{luminosity} = 2500 \times (3.8 \times 10^{26}\,\mathrm{W}) = 9.5 \times 10^{29}\,\mathrm{W}$$

$$b = \frac{L}{4\pi d^2}$$

$$1.92 \times 10^{-9} = \frac{9.5 \times 10^{29}}{4\pi d^2}$$

$$d = 6.3 \times 10^{18}\,\mathrm{m}$$

39 **a** If a Cepheid variable has a period of 15 days, what is its approximate maximum luminosity?
b If the star is 3.3 Mpc from Earth, what is the maximum observed apparent brightness?

40 A Cepheid variable is 15 kpc from Earth and is observed to have a maximum apparent brightness of $8.7 \times 10^{-13}\,\mathrm{W\,m^{-2}}$.
a Calculate the maximum luminosity of this star.
b Use Figure 16.34 to estimate the time period of the variation in the star's luminosity.

41 For very large distances astronomers may use supernovae (rather than Cepheids) as 'standard candles'. Suggest a property of supernovae which might be necessary for this.

What happens to a star when the supply of hydrogen is reduced?

Over a long period of time, the amount of hydrogen in the core of a star gets significantly less, so that eventually the outwards pressure is reduced and becomes smaller than the inwards gravitational pressure. This occurs when the mass of the core is about 12% of the star's total mass and there is still plenty of hydrogen remaining in the outer layers of the star. The star begins to contract and gravitational energy is again transferred to kinetic energy of the particles (the temperature of the core rises even higher than before – to 10^8 K and higher). This forces the outer layers of the star to expand and consequently cool.

At the higher temperatures in the core (in all but the very smallest stars) it is now possible for helium to fuse together to form carbon and possibly some larger nuclei, releasing more energy so that the star becomes more luminous. So, the star now has a hotter core but it has become larger and cooler on the surface. Its colour changes and it is now known as a **red giant** (or, if it is very large, a **red supergiant**). At this point it will leave the main sequence part of the HR diagram. All main sequence stars follow predictable patterns but the heavier the mass of a star, the higher the gravitational potential energy and the higher the temperature when it begins to collapse. We can identify three different outcomes, depending only on the mass of the original star: white dwarf, neutron star or black hole.

Red giants, white dwarfs, neutron stars and black holes

Red giants

As explained above, most stars will become red giants (or red supergiants) at the end of their time on the main sequence. They are described as *giant* stars because they have expanded considerably from their original size and, in doing so, their surfaces have cooled and therefore changed in colour to slightly red.

White dwarfs

After nuclear fusion in the core finishes, if the mass of a red giant star is less than a certain limit (about eight solar masses), the energy released as the core contracts forces the outer layers of the star to be ejected in what is known as a **planetary nebula**. (Be careful with this name – it is misleading because it has nothing to do with planets.) The core of the star that is left behind has a much reduced mass and is described as a *dwarf star*.

A process known as **electron degeneracy pressure** (electrons acting like a gas) prevents the star collapsing further so this kind of star can remain stable for a long time. Such stars are known as **white dwarfs** because they have low luminosities (they cannot be seen without a telescope), but their surface temperatures are relatively high ($L = \sigma AT^4$).

Studying the patterns we see in other stars helps us to understand our own Sun and what will happen to it in the future. It is about halfway through its time as a main sequence star and it will become a red giant in about seven billion years, after which it will become a white dwarf.

Neutron stars or black holes

Red giants with original masses greater than about eight solar masses are known as red supergiants and they do *not* evolve into white dwarfs. The electron degeneracy pressure is insufficient to resist the gravitational forces and the gravitational potential energy released is so high that there are dramatic changes in the core that result in an enormous explosion called a **supernova**. Here again, the result depends on the mass involved. If the original mass of the star was between 8 and 20 solar masses, the remaining core after the supernova will form a **neutron star**. If the mass was greater, a **black hole** is formed.

Neutron stars

After a supernova of a red supergiant, if the remaining core has a mass between approximately 1.4 and 3 solar masses it will contract to a neutron star. Neutron stars are extremely dense ($\rho \approx 5 \times 10^{17}\,\mathrm{kg\,m^{-3}}$), but resist further compression due to a process called **neutron degeneracy pressure**.

Black holes

If the remnant after a supernova has a remaining mass of more than approximately three solar masses, neutron degeneracy pressure is insufficient to resist further collapse. The result is a black hole, which produces such strong gravitational forces that not even the fastest particles, photons (for example, light) can escape.

Black holes cannot be observed directly, but they can be detected by their interaction with other matter and radiation. For example X-rays are produced when superheated matter spirals towards a black hole. NASA's Chandra Observatory was designed to search for black holes.

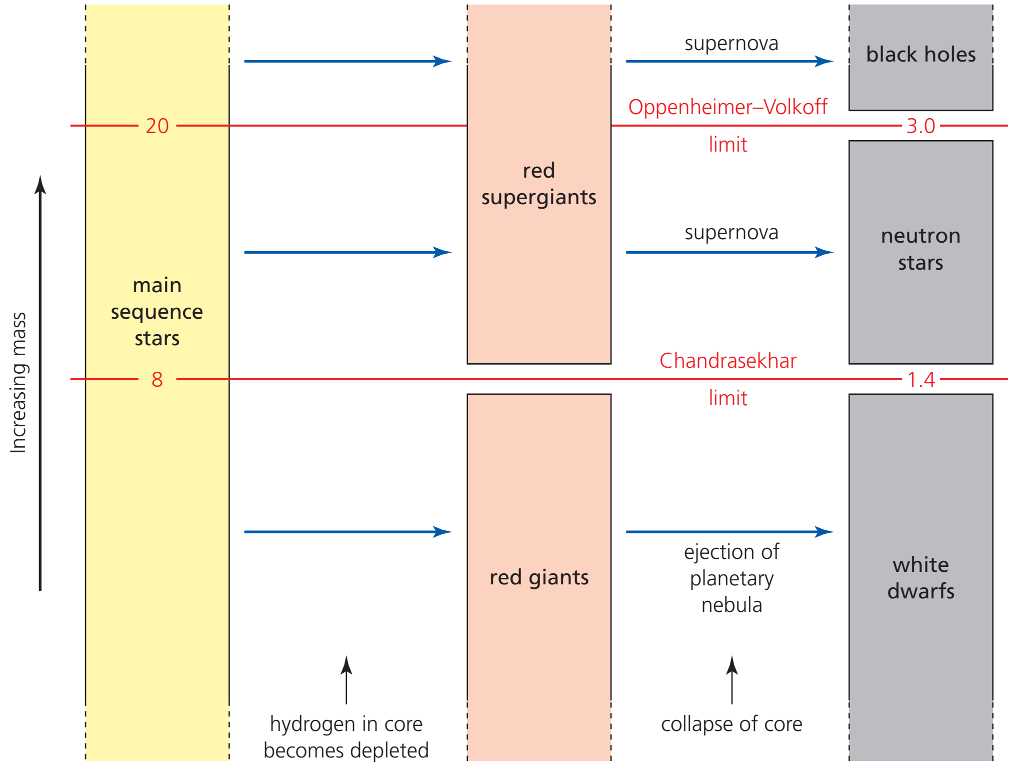
The first black hole was confirmed in 1971. Astronomers believe that our own galaxy, the Milky Way, has a supermassive black hole near its centre.

Chandrasekhar and Oppenheimer–Volkoff limits

The mass limits mentioned above are known by the names of prominent astronomers:

- The Chandrasekhar limit is the maximum mass of a white dwarf star (= 1.4 × solar mass).
- The Oppenheimer–Volkoff limit is the maximum mass of a neutron star (≈ 3 × solar mass).

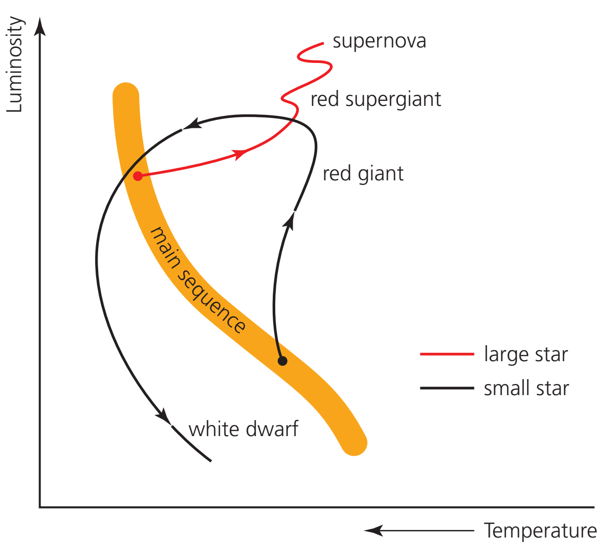
Figure 16.35 represents these limits in a simplified chart of stellar evolution.



■ **Figure 16.35** Evolution of stars of different masses (the numbers shown represent the approximate mass limits of the stars as multiples of the current mass of the Sun)

Stellar evolution on HR diagrams

When a main sequence star expands to a red giant, or a red supergiant, its luminosity and surface temperature change and this, and subsequent changes over time, can be tracked on an HR diagram. It is known as a star's **evolutionary path**. Typical evolutionary paths of low-mass and high-mass stars are shown in Figure 16.36.



■ **Figure 16.36** Evolutionary paths of stars after they leave the main sequence

42 Explain why neutron stars and black holes cannot be placed on a HR diagram.

43 Use the internet to learn more about electron and neutron degeneracy.

44 Suggest how a black hole can be detected, even though it cannot be seen.

45 Explain why the Chandrasekhar limit is such an important number in astronomy.

46 Explain why some supernovae result in neutron stars, while others result in black holes.

16.3 (D3: Core) Cosmology *– the Hot Big Bang model is a theory that describes the origin and expansion of the universe and is supported by extensive experimental evidence*

Cosmology is the study of the universe – how it began, how it developed and what will happen to it in the future. It has always been the nature of many individuals, societies and cultures to wonder what lies beyond the Earth. The fact that the Sun and the stars appear to revolve around the Earth led early civilizations, understandably but wrongly, to believe that a stationary Earth was the centre of everything. This belief was often fundamental to their religions. Indeed, even today some people still believe from their everyday observations, or their religious beliefs, that the Sun orbits around the Earth rather than the other way around.

Nature of Science

Models of the universe

In the **Newtonian model of the universe**, the Earth, the Sun and the planets were just tiny parts of an infinitely large and unchanging (static) universe that had always been the way it is, and always would be the same. In this model, the universe, on the large scale, is more or less the same everywhere. In other words it is uniform with stars approximately evenly distributed. Newton reasoned that unless all of these assumptions (sometimes called postulates) were valid, then gravitational forces would be unbalanced, resulting in the movement of stars (which were thought to be stationary at that time).

But there is a big problem with this Newtonian model of the universe, one that many astronomers soon realized. If the universe is infinite and contains an infinite number of stars, there should be no such thing as a dark sky at night, because light from the stars should be arriving from all directions at all times. (This is known as *Olbers's paradox*, named after one of the leading astronomers of the nineteenth century, Heinrich Wilhelm Olbers. A paradox is an apparently true statement that seems to contradict itself. 'I always lie' is a widely quoted paradoxical statement.)

It was clear that either the reasoning given above and/or the Newtonian model of the universe needed changing or rejecting. Since the mid to late 1960s, the **Big Bang model** of the universe has been widely accepted by astronomers and has solved Olbers's paradox.

Additional Perspectives

'The shoulders of giants'

Nicolas Copernicus, a Polish astronomer and cleric (Figure 16.37), is considered by many to be the founder of modern astronomy. In 1530 he published a famous paper stating that the Sun was the centre of the universe and that the Earth, stars and planets orbited around it (a *heliocentric model*). At that time, and for many years afterwards, these views directly challenged 'scientific', philosophical and religious beliefs. It was then generally believed that the Earth was at the centre of everything (a *geocentric model*). That profound and widespread belief dated all the way back to Ptolemy, Aristotle and others nearly 2000 years earlier. It should be noted, however, that Aristrachus in Ancient Greece is generally credited with being the first well-known person to propose a heliocentric model.

Figure 16.37 Copernicus

More than 100 years after the birth of Copernicus, and still before the invention of the telescope, an eccentric Danish nobleman, Tycho Brahe, became famous for the vast number of very accurate observations he made on the motions of the five visible planets. He worked mostly at an elaborate observatory on an island in his own country, but went to Prague a few years before his death in 1601.

Johannes Kepler was Brahe's assistant and later, after his death, he worked on Brahe's considerable, but unexplained, data to produce his three famous laws of planetary motion.

At about the same time in Italy, the astronomer Giordano Bruno had taken the heliocentric model further with revolutionary suggestions that the universe was infinite and that the Sun was not at the centre. The Sun was, Bruno suggested, similar in nature to the other stars. He was burned at the stake in 1600 for these beliefs – killed for his, so-called, heresy. About 30 years later, one of the greatest scientific thinkers of all time, Galileo Galilei, was placed on trial by the Roman Catholic Church under similar charges. Many years earlier he had used the newly invented telescope to observe the moons of Jupiter and had reasoned that the Earth orbited the Sun in a similar way, as had been proposed by Copernicus. Under pressure, he publicly renounced these beliefs and was allowed to live the rest of his life under house arrest. All this has provided the subject of many books, plays and movies.

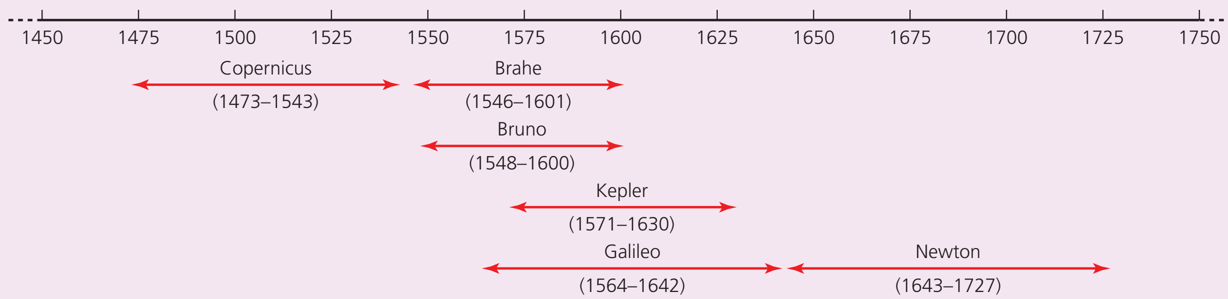


Figure 16.38 Time line of some famous early astronomers

Although Kepler had found an accurate way to describe the motion of the planets mathematically, an explanation was not produced until about 80 years later (Figure 16.38) when Newton was able to use the motion of the planets and the Moon as evidence for his newly developed theory of universal gravitation (Chapter 6).

1 Many people would place Newton and Galileo in a list of the top five scientists of all time but, to a certain extent, that is just a matter of opinion.

   a Why do you think Newton and Galileo are so highly respected?

   b What criteria would you consider when trying to decide if a scientist was 'great'?

2 Research the origins of the quotation 'the shoulders of giants', which forms the title of this Additional Perspectives section.

The Big Bang model

The Big Bang model is the current theory about how the universe began at one precise moment in time, 13.8 billion years ago. Before looking more closely at this theory, we will first consider the evidence for an **expanding universe**.

Using spectra to determine the velocity of stars and galaxies

If a source of light is not stationary but moving towards or away from an observer, there will be a *shift* (a very slight change) in all the wavelengths and frequencies of the light received. This is similar to the Doppler effect in the sound received from moving vehicles – as a police car approaches, we hear a higher-pitched sound (shorter wavelength) than when it is moving away from us (Figure 16.39).

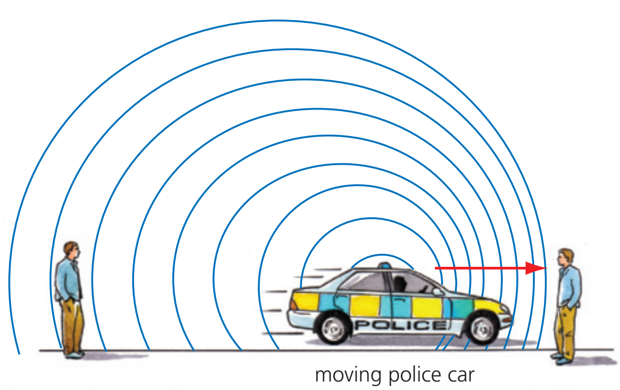


Figure 16.39 The Doppler effect for sound

In the case of light waves, the shift is very small and is usually undetectable unless a source is moving *very* quickly, such as a star or galaxy. In order to detect a shift for light we need to examine the line spectrum from the source and compare it to the line spectrum produced by the same element(s) on Earth.

We find that the *pattern* of the absorption lines on a spectrum is the same, but all the lines are very slightly shifted from the positions they would occupy if there were no motion of the source relative to the observer. Careful observation of the line spectrum received from a star (Figure 16.40) can be used to calculate the velocity of the star. In example A in Figure 16.40, all the absorption lines have been shifted towards lower frequencies and this is commonly described as a **red-shift**. A red-shift occurs in the radiation received from a star or galaxy that is moving away (*receding*) from the Earth. If a star or galaxy is moving towards Earth, then the shift will be towards higher frequencies and is called a **blue-shift**, as shown in example B. (This is unusual for galaxies.)

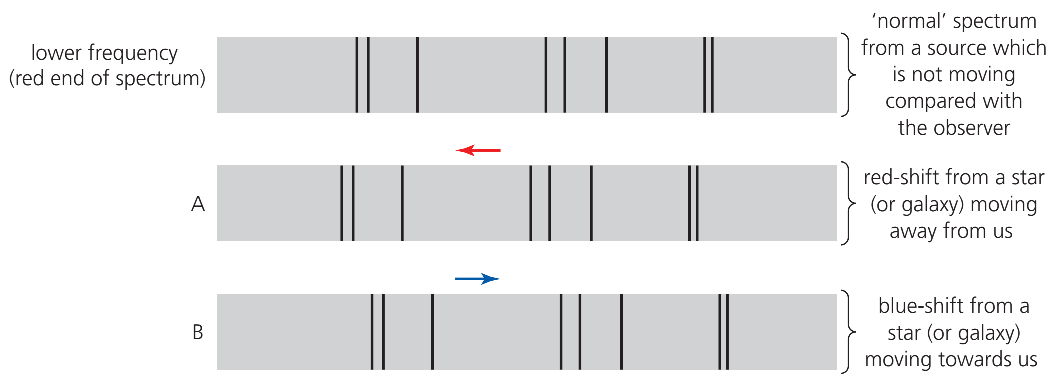


Figure 16.40 Red- and blue-shifts

For a given wavelength, λ_0, in a line spectrum, the shift (difference) in wavelength, $\Delta\lambda$, received from a fast-moving star or galaxy is proportional to its speed towards or away from the observer. The ratio of $\Delta\lambda/\lambda_0$ is the numerical representation of red-shift and is given the symbol z. For a speed v, which is significantly slower than the speed of light, c, the red-shift, z, is given by the equation

$$z = \frac{\Delta\lambda}{\lambda_0} \approx \frac{v}{c}$$

This equation is given in the *Physics data booklet* and is similar to the equation used in Chapter 9. Because it is a ratio, red-shift does not have a unit.

If we can measure the red shift for a known wavelength, we can calculate the recession speed of the source (star or galaxy). Basic calculations like these assume that the source of light is moving in a straight line directly away from the Earth. As we shall see, this *is* a reasonable assumption, although it is not necessarily perfectly true.

Worked example

7 A line in the hydrogen spectrum has a wavelength of 4.34×10^{-7} m. When detected on Earth from a distant galaxy, the same line has a wavelength of 4.76×10^{-7} m. What is the speed of the galaxy?

$\Delta\lambda = (4.76 \times 10^{-7}) - (4.34 \times 10^{-7}) = 4.2 \times 10^{-8}$ m

$$z = \frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$$

$$\frac{4.2 \times 10^{-8}}{4.34 \times 10^{-7}} = \frac{v}{3.00 \times 10^{8}}$$

$v = 2.90 \times 10^{7}\ \text{m s}^{-1}$

Because the shift is to a longer wavelength (a red-shift), we know that the motion of the galaxy is *away* from Earth. We say that the galaxy is *receding* from Earth. When the light from a large number of galaxies is studied, we find that *nearly all* the galaxies are receding from Earth and each other. This can only mean that the universe is expanding.

47 What is the red-shift of a galaxy with a recession speed of:
  a $2.2 \times 10^6\,\mathrm{m\,s^{-1}}$
  b 10% of the speed of light?

48 What is the recession speed of a galaxy ($\mathrm{km\,h^{-1}}$) if radiation of original wavelength $6.5 \times 10^{-7}\,\mathrm{m}$ undergoes a red-shift of $3.7 \times 10^{-8}\,\mathrm{m}$?

49 A star receding at a velocity of $9.2 \times 10^3\,\mathrm{km\,s^{-1}}$ emits radiation of wavelength 410 nm. What is the extent of the red-shift of this radiation when it is received on Earth and what is its received wavelength?

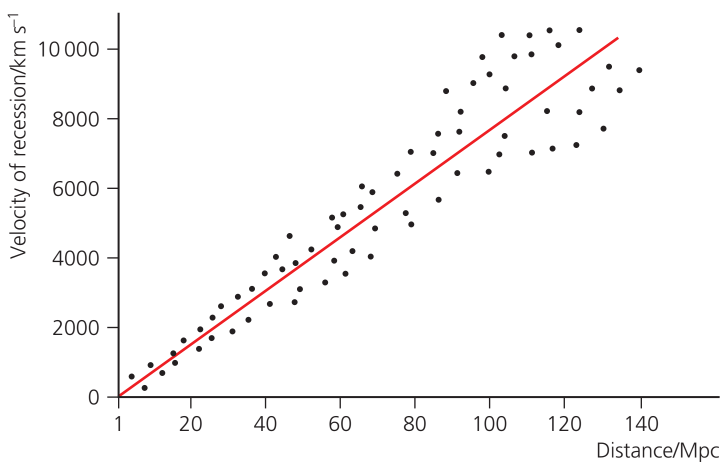
50 Hydrogen emits radiation of frequency $6.17 \times 10^{16}\,\mathrm{Hz}$. What frequency will be detected on Earth from a galaxy moving away at $1.47 \times 10^7\,\mathrm{m\,s^{-1}}$?

51 Only a very tiny percentage of galaxies are moving towards us. Research the blue-shift of the Andromeda galaxy, one of the galaxies in the Local group.

Hubble's law

In the mid-1920s, the American astronomer Edwin Hubble compared information about the **recession speeds** of relatively nearby galaxies (obtained from the red-shift of the light received) with the distances of the galaxies from Earth that were determined by using Cepheid variables within the galaxies. By 1929 Hubble had gathered enough data to publish a famous graph of his results for Cepheids within distances of a few Mpc from Earth. Figure 16.41 includes more results and for greater distances.

Figure 16.41 Variation of recession speeds of galaxies with their distances from Earth



Even today there are significant uncertainties in the data represented on this graph (although error bars are not shown on Figure 16.41). These uncertainties are mainly because the precise measurement of distances to galaxies is difficult, but also because galaxies move within their clusters. Nevertheless, the general trend is very clear and was first expressed in **Hubble's law**:

The current velocity of recession, v, of a galaxy is proportional to its distance, d (from Earth).

This can be written as:

$$v = H_0 d$$

This equation is listed in the *Physics data booklet*.

H_0 is the gradient of the graph and is known as the **Hubble constant**. Because of the uncertainties in the points on the graph, the Hubble constant is not known accurately, despite repeated measurements. The currently accepted value is about 70 km s^{-1} Mpc^{-1} (this unit is more widely used than the SI unit, s^{-1}). However, different determinations of the Hubble constant have shown surprising variations. Hubble's 'constant' is believed to be a constant for everywhere in the universe at this time, but over the course of billions of years its value has changed.

Worked example

8 Estimate the gradient of the graph in Figure 16.41 and compare it with the value given for the Hubble constant in the previous paragraph.

$$\text{gradient, } H_0 = \frac{v}{d} = \frac{9000}{120}$$
$$= 75\,\text{km s}^{-1}\,\text{Mpc}^{-1}$$

This value varies by 7% from the value quoted earlier, but neither figure includes any assessment of uncertainty, so it is possible that they are consistent with each other.

Hubble's law can be applied to the radiation received from all galaxies that are moving free of significant 'local' gravitational forces from other galaxies. That is, the law can be used for isolated galaxies or clusters (considered as one object), but is less accurate for individual galaxies moving within a cluster because the resultant velocity of an individual galaxy is the combination of its velocity with respect to the cluster and the recession velocity of the cluster as a whole. A few galaxies even have a resultant velocity *towards* the Earth at this time and radiation received from such galaxies is blue-shifted.

The use of the Hubble constant with the recessional speeds of distant galaxies provides astronomers with another way of calculating the distance to galaxies which are too far away to use alternative methods.

More about the Big Bang

The conclusion from Hubble's observations can only be that the universe is expanding because (almost) all galaxies are moving away from the Earth.

It is important to realize that this is true for galaxies observed in *all* directions and *would also be true for any observer viewing galaxies from any other location in the universe*. Almost all galaxies are moving away from all other galaxies. Our position on Earth is not unique, or special, and we are not at the 'centre' of the universe – the universe does not have a centre.

Calculations confirm that the further away a galaxy is, the faster it is receding. This simple conclusion has very important implications: the more distant galaxies are further away *because* they travelled faster from a common origin. Observations suggest that all the material that now forms stars and galaxies originated at the same place at the same time. An expanding model of the universe had been proposed a few years earlier by Georges Lemaître and this was developed in the 1940s into what is now called the Big Bang model.

If radiation from a star or galaxy is observed to have a blue-shift, it is because it is moving towards Earth. This is not evidence against the Big Bang model because such an object is moving within a gravitationally bound system (a galaxy, a cluster of galaxies or a binary star system) and at the time of observation it was moving towards the Earth faster than the system as a whole was moving away. For example, our neighbouring galaxy, Andromeda, exhibits a small blue-shift – it is moving towards us as part of its motion within our local group of galaxies, which is a gravitationally bound system.

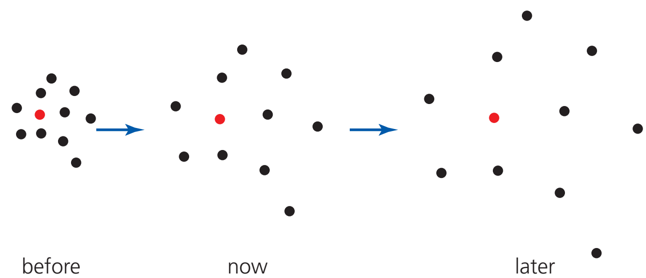
In the Big Bang model, the universe was created at a point about 13.8 billion (1.38×10^{10}) years ago. At that time it was incredibly dense and hot, and ever since it has been expanding and cooling down.

The expansion of the universe is the expansion of space itself and it should not be imagined as being similar to an explosion, with fragments flying into an existing space (void), like a bomb exploding.

It may be helpful to visualize the expansion of space using marks on a very large rubber sheet to represent galaxies. (Imagine that the sheet is so large that the edges cannot be seen.) If the sheet is stretched equally in all directions, all the marks move apart from each other. Of course, a model like this is limited to only two dimensions (Figure 16.42).

The red-shift of light should be seen as a consequence of the expansion of space rather than being due to the movement of galaxies through a fixed space.

Figure 16.42 An expanding universe



It is very tempting to ask 'what happened before the Big Bang?' In one sense, this question may have no answer because the human concept of time is all about change – and before the Big Bang there was nothing to change.

The Big Bang should be considered as the creation of *everything* in our universe – matter, space and time.

Nature of Science

Simplicity

Expressed in basic terms, the Big Bang model of the universe is elegant in its simplicity. In judging scientific theories and models, as well as other human endeavours, simplicity is often (but not always) an admirable aim. This has been expressed in what is known as **Occam's razor** – if you need to choose between two or more possible theories, select the one with the fewest assumptions. Until you know that a more complicated theory is preferable, simplicity may be the best criterion to judge between opposing models.

More complicated theories are more difficult to test and, if they are found to be in doubt, it is often possible to add another layer of (unproven) theory to retain some of their credibility.

Age of the universe

We can make an estimate of the time since the Big Bang (the age of the universe) using Hubble's constant ($70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$).

Because time, t = distance, d/velocity, v and $v = H_0 d$, we can write:

$$T \approx \frac{1}{H_0}$$

where T is the approximate age of the universe, often called **Hubble time**. This equation is given in the *Physics data booklet*.

Calculated using this equation, T can be considered to be an approximate and upper limit to the age of the universe for the following reasons.

- It is not sensible to assume that the recession speed of the galaxies has always been the same. It is reasonable to assume that the speed of galaxies was fastest in the past when they were closer together and that they are now slowing down because of gravitational attraction. (We now know that this is not true: discussed in more detail later.)
- We do not know that the expansion started at the same time as the Big Bang.
- The uncertainty in the Hubble constant is significant.

We would prefer the time to be in SI units, and in SI units Hubble's constant becomes:

$$\frac{70 \times 10^3}{3.26 \times 10^6 \times 9.46 \times 10^{15}} = 2.27 \times 10^{-18}\,\text{s}$$

so that

$$T = \frac{1}{H_0} = \frac{1}{2.27 \times 10^{-18}} = 4.4 \times 10^{17}\,\text{s (or } 1.4 \times 10^{10} \text{ years).}$$

52 What is the recession speed (km s^{-1}) of a galaxy that is 75 Mpc from Earth?

53 How far away is a galaxy travelling at 1% of the speed of light?

54 Galaxy A is a distance of 76 Mpc from Earth and is receding at a velocity of $5500\,\text{km s}^{-1}$. Another galaxy, B, is receding at $7300\,\text{km s}^{-1}$. Without using a value for H_0, estimate the distance to galaxy B.

55 A spectral line of normal wavelength 3.9×10^{-7} m is shifted to 4.4×10^{-7} m when it is received from a certain distant galaxy.
  a How fast is the galaxy receding?
  b How far away is it?

Cosmic microwave background (CMB) radiation

When it was first proposed seriously in the late 1940s, many astronomers were not convinced by the Big Bang model. (They mostly preferred what was then known as the Steady State Theory of an unchanging universe.) However, the discovery in 1964 by Penzias and Wilson of **cosmic microwave background (CMB) radiation** provided the evidence that confirmed the Big Bang model for most astronomers. Penzias and Wilson discovered that low-level microwave radiation can be detected coming (almost) equally from all directions (it is **isotropic**), rather than from a specific source. (Later, important tiny variations were discovered in the CMB, a discovery that has vital implications for understanding the non-uniform structure of the universe and the formation of galaxies (Figure 16.43.)

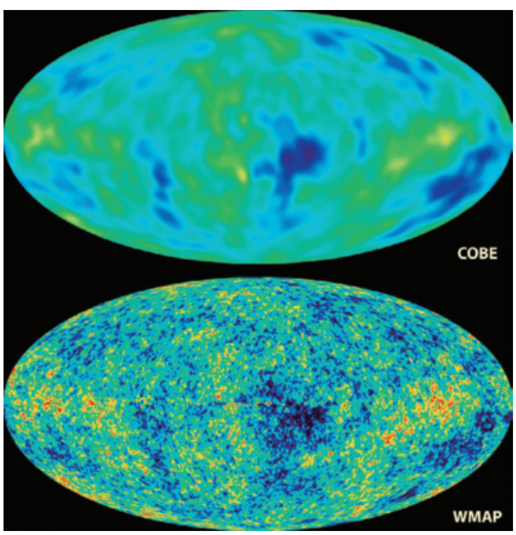


Figure 16.43 'Ripples in Space'; a map of the whole sky at microwave wavelengths showing the *very small* variations (1 part in 100 000) in the CMB radiation – firstly from COBE satellite and, later, in more detail from the WMAP satellite

Cosmic background radiation has been a major area of astronomical research for many years, including by the Cosmic Background Explorer (COBE) satellite. A very large amount of data has been collected and analysed by astronomers from many different countries.

We have seen before that everything emits electromagnetic radiation and that the range of wavelengths emitted depends on temperature. The Big Bang model predicts that the universe was incredibly hot at the beginning and has since been cooling down as it expands, so that the average temperature of the universe should now be about 2.76 K.

Figure 16.44 shows the black-body radiation spectrum emitted from matter at 2.76 K. When this isotropic radiation was discovered by Penzias and Wilson coming (almost) equally from all directions, the *Hot* Big Bang model was confirmed.

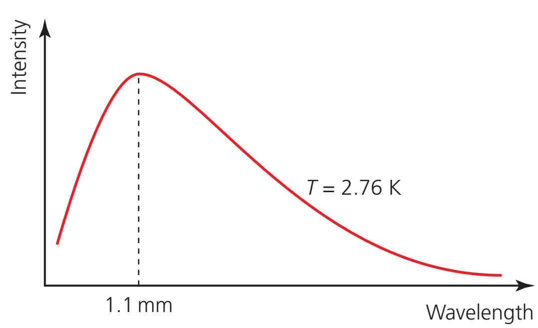


Figure 16.44 Spectral distribution for a temperature of 2.76 K

Wien's law (for black bodies) can be used to confirm the peak wavelength associated with this temperature:

$$\lambda_{max}T = 2.9 \times 10^{-3}\,\text{m K}$$

$$\lambda_{max} = \frac{2.9 \times 10^{-3}}{2.76} = 1.1 \times 10^{-3}\,\text{m}$$

An alternative (and equivalent) interpretation of CMB radiation is that the shorter wavelengths emitted when the universe was hotter have stretched out because of the expansion of space.

The observable universe

After the development of the Big Bang model it seemed that the universe could be finite, with a finite number of stars, each having a finite lifetime, thus limiting the amount of radiation that could reach Earth. More importantly, even if the universe is infinite, it was now known to have a definite age, which means that the universe that is observable to us is limited by the distance that light can travel in the time since the Big Bang.

The universe that we can (in theory) observe from Earth is a sphere around us of radius 4.6×10^{10} ly. This is known as the **observable universe** or the visible universe. (This distance is longer than 1.4×10^{10} ly because space has expanded since the Big Bang.) If there is anything further away, we cannot detect it because the radiation has not had enough time to reach us.

56 Summarize the two major discoveries that support the Big Bang model of the universe.

57 Astronomers look for 'shifts' in spectra as evidence for an expanding universe. The spectrum of which element is most commonly used, and why?

58 Draw a diagram to help explain why the light from some galaxies may be blue-shifted.

59 How will the average temperature of the universe change in the future if:
a the universe continues to expand
b the universe begins to contract?

The accelerating universe and red-shift (z)

What happens to the universe in the future is obviously dependent on the rate at which it is expanding and whether or not the expansion will continue indefinitely. Previously it was believed that the receding galaxies were simply losing kinetic energy and gaining gravitational potential energy, like objects projected away from the Earth, and that the fate of the universe depended on their initial speeds and the mass in the universe. But in recent years it has been discovered that the rate of expansion of the universe is *not* decreasing, but *increasing*. This is discussed in more detail in Section 16.5 (Additional Higher).

The evidence for the accelerating expansion of the universe comes from the observation of supernovae. When a certain kind (Type 1a) of supernova occurs, the energy released is always about the same and it is well-known to astronomers. This information can be used to determine the distance to such events using $b = L/4\pi d^2$. This means that such supernovae can be used as 'standard candles' for determining the distances to distant galaxies. Work on this topic by three physicists, Perlmutter, Riess and Schmidt (Figure 16.45), was jointly awarded the Nobel prize for physics in 2011.

Figure 16.45 Adam Riess, Saul Perlmutter and Brian Schmidt

The red-shifts from Type 1a supernovae have been found to be bigger than previously expected for stars at that distance away, strongly suggesting an 'accelerating universe'. This, of course, requires a new explanation and astronomers have proposed the existence of **dark energy**, a form of energy of low density, but present throughout the universe. Again, this will be discussed in more detail in Section 16.5.

Cosmic scale factor, *R*

Astronomers use the **cosmic scale factor** to represent the size of the universe by comparing the distance between any two specified places (two galaxies, for example) at different times. These distances, and the cosmic scale factor, increase with time because the universe is expanding.

$$\text{cosmic scale factor (at a time } t\text{)}, R = \frac{\text{separation of two galaxies at time } t}{\text{separation of the same two galaxies now}}$$

Because it is a ratio, the cosmic scale factor does not have a unit. It varies with time.

From the definition, it should be clear that at this time $R = 1$, in the past $R < 1$ and (in an expanding universe) in the future $R > 1$. If at some time in the future the universe has doubled in size, R will equal 2 at that time.

More generally, we can define the cosmic scale factor as follows:

$$\text{cosmic scale factor (at a time, } t\text{)}, R = \frac{\text{separation of two galaxies at time } t}{\text{separation, } d_0\text{, of the same two galaxies at a specified time, } t_0}$$

$$R(t) = \frac{d(t)}{d_0}$$

Figure 16.46 shows some predictions for the possible size of the universe in the future (and how it might have been in the past).

- The red line represents an accelerating universe. This will be discussed in more detail in Section 16.5.
- The blue line represents a universe that will continue to expand for ever (but at a decreasing rate).
- The green line represents a universe that will expand for ever but at a rate that reduces to zero after infinite time.
- The orange line represents a universe that will reach a maximum size and then contract.

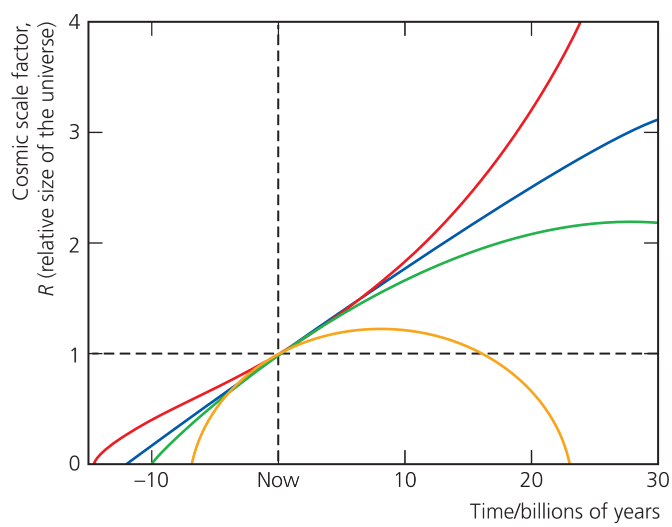


Figure 16.46 Possible futures for the universe

Relationship between red-shift and cosmic scale factor

We know that:

$$\text{red-shift, } z = \frac{\Delta\lambda}{\lambda_0} = \frac{\lambda - \lambda_0}{\lambda_0}$$

where λ is the wavelength received from a distant galaxy because of the expansion of space, and λ_0 is the wavelength that was emitted.

Because the expansion of the wavelength can be represented by an increase in the cosmic scale factor between the time the light was emitted, R_0, and the time it was received, R, we can write:

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{R - R_0}{R_0}$$

or:

$$z = \frac{R}{R_0} - 1$$

This equation is given in the *Physics data booklet*.

Worked example

9 The light from a distant galaxy was found to have a red-shift of 0.16.

a What was the recession speed of the galaxy?

b Determine the cosmic scale factor when the light was emitted.

c Estimate the size of the observable universe at that time (size now = 4.6×10^{10} ly).

a $z \approx \frac{v}{c}$

$0.16 = \frac{v}{3.0 \times 10^8}$

$v = 4.8 \times 10^7\,\mathrm{m\,s^{-1}}$

b $z = \left(\frac{R}{R_0}\right) - 1$

$0.16 = \left(\frac{1}{R_0}\right) - 1$

$R_0 = 0.86$

c $0.86 \times 4.6 \times 10^{10} = 4 \times 10^{10}$ ly

60 a Explain what is meant by the term 'standard candle'.

b Why are observations of supernovae considered to be the best way of determining the distances to remote galaxies?

61 Suggest what future for the universe is represented by the orange line in Figure 16.46.

62 Measurements of the light from a distant galaxy show that a line on its spectrum is 4.8×10^{-8} m longer than when measured on Earth. If the light was emitted with a wavelength of 6.6×10^{-7} m,

a what is the value of the red-shift?

b Calculate the cosmic scale factor at the time the light was emitted.

ToK Link

The history of astronomy has many paradigm shifts

A **paradigm** is a set of beliefs, or patterns of thought, with which individuals or societies organize their thinking about a particular issue, whether it is big or small. It is like a framework for all our thoughts and actions when, for example, we try to understand how electricity flows down a wire, or decide which foods are healthy to eat. In scientific terms, a paradigm could be said to be a pattern of beliefs and practices that effectively define a particular branch of science at any period of time. An obvious example from this chapter would be the set of ideas associated with the, now discredited, belief that the Earth is at the centre of the universe and the various consequences of that fundamental idea.

The phrase **paradigm shift** has been used increasingly during the last 50 years since it was first popularized by Thomas Kuhn and others in the early 1960s. It is used especially with respect to developments in science. There are plenty of examples which suggest that, while scientific understanding, knowledge and practices obviously evolve and, hopefully, improve over time, many of science and technology's greatest achievements have occurred following a relatively sudden (and perhaps unexpected or even seemingly unimportant) discovery or invention, or following the genius of an individual who has the insight to look at something in a completely new way. The phrase 'to think outside the box' has become very popular in recent years and it neatly summarizes an encouragement to look at a problem differently from the way others think about it (the 'box' being the paradigm).

A paradigm shift occurs when new insights, technology and discoveries have such a fundamental effect that current ideas or beliefs have to be rejected. Most individuals, organizations and societies find that a very difficult thing to do, even to the point where they strongly reject overwhelming evidence that their prevailing beliefs or actions are no longer reasonable. The response of the Roman Catholic Church to scientific evidence that the Earth revolved around the Sun was to simply ignore it and persecute those who held those beliefs.

The Big Bang model is another example of a paradigm shift in astronomical thinking and, if extra-terrestrial life were ever discovered, then most of us would look at ourselves in a completely new way – a tremendous paradigm shift! On a less profound scientific level, the technology of the internet and the introduction of social networking sites are having such a dramatic effect on the way that many people interact, that they can be described as producing a paradigm shift in communications. Characteristically, there are many people who are unwilling to accept such changes in their lives and who believe that they are unnecessary, or even harmful.

16.4 (D4: Additional Higher) Stellar processes – *the laws of nuclear physics applied to nuclear fusion processes inside stars determine the production of all the elements up to iron*

We will begin by looking in more detail at the processes that lead to the formation of stars from **interstellar medium** (ISM), which is about 99% gas (mostly hydrogen and helium) and 1% dust. This medium has both very low temperature and low density. The medium will *not* be totally uniform (homogeneous) and it can also be disturbed by neighbouring stars or even the shock waves from a supernova.

The forces of gravity may be very small, but given enough time the gas and dust can gather together more where the density is slightly higher. The main thing stopping the eventual collapse of a nebula (or part of a nebula) under gravitational forces is the opposing pressure provided by the movement of the gas molecules.

Jeans criterion

The English astronomer Sir James Jeans did a lot of the early work on the conditions necessary for star formation. In simple terms, if the gravitational potential energy of a mass of gas is higher than the kinetic energy of its molecules, it will tend to collapse. A star cannot be formed unless the mass of the gas is greater than a certain critical value, called the **Jeans mass**, M_J. The value of the Jeans mass is temperature dependent. If the interstellar medium is warmer, the mass necessary for the formation of a star will be higher.

The collapse of an interstellar cloud to form a star can only begin if its mass $M > M_J$.

Calculations using the Jeans criterion are *not* included in this course, but it is instructive to consider an example. For hydrogen gas with a tiny density of 10^8 atoms m^{-3} at a temperature of 100 K, the Jeans mass, M_J, is approximately 10^{33} kg. This mass is equivalent to at about 1000 × the mass of our Sun. These figures demonstrate that a very large mass is needed before interstellar medium can begin to collapse. Although when collapse does occur, the mass involved is large enough for the formation of more than one star.

Nuclear fusion

Nuclear fusion in the cores of stars is the dominant energy transfer that provides the power for the radiation they emit. Fusion can occur because of the very high temperatures created when gravitational potential energy is transferred to the kinetic energy of particles as the interstellar mass has been pulled together by gravitational forces.

It can take a long time for stars to fuse most of their hydrogen into helium and during this time they are known as main sequence stars. When the supply of hydrogen in a star begins to be depleted ('run out'), different fusion processes can occur (at higher temperatures) as the star enters the later stages of its lifetime and moves off the main sequence on the HR diagram. We will now examine these fusion processes in greater detail.

Nuclear fusion in the main sequence

Earlier in this chapter we summarized the fusion of hydrogen into helium:

$$4{}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + 2{}^{0}_{1}\mathrm{e} + \text{neutrinos and photons}$$

But the process is a little more complicated. It is known as the **proton–proton cycle** and has three separate stages:

- Two protons fuse to make a ${}^{2}_{1}\mathrm{H}$ (deuterium) nucleus. In this process a positron and an (electron) neutrino are emitted.

$$ {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{1}\mathrm{e}^{+} + {}^{0}_{0}\nu_{e}$$

- The deuterium nucleus fuses with another proton to make He-3. In this process a gamma ray photon is emitted.

$$ {}^{2}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{0}_{0}\gamma$$

- Two He-3 nuclei combine to make He-4. Two protons are released in this reaction.

$$ {}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + 2{}^{1}_{1}\mathrm{H}$$

These three stages are illustrated in Figure 16.47.

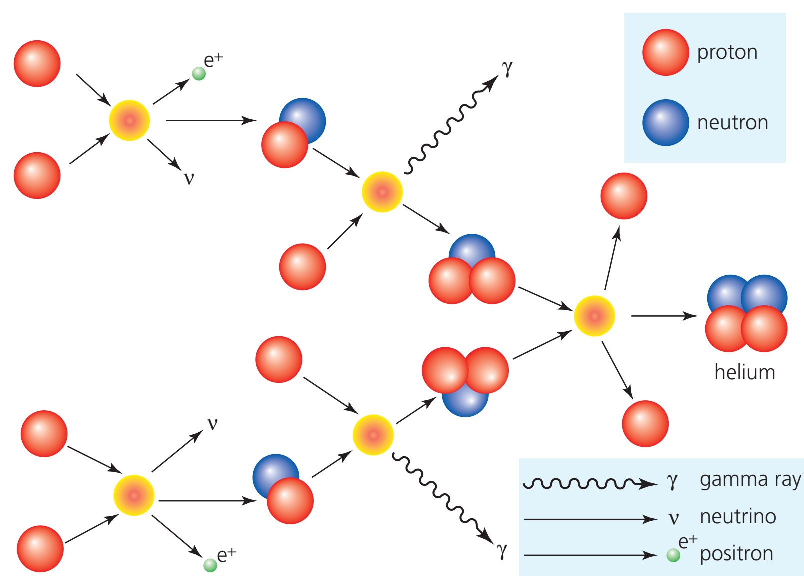


Figure 16.47 The proton–proton cycle

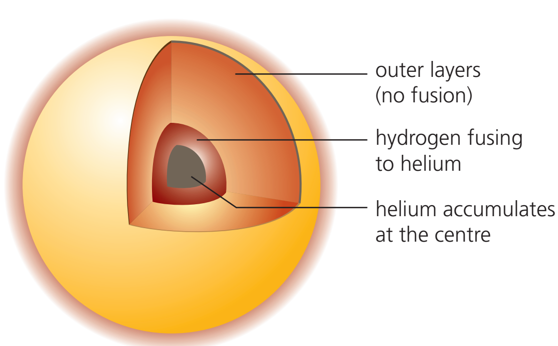


Figure 16.48 Internal structure of a main sequence star

The nuclear potential energy released in each cycle is 26.7 MeV and this is transferred to the kinetic energy and electromagnetic energy of the products. Energy is continually transferred to the surface of the star, from where it is radiated away at the same rate as it is produced by nuclear fusion, so the star remains in equilibrium. Because helium atoms are more massive than hydrogen atoms, they will remain near the centre of the star where they were formed (see Figure 16.48).

Main sequence stars remain stable for a long time because thermal gas pressure and radiation pressure outwards oppose the gravitational pressure inwards.

Time for which stars stay on the main sequence

When the supply of hydrogen becomes sufficiently depleted (after about 12 % of the total mass of hydrogen in the star has been fused) the star will no longer be in equilibrium. The inert helium core will begin to collapse inwards under the effect of gravitational forces and this marks the beginning of its end as a main sequence star. The 'lifetime' of the star as a main sequence star depends on the original mass of hydrogen and the rate of nuclear fusion. But more massive stars have more concentrated cores at higher temperatures and this means that they deplete their hydrogen *much* quicker.

More massive stars have shorter main sequence lifetimes.

Earlier in this chapter we introduced the following equation linking the luminosity, L, of a main sequence star to its original mass, M:

$$L \propto M^{3.5}$$

This equation is given in the *Physics data booklet*.
The luminosity of a stable main sequence star can be assumed to be constant, so:

$$L = \frac{\text{total energy released by nuclear fusion}}{\text{time spent as a main sequence star, } T}$$

It is reasonable to assume that the energy released is approximately proportional to the mass of the star, so:

$$L \propto \frac{M}{T}$$

Combining these last two equations, we get:

$$M^{3.5} \propto \frac{M}{T}$$

or:

$$T \propto \frac{1}{M^{2.5}}$$

This equation is *not* given in the *Physics data booklet*.

The lifetime of our Sun

We know the following facts about the Sun:

- mass, $M_\odot = 1.99 \times 10^{30}\,\text{kg}$
- luminosity = $3.85 \times 10^{26}\,\text{W}$
- Each proton–proton cycle releases 26.7 MeV (= 4.27×10^{-12} J) of energy.
- When they are first formed, main sequence stars consist of approximately 75% hydrogen.
- It will end its main sequence lifetime when about 12% of its hydrogen has been fused into helium.

We can calculate a value for its main sequence lifetime as follows:

amount of hydrogen that will be fused ('burned') during the main sequence lifetime = 12% of 75% of $1.99 \times 10^{30}\,\text{kg} = 1.79 \times 10^{29}\,\text{kg}$

mass involved with each proton–proton cycle = $4 \times 1.67 \times 10^{-27} = 6.68 \times 10^{-27}\,\text{kg}$

number of proton–proton cycles during the main sequence lifetime

$$= \frac{1.79 \times 10^{29}}{6.68 \times 10^{-27}} = 2.68 \times 10^{55}$$

current rate of proton–proton cycles $= \frac{3.85 \times 10^{26}}{4.27 \times 10^{-12}} = 9.02 \times 10^{37}\,\text{s}^{-1}$ (assumed constant for the main sequence lifetime)

main sequence lifetime of our Sun $= \frac{2.68 \times 10^{55}}{9.02 \times 10^{37}} = 2.97 \times 10^{17}\,\text{s}$ (or about 9.4×10^{9} years)

Our Sun (mass $M_{\odot}$) is expected to stay on the main sequence a total of about 10^{10} years.

We can also estimate the decrease in the mass of the Sun due to nuclear fusion reactions from $\Delta E = \Delta mc^2$ (Chapter 7):

energy transferred during main sequence lifetime, ΔE = power × time

$= 3.85 \times 10^{26} \times 2.97 \times 10^{17} = 1.14 \times 10^{44}\,\text{J}$

$\Delta E = \Delta mc^2$

$1.14 \times 10^{44} = \Delta m \times (3.0 \times 10^{8})^2$

$\Delta m = 1.3 \times 10^{27}\,\text{kg}$

This is equivalent to $4.3 \times 10^{9}\,\text{kg}\,\text{s}^{-1}$!

Worked example

10 Estimate the main sequence lifetime of a star that is twice the mass of our Sun.

$$\frac{T_{star}}{T_{Sun}} = \left(\frac{M_{\odot}}{M_{star}}\right)^{2.5}$$

$$= \left(\frac{1}{2}\right)^{2.5}$$

$$\log \frac{T_{star}}{T_{Sun}} = 2.5 \log 0.5 = -0.753$$

$$\frac{T_{star}}{T_{Sun}} = 0.17$$

$$T_{star} = 0.17 \times T_{Sun}(10^{10}) = 1.7 \times 10^{9} \text{ years}$$

The star is twice as massive, but its lifetime is shorter than $\frac{1}{5}$ that of the Sun.

63 An approximate value for the Jeans mass can be calculated from the following equation (which does not need to be remembered):

$$M_J^2 = \left(\frac{5kT}{Gm}\right)^3 \times \frac{3}{4\pi\rho}$$

where M is the mass of the individual atoms particles and ρ is the mean density of the medium.

a Calculate a value for M_J for hydrogen at a temperature of 40 K and density of 200 molecules per cm^3.

b i Explain why a greater Jeans mass would be needed for the same gas with the same density, but at a higher temperature.

ii If the temperature was 50 K instead of 40 K (at the same density), by what factor would the Jeans mass increase?

64 a Estimate the luminosity of a star (in terms of $L_{\odot}$) which has a mass ten times heavier than the mass of the Sun.

b What is the approximate mass of a star (in terms of $M_{\odot}$) which is half as luminous as the Sun?

65 a What mass of star (in terms of $M_{\odot}$) will have a main sequence lifetime twice as long as the Sun?

b Estimate the lifetime of a star that has a mass 20 times greater than our Sun.

66 a A main sequence star has a luminosity of 4.9×10^{28} W. What is the annual decrease in mass due to nuclear fusion?

b What is this change of mass expressed as a percentage of the original mass of the star?

Nucleosynthesis off the main sequence

After the hydrogen becomes depleted, the core of the star begins to contract because, once the rate of fusion is reduced, the gravitational forces are greater than the outward forces. Gravitational potential energy is then transferred to kinetic energy of the nuclei in the core, and to increased thermal gas pressure, which results in the significant expansion of the outer layers of the star. This results in the envelope cooling, creating a red giant or red supergiant (as described earlier in this chapter). These changes cause the star to leave the main sequence.

The temperatures in the cores of red giants are sufficient to cause the fusion of helium nuclei (or heavier elements). The creation of the nuclei of heavier elements by fusion is called **nucleosynthesis**.

In general, the contraction of the cores of main sequence stars of greater mass will result in higher temperatures, which means that the nuclei then have higher kinetic energies, so that they can overcome the larger electric repulsive forces involved in the fusion of heavier elements.

The following is a simplified outline of the processes involved:

- For stellar masses lower than $4M_\odot$ (red giants), the core temperature can reach 10^8 K and this is large enough for the nucleosynthesis of carbon and oxygen. (Helium is still produced in an outer layer.) For example:

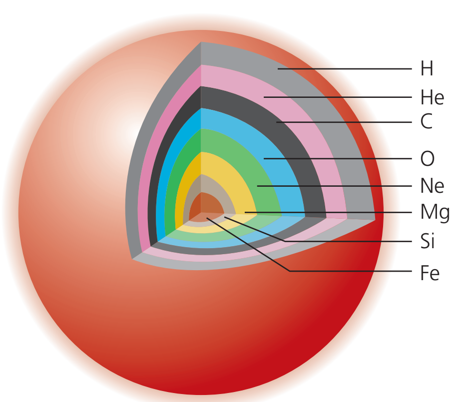
$$^{4}_{2}\text{He} + ^{4}_{2}\text{He} \rightarrow ^{8}_{4}\text{Be} + ^{0}_{0}\gamma$$

$$^{8}_{4}\text{Be} + ^{4}_{2}\text{He} \rightarrow ^{12}_{6}\text{C} + ^{0}_{0}\gamma$$

$$^{12}_{6}\text{C} + ^{4}_{2}\text{He} \rightarrow ^{16}_{8}\text{O} + ^{0}_{0}\gamma$$

- For stellar masses between $4M_\odot$ and $8M_\odot$ (larger red giants), the core temperature exceeds 10^9 K and this is large enough for the nucleosynthesis of neon and magnesium. (Helium, carbon and oxygen are still produced in the outer layers.)
- For stellar masses over $8M_\odot$ (red supergiants), the core temperature is large enough for the nucleosynthesis of elements as heavy as silicon and iron. (The lighter elements are still produced in the outer layers.) From Chapter 7 we know that the nucleus of iron is one of the most stable (it has one of the highest average binding energies per nucleon). This means that there would have to be an energy input to create heavier nuclei. (See later in this chapter.)

The structure of stars off the main sequence is layered ('like the skins of an onion') as the heavier elements are found closer to the centre. A red supergiant will have the most layers (see Figure 16.49).



■ **Figure 16.49** The layers of a red supergiant

67 Write a possible equation for a nuclear reaction which produces silicon-14.

68 What elements will be in the Sun when it finishes its main sequence lifetime?

69 Explain why nuclear fusion within main-sequence stars cannot produce nuclides with nucleon numbers greater than 62.

The formation of elements heavier than iron by neutron capture

Neutrons are produced in some nuclear fusion reactions within a star. For example:

$$^{13}_{6}\text{C} + ^{4}_{2}\text{He} \rightarrow ^{16}_{8}\text{O} + ^{1}_{0}\text{n}$$

Because neutrons are uncharged, they do not experience electrostatic repulsion and they can get close enough to nuclei to come within range of the attractive nuclear strong forces and be 'captured'.

$$^{1}_{0}\text{n} + ^{A}_{Z}\text{X} \rightarrow ^{A+1}_{Z}\text{X}$$

If this happens, it will increase the mass number of the nucleus and affect its stability. The nucleus may then decay by the emission of a beta negative particle, which will result in the formation of a new element with a higher proton number (Chapter 7). But various other outcomes are also possible, depending on factors such as the neutron density, the temperature and the half-life of the beta decay. We can identify two principal processes: the s-process and the r-process.

The s-process: slow neutron capture

The **s-process** occurs in certain kinds of red giants over a long time at relatively low neutron density and intermediate stellar temperatures. Under these conditions neutron capture is much less probable than beta decay, which means that after neutron capture, beta decay will nearly always occur before the capture of another neutron. In general:

$${}^{1}_{0}\mathrm{n} + {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A+1}_{Z}\mathrm{X} \rightarrow {}^{A+1}_{Z+1}\mathrm{Y} + {}^{0}_{-1}\mathrm{e} + \overline{\nu}$$

In this way, starting from the heavier nuclides found in a red giant star, heavier and heavier elements can be created over a very long time, but none heavier than bismuth-209.

The r-process: rapid neutron capture

This process can form nuclides of a wide range of elements, including the most massive. The **r-process** occurs very quickly in supernovae, which have very high neutron densities and temperatures. Under these conditions, neutron capture is much more likely than beta decay, which means that repeated neutron captures can rapidly result in nuclides with large mass numbers. Beta decay causes transmutation to different elements and this process is assisted by the presence of large numbers of neutrinos in a supernova.

Supernovae

Supernovae are sudden, unpredictable and very luminous stellar explosions. (The name 'supernova' expresses these facts: super-bright and new.) For a few weeks their luminosities can be higher than an entire galaxy. These unusual events have time scales that are very different from most other events in the universe and this makes them both fascinating and useful to astronomers.

It has been estimated that a supernova will occur about once in every 50 years in a typical galaxy. The last known supernova in our own galaxy was visible without a telescope and occurred in 1604 (Figure 16.50). Its appearance was used by astronomers of the time as evidence that the universe was *not* fixed and unchanging. It occurred about 20 000 ly from Earth and was visible in the daytime for a few weeks. Its remnant can still be seen with a telescope. Until recently the observation of supernovae was fairly random and many were detected by amateur astronomers, but now the search has become much more automated and computer controlled.

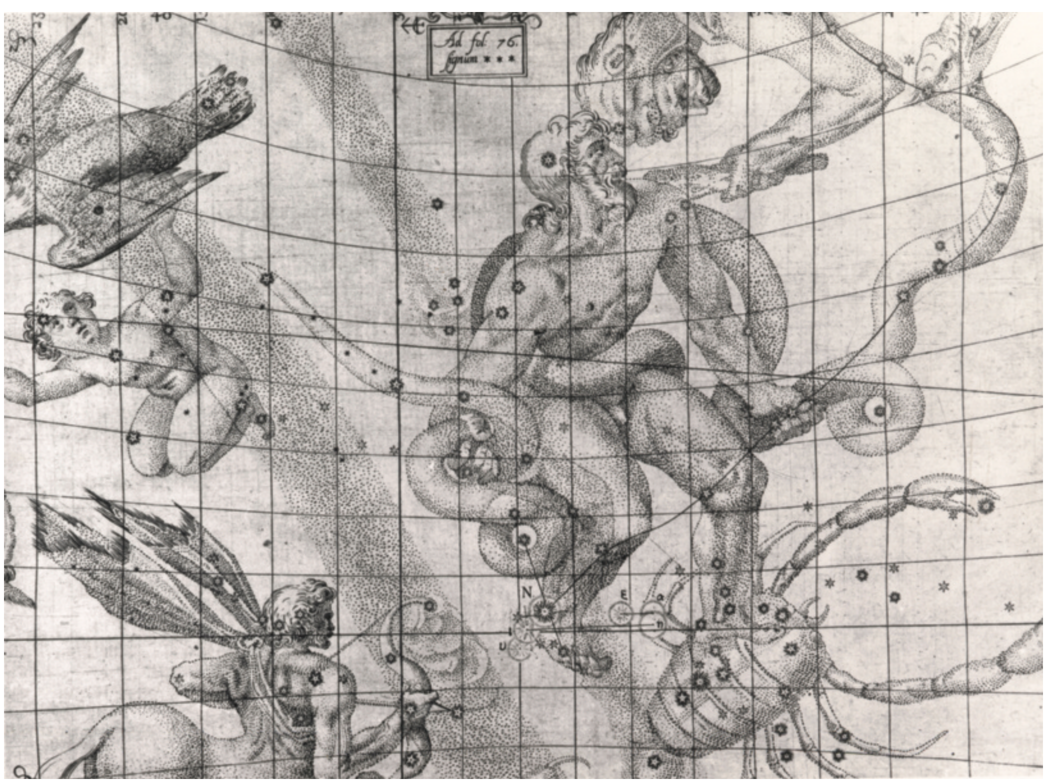


Figure 16.50 Johannes Kepler's original drawing showing the 1604 supernova in the constellation of Ophiuchus (the 'serpent bearer'). It is shown with the letter *N* which is nine grid squares down from the top and eight from the left

Supernovae are important in the creation of heavy elements and they can also be responsible for causing disturbances in the interstellar medium that can instigate the birth of stars.

Type Ia and Type II supernovae

Supernovae are classified initially by reference to the hydrogen lines in their spectra but also from their 'light curves' (see Figure 16.51).

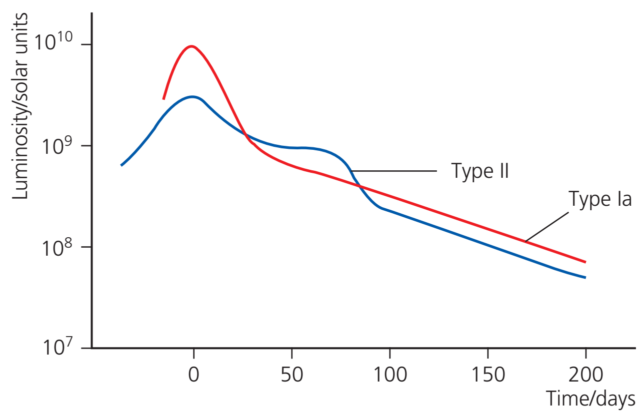


Figure 16.51 Light curves for two types of supernovae

Type Ia supernovae

If one of the stars in a binary system has become a white dwarf (with a carbon–oxygen core), its gravitational field may be strong enough to attract matter from its neighbouring star. This increase in mass means that electron degeneracy pressure is no longer high enough to resist the collapse of the star. (The mass of the white dwarf has risen to the Chandrasekhar limit for the maximum mass of a white dwarf (= $1.4M_\odot$).) The rapid increase in temperature resulting from the transfer of gravitational potential energy to the kinetic energy of particles causes rapid and widespread carbon fusion, producing a supernova which, in its early stages, could be 10^{10} more luminous than the Sun (see Figure 16.52).

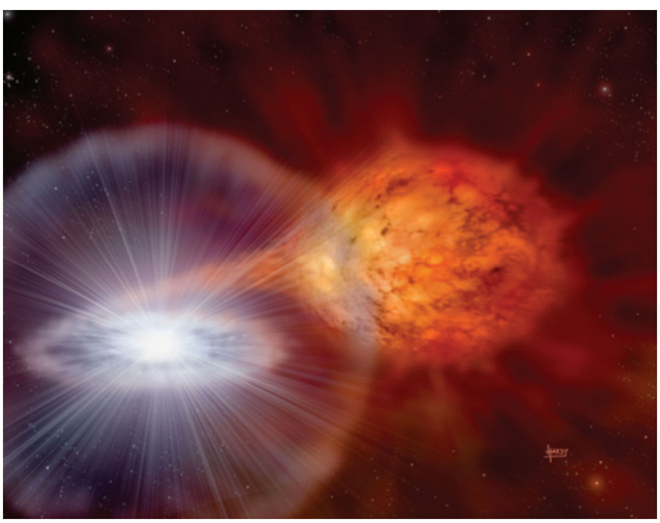


Figure 16.52 An artist's impression of a Type Ia supernova

Because these reactions only occur when the star has acquired a certain (well-known) mass, the luminosities, L, of Type Ia supernovae are always about the same. This means that the distance, d, from a Type Ia supernova to Earth can be determined using $b = L/4\pi d^2$, once the initial apparent brightness, b, has been measured. As mentioned earlier in the chapter, this has made this type of supernova very useful in determining the distance to galaxies in which supernovae occur. This is why they are known as 'standard candles' for galaxies up to 1000 Mpc away from Earth.

Type II supernovae

When the nuclear reactions in a red supergiant finish, the star collapses but the mass and energy involved are so huge that the nuclei in the core get deconstructed back to protons, neutrons, electrons, photons and a large number of neutrinos. The process of these particles interacting is complicated, but the consequence is an enormous shock wave travelling outwards, tearing apart the outer layers of the star and spreading enormous distances into the surrounding space. Rapid neutron capture occurs, resulting in the creation of the heavier elements. The remaining core will become a neutron star or a black hole (as discussed earlier in the chapter).

Additional Perspectives

'Where did the atoms in our bodies come from?

This question can have different answers depending on the timescale being considered. Of course, chemical and biological processes are responsible for redistributing atoms and it is not difficult to believe that a carbon atom in a person's body was part of a plant growing on the other side of the Earth or a fish swimming in a river six months earlier. Looking further back, the same atom might have been part of a dinosaur millions of years ago.

It is unlikely that any of the atoms that were in your body when you were born are still in your body. Over a long period of time it may be reasonable to assume that atoms are redistributed randomly, and a famous kinetic theory question asks students to estimate, for example, how many of the carbon atoms that were in the body of Isaac Newton are now part of their body.

On the cosmological scale, which covers billions of years, all the atoms in your body were originally in interstellar space, nebulae, stars and supernovae, and their origins go further back to the earliest stages of the universe and the Big Bang. We are truly made of 'stardust'. And looking forward billions of years, that is the state to which our atoms will return.

1 Find out how long a typical atom remains in a human body.

ToK Link

A philosophical question

If our bodies and brains are no longer made of the same atoms that they were before, to what extent are we the same person?

70 Write down another possible nucleosynthesis reaction that results in the emission of a neutron.

71 Write down equations to represent the following s-process: iron-56 captures three neutrons and then emits a beta-negative particle and transmutes into cobalt.

72 Traces of uranium are found on Earth in many places. Explain where they came from.

73 Summarize the differences between Type Ia and Type II supernovae.

16.5 (D5: Additional Higher) Further cosmology – *the modern field of cosmology uses advanced experimental and observational techniques to collect data with an unprecedented degree of precision, and as a result very surprising and detailed conclusions about the structure of the universe have been reached*

Astronomical and cosmological research has been a substantial growth area in science in recent years. Advances in satellite engineering, imaging techniques and the computerized collection and analysis of data in many countries have all contributed to a rapid growth in our knowledge of the universe which, in turn, has increased the relative importance of astronomy in the spectrum of scientific subjects and also raised the general public's awareness and interest.

The knowledge base of an astronomer must now extend from the very large (obviously) to the very small, because the properties of sub-atomic particles and radiation are fundamental to the behaviour of stars and understanding the beginnings of the universe.

In this section we will discuss the central issues of the latest cosmological research – dark matter, dark energy and the possible fate of the universe. But we will begin by explaining the *cosmological principle* and clarifying our understanding of red-shifts.

The cosmological principle

This is a starting point in developing an understanding of the universe. It has already been implied throughout this chapter, but it should be stated formally. Astronomers believe that the *large-scale* structure of the universe is the same everywhere and that when we look in different directions, we see essentially the same thing.

It may seem that this chapter has involved the discussion of astronomical differences, for example, between different types of stars. In addition, when we look at the night sky, the views in different directions may be similar, but they are obviously not exactly the same. However, the universe is unimaginably enormous and on that scale these differences are usually insignificant.

The **cosmological principle** can be summarized as:

The universe is homogeneous and isotropic.

- The universe is **homogeneous** – any large section of the universe will be similar to any other large section.
- The universe is **isotropic** – what can be observed by looking in any one direction from anywhere in the universe is similar to what can be seen by looking in any other direction from the same place, or in any direction from any other place.

It may seem that if the first point is accepted, then the second must be true, but if the universe had an 'edge', then for some observers the view could be different in different directions, even if the universe was homogeneous.

Isotropy implies that the universe has no edge and no centre.

The cosmological origin of red-shift

When electromagnetic radiation is received that has a longer wavelength than when it was emitted, it is described as having a red-shift. There is more than one possible reason why radiation may be red-shifted.

1. The source of radiation and the observer could be moving apart from each other in unchanging space. This is known as the **Doppler effect**. The radiation will be shifted towards shorter wavelengths if the separation is decreasing (blue-shift). The change in wavelength can be determined from the equation $\frac{\Delta\lambda}{\lambda_0} \approx v/c$ but only if $v \ll c$ (maybe for $v = 0.25c$ and below).
2. The space between the source and the observer has expanded between the time when the radiation was emitted and the time when it was received. The wavelengths are increased by the same factor as the space. This is known as the **cosmological red-shift**. Cosmological blue-shifts are not possible.

The cosmological red-shift of radiation from distant galaxies provides evidence for the Big Bang model of the universe.

The equation $\Delta\lambda/\lambda_0 \approx \frac{v}{c}$ (if $v \ll c$) can also be applied to cosmological red-shifts (but for the most distant galaxies, this simplified equation cannot be used).

3. (**Gravitational red-shifts** (discussed in Chapter 13) occur as a result of radiation moving out of gravitational fields.)

It is possible for radiation from a star or galaxy to have *both* a cosmological red-shift and a Doppler shift. For example, some binary star systems receding from Earth will have a cosmological red-shift, while the two stars have Doppler shifts (one blue and one red). All galaxies will tend to recede, but a 'nearby' galaxy in a cluster will have a relatively low recession speed and, therefore, may be moving towards Earth in its orbit within the cluster, such that the Doppler blue-shift exceeds the cosmological red-shift.

A detailed calculation of any astronomical red-shift would need to take all these factors into account. This is *not* required for this course.

Mass in the universe

We can consider that the galaxies are gaining gravitational potential energy and losing kinetic energy as space expands and their separations increase. If the galaxies have sufficient energy, this expansion can continue forever; if they do not have enough energy, they will eventually be pulled back together by gravitational forces and space will contract. We know the recession speeds of galaxies, so in principle it would be a straightforward calculation using classical gravitation theory to determine what will happen in the future, *if* we have accurate information about the mass in the universe.

Astronomers commonly refer to the *average density* (total mass/total volume) of the universe.

Critical density

The **critical density**, ρ_c, of the universe is the theoretical density that would *just* stop the expansion of the universe after an infinite time.

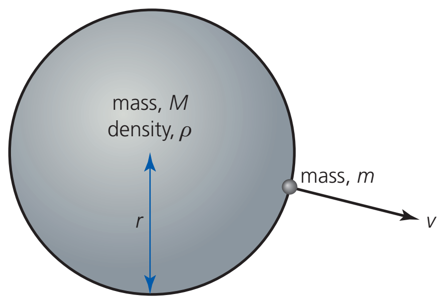


Figure 16.53 Estimating critical density

A theoretical value for the critical density can be obtained using classical Newtonian gravitation, as follows.

Consider a homogeneous spherical cloud of interstellar matter of mass M, radius r and density ρ (see Figure 16.53). A mass m at a distance r from the centre is moving away with a speed $v = Hr$, where H is the value for the Hubble 'constant' at that particular time.

The total energy, E_T, of mass m is equal to the sum of its kinetic energy and gravitational potential energy:

$$E_T = \frac{1}{2}mv^2 + (-GMm/r)$$

remembering that gravitational potential energy is negative.

But $M = \frac{4}{3}\pi r^3 \rho$ and $v = Hr$, so:

$$E_T = \frac{1}{2}m(Hr)^2 - G\frac{4}{3}\pi r^3 \rho m/r$$

If mass m moves outwards until it reaches infinity after an infinite time, its total energy will then be zero. (This is similar to the calculation of an escape velocity from a planet, covered in Chapter 10). If $E_T = 0$ and $\rho = \rho_c$:

$$\frac{1}{2}m(Hr)^2 - G\frac{4}{3}\pi r^3 \rho_c m/r = 0$$

Simplifying, we get:

$$\rho_c = \frac{3H^2}{8\pi G}$$

This equation is given in the *Physics data booklet*.

Worked example

11 Calculate a value for the current critical density of the universe using $H = H_0 = 70\,\text{km s}^{-1}\,\text{Mpc}^{-1}$.

In SI units:

$$H_0 = \frac{70 \times 10^3}{3.26 \times 10^6 \times 9.46 \times 10^{15}} = 2.27 \times 10^{-18}\,\text{s}$$

$$\rho_c = \frac{3H^2}{8\pi G} = \frac{3 \times (2.27 \times 10^{-18})^2}{8\pi \times 6.67 \times 10^{-11}} = 9.2 \times 10^{-27}\,\text{kg m}^{-3}$$

The value of the critical density is time dependent, decreasing as the universe expands (and H changes). The current *theoretical* value is believed to be the equivalent of about (only) six hydrogen atoms per cubic metre.

74 a Explain why looking at the night sky on a clear night you can see many more stars in some directions than in others.

b Explain why this fact does not contradict the cosmological principle.

75 Explain why cosmological blue-shifts are never detected.

76 Suggest why high-energy physics experiments at CERN may help astronomers understand the early universe.

77 Explain why the equation $\Delta\lambda/\lambda_0 \approx v/c$ cannot be used to calculate the recession speed of a very distant galaxy accurately.

78 Suggest why astronomers refer to density of the universe, rather than its mass.

79 **a** Show that a density of $9.2 \times 10^{-27}\,\text{kg}\,\text{m}^{-3}$ is approximately equivalent to six hydrogen atoms per cubic metre.
b Compare the critical density of the universe to a typical density for the air you are breathing.

Estimating the actual average density of the universe

What happens to the universe in the future depends on how the *actual* average density compares to the critical density. Because we have a good understanding of the masses of individual stars, galaxies and nebulae, as well as their separations and distribution, it would seem that straightforward calculations should lead to an estimate of the total mass in a typical large volume, from which an average density can be calculated. This is certainly possible, but the results of such calculations applied to galaxies are inaccurate and they are much less than the more reliable values of mass determined by applying the laws of physics to the rotation of galaxies.

Rotation curves and the mass of galaxies

The theoretical velocities of stars rotating with a galaxy around its centre of mass can be calculated from the laws of classical physics. It is convenient to consider the stars close to the centre separately from the more distant stars, as follows.

1 *Close to the centre of a galaxy* the circular orbital velocity of a star increases approximately proportionately to its distance from the centre. We can explain this using Newtonian gravitation: assume that a galaxy is homogeneous and spherical, with radius r and density ρ. It would act as if all its mass, M, was concentrated at its centre. A mass m on the circumference would experience a force GMm/r^2. Equating this to the expression for centripetal force we get:

$$\frac{mv^2}{r} = \frac{GMm}{r^2}$$

so that:

$$v^2 = \frac{GM}{r}$$

Because $M = \frac{4}{3}\pi r^3 \rho$:

$$v^2 = \frac{4}{3}\pi G r^2 \rho$$

or:

$$v = \sqrt{\frac{4\pi G\rho}{3}}\,r$$

This equation, showing that the rotational speed of the galaxy is proportional to the distance from the centre, is given in the *Physics data booklet*. Because of the simplifying assumptions involved, it only gives an approximate value for the speeds closer to the centre of the galaxy.

2 *At longer distances* the situation becomes similar to, for example, planets freely orbiting a massive central star, so that the rotational velocity decreases with distance.
($v \propto \sqrt{\frac{1}{r}}$ – see Chapter 6)

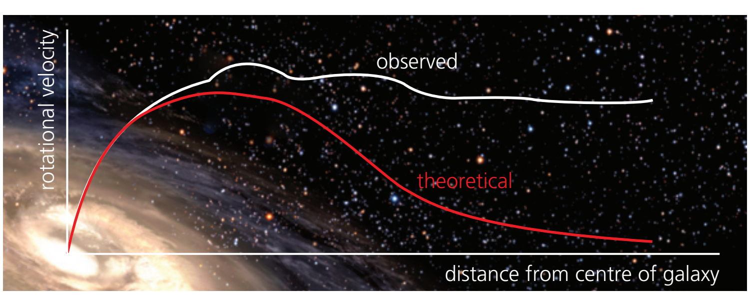


Figure 16.54 Comparison of theoretical and observed rotational curves

Detailed analysis will produce a combined theoretical **rotational curve** (graph of v–r), such as shown in red in Figure 16.54. However, actual measurements made from red-shift observations show a significantly different pattern (shown in white in Figure 16.54). (The red-shifts due to the recession of the galaxy as a whole and the orbital motions of the stars need to be distinguished.) The calculated orbital speeds for the outer stars of the galaxy are approximately constant.

The difference between theory and observation demands an explanation. It could be that there is something wrong with the basic physics used in the theory, but the preferred explanation is that there must be a lot more mass in galaxies than can be observed directly, and that this mass is concentrated in the outer reaches of the galaxy in a **dark matter halo**.

Dark matter

Dark matter is the name given to the proposed matter that must be present in the universe, but which has never been detected directly because it neither emits nor absorbs radiation.

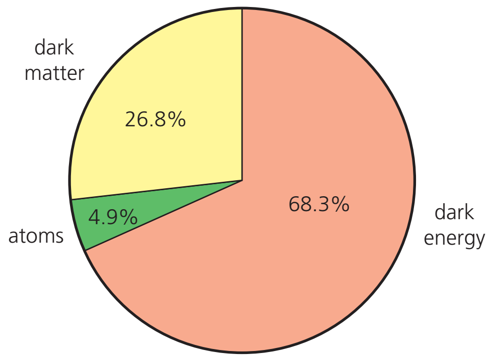


Figure 16.55 The constituents of the universe

Dark matter is believed to be about five times more plentiful in the universe than observable matter (atoms), but **dark energy** (see later in this section) is thought to be the dominant form of mass–energy in the universe (see Figure 16.55).

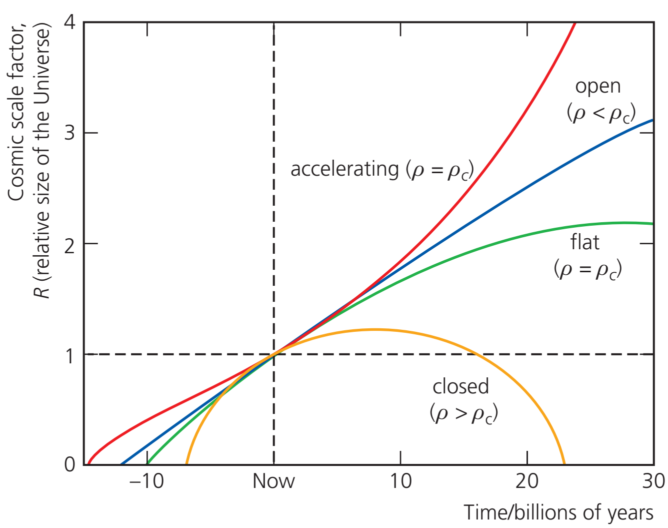
Many theories have been proposed about the nature of dark matter, including:

- **MACHOs** – **m**assive **a**stronomical **c**ompact **h**alo **o**bjects. These could be old stars or small 'failed' stars, very large planets or even black holes, any or all of which simply do not emit enough radiation for us to detect them. It is considered unlikely that there could be a sufficient number of such objects to explain dark matter fully.
- **WIMPs** – **w**eakly **i**nteracting **m**assive **p**articles. (Note that here 'massive' simply means 'with mass'; it does not imply large individual masses.) There could be very large numbers of particles that we do not know about yet simply because they are very difficult to detect. Including…
- **Neutrinos** – the masses of neutrinos are presumed to be very small, but they are still not known with any certainty. Neutrinos are present in the universe in vast numbers so they could contribute significant mass.

Possible futures for the universe

Figure 16.56 shows possible futures for the universe as it expands. This diagram is similar to Figure 16.46 but it is worth repeating here because it is so important. Note that the density affects not only the future, but also our estimate of the age of the universe.

Figure 16.56 How the average density of the universe affects its future



- **A flat universe** ($\rho = \rho_c$) – the rate of expansion will reduce to zero after an infinite time.
- **A closed universe** ($\rho > \rho_c$) – if the density of the universe is higher than the critical density, then at some time in the future the universe will stop expanding and then begin to contract and eventually end as a 'Big Crunch'.
- **An open universe** ($\rho < \rho_c$) – if the density of the universe is lower than the critical density, then the universe will continue to expand forever.

An accelerating universe

The latest calculations (involving dark matter) suggest that the actual density of the universe is (surprisingly?) very close to the critical density, which might suggest that any of the three possibilities listed above are feasible. However, as mentioned earlier in this chapter, recent measurements on the red-shifts of galaxies containing Type Ia supernovae indicate that the expansion of the universe has been *accelerating* (for about half its lifetime), as shown by the red line in Figure 16.56. This requires a different explanation: **dark energy**.

Nature of Science

Cognitive bias

In science, as in all areas of human experience, we usually believe what we want to believe. In other words, we are inclined to accept information that supports our existing experiences or beliefs, and inclined to reject information that would cause us to change our thinking. Of course, scientists strive to be objective and evaluate new data or theories without bias, but **confirmation bias** is present, often without people being aware of it, and this tends to make people reject the unexpected in favour of accepting the expected.

The concept that the expansion of the universe was slowing down because of the gravitational attraction between galaxies was widely accepted and in line with available evidence. The recent paradigm shift to an accelerating universe (especially without any substantial supporting explanation) has only been accepted because of the overwhelming evidence.

ToK Link

Limits of understanding

Experimental facts show that the expansion of the universe is accelerating yet no one understands why. Is this an example of something that we will never know?

British Astronomer Royal Martin Rees is quoted as saying:

'A chimpanzee can't understand quantum mechanics. It's not that the chimpanzee is struggling to understand quantum mechanics. It's not even aware of it. There is no reason to believe that our brains are matched to understanding every level of reality.'

While it may be reasonable not to worry about things that we do not know, and of which we are totally unaware, it is unlikely that most scientists would ever happily accept that something as important as the fate of the universe can never be known, especially when it is a central theme of modern astronomical research. Similar comments may apply to the reasons for the origin of the universe: we may never know, but astronomers will keep looking for answers.

Dark energy

Dark energy has been proposed in the last 20 years as an explanation for the accelerating expansion of the universe.

Dark energy has been described as providing a 'negative pressure' on the universe; a pressure opposing any possible contraction. It has not been detected directly and is still hypothetical, although it is believed that it may be homogeneous – throughout all space at a *very* low density. Even at such a low density, because it is everywhere, it may provide about 68% of the mass–energy content of the universe (see Figure 16.55). Many astronomers consider that it is an intrinsic property of space and that when space expands, so too will the amount of dark energy.

80 Use data available in this chapter (or elsewhere) to make an approximate order of magnitude estimate for the total mass of all the stars in the observable universe.

81 Use the internet to learn more about WIMPS and MACHOS.

82 The diameter of the observable Universe is 28×10^9 pc. Estimate its total mass.

83 If the Hubble constant was reassessed to be 10% higher, by what factor would the value of critical density of the universe change?

84 Use classical gravitational theory (as used in Chapter 10 for satellite orbits) to show that we might expect the orbital speeds of stars a long way from the galactic centre to be inversely proportional to the square root of their distance from the centre.

85 The maximum Doppler shift, z, due to a star orbiting within its galaxy at a distance of 9.5×10^{15} km from its centre was measured to be 2.7×10^{-3}.
a Estimate the maximum speed of the star.
b What assumption did you make in answering (a)?
c Determine a value for the average density of the galaxy.

Fluctuations in the CMB

As we have seen, the discovery in the 1960s of isotropic microwave radiation (corresponding to a wavelength of 2.76 K) arriving at Earth from all directions was convincing evidence for the Big Bang model of the universe. This radiation is called cosmic microwave background radiation (CMB). In the last 25 years a great deal of research has been done into looking for *tiny* variations (fluctuations) in the CMB. Figure 16.57 shows an image of the fluctuations in CMB compiled from data from the Planck mission. Different temperatures are represented by different colours, but the maximum variation is only 0.0002 K! A significant ‘cold spot’ is ringed.

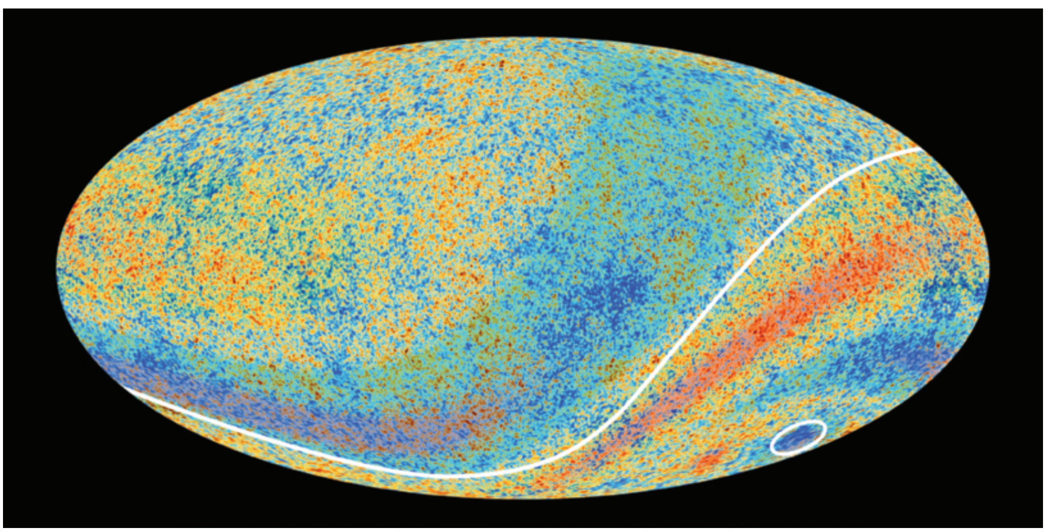


Figure 16.57 Fluctuations in the CMB as published by the Planck mission in 2013

It is clear from such images that the CMB is not *perfectly* isotropic. For example, there is a clear difference either side of the white line (which divides the opposite hemispheres of the sky). These variations in CMB are known as **anisotropies** and they provide astronomers with information about the early universe, at the time that the radiation was emitted. The early universe was opaque to electromagnetic radiation until it was 380 000 years old. This may seem like a long time, but it was very early in the history of the universe and knowledge from the CMB dates from that time. For example, the associated fluctuations in density may have been responsible for the later formation of galaxies and clusters of galaxies.

Linking average universe temperature to the cosmological scale factor

As the universe expands, the wavelength at which the maximum radiation intensity is detected, λ_{max}, also stretches and this is represented by the cosmic scale factor, R. That is:

$$\lambda_{max} \propto R$$

but Wien's law tells us $\lambda_{max} T$ = constant (2.9×10^{-3} m K), so that:

$$T \propto \frac{1}{R}$$

This equation is *not* given in the *Physics data booklet*.

Worked example

12 The average temperature of the universe now (when $R = 1$) is 2.76 K.

a What was the cosmic scale factor when the average temperature was 50 K?

b The distance between Earth and a certain galaxy is now 4.0×10^8 ly. What was the distance when the average temperature of the universe was 50 K?

a $T \propto \frac{1}{R}$ or TR = constant

$(TR)_{now} = (TR)_{then}$

$2.76 \times 1 = 50R_{then}$

$R_{then} = 0.056$

b $\frac{R_{now}}{R_{then}} = \frac{d_{now}}{d_{then}}$

$\frac{1}{0.056} = \frac{4.0 \times 10^8}{d_{then}}$

$d_{then} = 2.2 \times 10^7$ ly

CMB missions

The importance of the CMB is demonstrated by the fact that four major satellite programmes have involved it:

- **COBE** – Cosmic Background Explorer, launched in 1989
- **WMAP** – Wilkinson Microwave Anisotropy Probe, launched in 2001
- **Planck mission** – launched in 2009
- **James Webb telescope** – scheduled for launch in 2018.

The improving technology for successive missions has resulted in rapidly increasing precision and quantity of data. Comparison of Figure 16.43 (COBE and WMAP) with Figure 16.57 (Planck mission) illustrates the improved resolution.

The Planck mission has now ended, although its data is still being examined. In March 2013 the European Space Agency published Figure 16.57 and their latest estimates for some important astronomical data:

- The universe is 13.798 ± 0.037 billion years old.
- The universe contains 4.9% ordinary matter, 26.8% dark matter and 68.3% dark energy.
- The Hubble constant was measured to be 67.80 ± 0.77 km s^{-1} Mpc^{-1}. (This figure is significantly different from other recent quoted values, e.g. from WMAP.)

86 Explain why the average temperature of the universe is inversely proportional to the cosmic scale factor.

87 In the distant future the average temperature of the universe may cool to 1 K. What will the cosmic scale factor be at that time?

88 **a** Use the internet to find out what the latest accepted value is for the Hubble constant.

b Why is it sometimes called the Hubble *parameter*?

89 Find out more about the proposed James Webb telescope.

Summary of knowledge

16.1 Stellar quantities

- Nebulae are enormous diffuse 'clouds' of interstellar matter, mainly gases (mostly hydrogen and helium) and dust. Large nebulae are the principal locations for the formation of stars.
- Over a very long period of time, gravity pulls atoms closer together and eventually they can gain very high kinetic energies (that is, the temperature becomes extremely high – millions of kelvin) if the overall mass is large. The hydrogen nuclei (protons) can then have enough kinetic energy to overcome the very high electric forces of repulsion between them and fuse together to make helium. When this happens on a large scale it is called the birth of a (main sequence) star.
- A main sequence star can remain in equilibrium for a long time because the gravitational pressure inwards is balanced by thermal gas pressure and radiation pressure outwards.
- Many spots of light that seem to be stars are in fact binary stars, with two stars orbiting their common centre of mass.
- The forces of gravity cause billions of stars to collect in groups (galaxies), orbiting a common centre of mass. Galaxies also form into groups called clusters of galaxies. These clusters are not distributed randomly in space and are themselves grouped in super clusters (the largest structures in the universe).
- Stars formed from the same nebula within a galaxy may also form groups called stellar clusters, which are bound together by gravity and move together. Globular clusters contain large numbers of stars so that gravity forms them into roughly spherical shapes. Open clusters are newer and have fewer stars in less-well-defined shapes.
- Stellar clusters should not be confused with constellations, which are simply patterns of stars as seen from Earth. The stars in a constellation may have no connection to each other and may not even be relatively close, despite appearances.
- Planetary systems, like our solar system, are formed around some stars in the same process that created the star. The planets move in elliptical paths with periods that depend on the distance from the star. Comets are much smaller than planets, with typically much longer periods and more elliptical paths. When they are close to the Sun (and the Earth) they may become visible to us, and may have a 'tail' of particles created by the solar wind.
- Astronomers use several different units for measuring distance. The light year, ly, is defined as the distance travelled by light in a vacuum in 1 year. The astronomical unit (AU) is equal to the mean distance between the Earth and the Sun. The parsec (pc) = 3.26 ly.
- The order of magnitude of the diameter of the observable universe is 10^{11} ly. A typical galaxy has a diameter of about 10^4 ly and the distance between galaxies is typically 10^7 ly.
- The measurement of astronomical distances is a key issue in the study of astronomy. The distance to nearby stars can be calculated from a measurement of the parallax angle between their apparent positions (against a background of more distant, fixed stars) at two times separated by 6 months.
- One parsec is defined as the distance to a star that has a parallax angle of one arc-second.
- d (parsec) = $1/p$ (arc-seconds)
- For stars further away than a few hundred parsecs the stellar parallax method is not possible because the parallax angle is too small to measure accurately.
- The apparent brightness, b, of a star (including the Sun) is defined as the intensity (power/perpendicular receiving area) on Earth. The units are $W\,m^{-2}$.
- The luminosity, L, of a star is defined as the total power it radiates (in the form of electromagnetic waves). It is measured in watts, W.

- Understanding the relationship between luminosity and apparent brightness is very important in the study of astronomy – apparent brightness, $b = L/4\pi d^2$, where d is the distance between the star and Earth. This assumes that the radiation spreads equally in all directions without absorption in the intervening space. For very distant stars this assumption can lead to inaccuracies.
- The luminosity (power) of a star can be determined from the Stefan–Boltzmann law (Chapter 8): $P = e\sigma AT^4$, which reduces to $L = \sigma AT^4$ if we assume that stars behave like perfect black bodies and so have emissivities of 1.

16.2 Stellar characteristics and stellar evolution

- Intensity–wavelength graphs are very useful for representing and comparing the black-body radiation from stars with different surface temperatures. Such graphs can be used to explain why stars emit slightly different colours.
- Wien's displacement law (Chapter 8) can be used to calculate the surface temperature of a star if the wavelength at which the maximum intensity is received can be measured: $\lambda_{max}T = 2.9 \times 10^{-3}\,\text{m K}$.
- The elements present in the outer layers of a star can be identified from the absorption spectrum of light received from the star.
- Stars that are formed from greater masses will have stronger gravitational forces pulling them together. This will result in higher temperatures at their core and faster rates of nuclear fusion. More massive main sequence stars will have bigger sizes, higher surface temperatures, brighter luminosities and shorter lifetimes.
- For main sequence stars the approximate relationship between mass and luminosity is represented by the equation $L \propto M^{3.5}$.
- The Hertzsprung–Russell (HR) diagram is a common way of representing different stars on the same chart. The (logarithmic) axes of the diagram are luminosity and temperature (reversed). The sizes of different stars can be compared if lines of constant radius are included on the diagram.
- The majority of stars are located somewhere along a diagonal line from top-left to bottom-right of the HR diagram. This is called the main sequence. The only basic difference between these stars is their mass – which results in different luminosities and temperatures because of the different rates of fusion.
- Other types of stars, like red giants, white dwarfs, supergiants and Cepheid variables (on the instability strip) can be located in other parts of the HR diagram.
- The outer layers of Cepheid variable stars expand and contract regularly under the competing influences of gravity and thermal gas pressure. The period of the resulting changes in the observed apparent brightness is related to the star's luminosity and represented in a well-known relationship, so that a Cepheid's luminosity can be determined from its period. $b = L/4\pi d^2$ can then be used to determine the distance, d, to the star and therefore the galaxy in which it is situated.
- Inaccuracies in the data involved mean that these estimates of distance, especially to the furthest galaxies, are uncertain. This uncertainty has been a significant problem when estimating the age of the universe.
- When the supply of hydrogen in a main sequence star reduces below a certain value, the previous equilibrium is not sustained and the core will begin to collapse inwards. Gravitational energy is again transferred to kinetic energy of the particles and the temperature of the core rises even higher than before. This results in the outer layers of the star expanding considerably and, therefore, cooling. It is then possible for the helium in the core to fuse together to form carbon and possibly some larger nuclei, releasing more energy so that the star becomes more luminous. So, the star has a hotter core but it has become larger and cooler on the surface. Its colour therefore changes and it is then known as a red giant (or a red supergiant).

- After nuclear fusion in the core finishes, if the original mass of a red giant star was less than a certain value (about eight solar masses), the energy that is released as the core contracts forces the outer layers of the star to be ejected in what is known as a planetary nebula. The core of the star that is left behind has a much reduced mass. It is small and luminous and is described as a white dwarf. A white dwarf star can remain stable for a long time because of a process known as electron degeneracy pressure. The Chandrasekhar limit is the maximum mass of a white dwarf star (= 1.4 × solar mass).
- Red giants with original masses heavier than eight solar masses are known as red supergiants, but electron degeneracy pressure is not high enough to prevent further collapse and the resulting nuclear changes in the core produce a massive explosion called a supernova.
- If the core, after a supernova, has a mass of less than approximately three solar masses (called the Oppenheimer–Volkoff limit), it will contract to a very dense neutron star. It can remain stable for a long time because of a process known as neutron degeneracy pressure. If the mass is larger than the Oppenheimer–Volkoff limit, the core will collapse further to form a black hole.
- The changes to stars after they leave the main sequence can be traced on the HR diagram.

16.3 Cosmology

- When the line spectra emitted from galaxies are compared with the line spectra from the same elements emitted on Earth, the observed wavelengths (and frequencies) are slightly different. In most cases there is a very small increase (shift) in wavelengths, $\Delta\lambda$. Because red is at the higher wavelength end of the visible spectrum this change is commonly known as a 'red-shift'. More precisely, red-shift is defined by $z = \Delta\lambda/\lambda_0$, where λ_0 is the wavelength measured at source.
- Red-shift occurs because the distance between the galaxy and Earth is increasing. This is similar to the Doppler effect in which the wavelength of a source of sound that is moving away from us is increased.
- If the shift is to a longer wavelength (a red-shift), we know that the motion of the star or galaxy is away from Earth. We say that the star is receding from Earth.
- When the light from a large number of galaxies is studied, we find that nearly all the galaxies are receding from Earth, and each other. This can only mean that the universe is expanding.
- The magnitude of the red-shift, z (= $\Delta\lambda/\lambda_0$), can be shown to be approximately equal to the ratio of the recession speed to the speed of light ≈ v/c. This equation can be used to determine the recession speed of galaxies, but it cannot be used for galaxies that are moving at speeds close to the speed of light.
- The light from a small number of stars and galaxies is blue-shifted because their rotational speed within their galaxy or cluster of galaxies is faster than the recession speed of the whole system.
- A graph of recession speed, v, against distance from Earth, d, shows that the recession speed of a galaxy is proportional to its distance away. This is important evidence for the Big Bang model of the universe – the universe began at one point at a particular time (13.8 billion years ago) and has been expanding ever since. This was the creation of everything, including both space and time.
- Hubble's law is $v = H_0 d$ where H_0 is known as the Hubble constant (the gradient of the graph). The current value of the Hubble constant is not precisely known because of uncertainties in measurements of v and d. This equation can be used to estimate the age of the universe ($T = 1/H_0$), although it would wrongly assume that the universe has always been expanding at the same rate.
- It is important to understand that space itself is expanding, rather than galaxies expanding into a pre-existing empty space. The universe has no centre and no visible edge.
- The discovery of cosmic microwave background (CMB) radiation coming (almost) equally from all directions (isotropic) confirmed the Hot Big Bang model of the universe. The radiation is characteristic of a temperature of 2.76 K, which is the predicted temperature

to which the universe would have cooled since its creation. Alternatively, the current wavelength of CMB can be considered as a consequence of the expansion of space (the wavelength emitted billions of years ago was much smaller).

- Astronomers use the cosmic scale factor, R, to represent the size of the universe – R (at a time t) = the separation of two galaxies at time t the separation of the same two galaxies at some other selected time (usually now, so that the value of R now is 1).
- Red-shift is related to the cosmic scale factor by $z = (R/R_0) - 1$, where R_0 was the value of R at the time the radiation was emitted.
- Possible futures of the universe depend on if, and how, the expansion will continue. Simplified graphs of size of the universe (or cosmic scale factor) against time can be used to show the basic possibilities. They also represent different possibilities for the previous rates of expansion.
- The luminosities of Type Ia supernovae are known to be (almost) all the same, so that their distances from Earth can be calculated. However, recent measurements of their associated red-shifts suggest that these very distant stars are further away than the Hubble law predicts. In other words, the universe is expanding quicker than previously believed – the universe is 'accelerating'. It had been assumed that the forces of gravity would reduce the rate of expansion of the universe.
- The concept of 'dark energy' existing in very low concentration throughout space has been proposed as a possible explanation for the increasing rate of expansion of the universe.

16.4 Stellar processes

- The inwards collapse of clouds of interstellar matter because of gravitational forces is opposed by the random motions of the particles, creating an outwards pressure. In order for star formation to begin, the total mass of the cloud has to be high enough to create sufficient inwards gravitational forces. For a given temperature, the minimum mass required is called the Jeans mass, M_J. The Jeans mass is large enough for the formation of many stars from the same cloud.
- The Jeans criterion is that the collapse of an interstellar cloud to form a star can only begin if its mass, M, is higher than M_J.
- The fusion of hydrogen to helium in main sequence stars is a three-stage process known as the proton–proton cycle. It involves the release of a large amount of energy in the form of the kinetic energy of the nuclei, gamma rays and neutrinos.
- Because helium is denser than hydrogen, it remains at the centre of the star where it was formed.
- $L \propto M^{3.5}$ shows that more massive stars are much more luminous. If we assume that the luminosity of a star is proportional to mass/lifetime, T, then the lifetime of a main sequence star is approximately represented by $T \propto 1/M^{2.5}$. Using this equation, if we know the mass of a star, we can compare its lifetime to that of our Sun (the mass and lifetime of which are well known).
- A typical main sequence star begins its life with about 75% hydrogen and its main sequence lifetime will end when about 12% of its total hydrogen has been fused into helium. It will then form a red giant or supergiant, as described earlier.
- The temperatures in the cores of red giants and supergiants are sufficient to cause the fusion of helium nuclei (or heavier elements). The creation of the nuclei of heavier elements by fusion is called nucleosynthesis.
- For stellar masses lower than $4\,M_\odot$ (red giants) the core temperature can reach 10^8 K and this is large enough for the nucleosynthesis of carbon and oxygen.
- For stellar masses between $4\,M_\odot$ and $8\,M_\odot$ (large red giants) the core temperature can exceed 10^9 K and this is large enough for the nucleosynthesis of neon and magnesium.

- For stellar masses heavier than $8M_{\odot}$ (red supergiants) the core temperature is high enough for the nucleosynthesis of elements as heavy as silicon and iron. Because iron and nickel are the most stable nuclei, the nucleosynthesis of heavier elements by fusion is not possible.
- The structure of stars off the main sequence is layered ('like the skins of an onion') as the heavier elements are formed closer to the centre. A red supergiant will have the most layers.
- The formation of elements heavier than iron involves the processes of repeated neutron capture. Many neutrons are released during fusion processes in stars. Because they are uncharged they are not repelled by other nucleons and they can enter nuclei and be 'captured' by strong nuclear forces.
- Slow neutron capture (s-process) can occur in red giants over long periods of time at intermediate temperatures and neutron densities. The new nucleus formed undergoes beta decay to an element with increased proton number.
- Rapid neutron capture (r-process) can occur very quickly in supernovae at extreme temperatures and neutron densities. Many neutrons are captured by the same nucleus before beta decay occurs. The heaviest elements are formed this way.
- Supernovae are sudden, unpredictable and very luminous stellar explosions.
- Type Ia supernovae occur when a white dwarf star attracts enough matter from a close neighbour (in a binary system) to increase its mass sufficiently so that electron degeneracy pressure is no longer sufficient to resist its sudden collapse and increase in temperature. Widespread and sudden fusion results in the explosion. As explained before, this process occurs at a precise mass and the resulting luminosity is always the same, such that they are used as 'standard candles' to determine the distance to remote galaxies.
- Type II supernovae are the result of the inwards collapse of red supergiants when the fusion processes stop.

16.5 Further cosmology

- The cosmological principle states that (on the large scale) the universe is homogeneous and isotropic.
- There are two main reasons why radiation from a star or galaxy may be red-shifted:
  - The expansion of the universe. The space between the source and the observer has expanded between the time the radiation was emitted and the time it was received. This is called the cosmological red-shift.
  - The source of radiation and the observer could be moving relative to each other in unchanging space. This is known as the Doppler effect and it can also result in a blue-shift if the source and observer are moving closer together.
- It is possible for cosmological red-shift and the Doppler shift to occur at the same time, for example if a star is moving in its galaxy towards Earth, while the galaxy as a whole is receding due to the expansion of space.
- To understand the origins and future of the universe we seem to need to know how much mass it contains. But astronomers refer to the average density of the universe because it is assumed to be homogeneous and we are unable to observe all of it.
- The critical density, ρ_c, of the universe is the theoretical density that would *just* stop the expansion of the universe after an infinite time.
- Critical density can be related to the Hubble constant using classical physics: $\rho_c = 3H^2/8\pi G$.
- The actual average density of the universe can be estimated from the masses of the galaxies and their distribution. But adding the masses of the observed stars in a galaxy together does not produce an accurate figure for its total mass.
- Classical physics theory can be used to plot a graph of the orbital speed of stars in a galaxy against their distance, *r*, from the centre (a 'rotation curve').

- For stars close to the centre, the theoretical equation:

$$v = \sqrt{\frac{4\pi G\rho}{3}}\,r$$

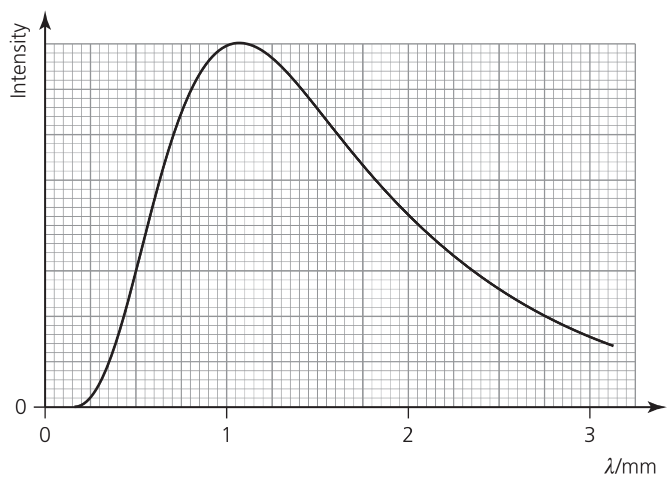
predicts the actual speeds reasonably accurately, but for more distant stars the prediction of rotational speeds does not match actual observations (using red-shift measurements). The more distant stars rotate at much higher speeds than expected. Astronomers explain this by proposing that the galaxy contains a large amount of matter that cannot be detected, called 'dark matter' (mostly in an outer halo).
- Dark matter is the name given to the proposed matter that must be present in the universe, but which has never been detected because it neither emits nor absorbs radiation.
- Dark matter is a subject of much continuing research in astronomy as explanations for this 'missing' mass are sought. MACHOs and WIMPs (including neutrinos) are two possible categories of particle that may explain dark matter.
- If the actual average density of the universe equals the critical density, the universe will expand at a decreasing rate, which will become zero after an infinite time – this is called a flat universe.
- If the actual average density of the universe is higher than the critical density, the universe will expand to a maximum size and then contract back to a point – this is called a closed universe.
- If the actual average density of the universe is lower than the critical density, the universe will continue to expand forever – this is called an open universe.
- The latest calculations (including dark matter) suggest that the actual average density of the universe is close to the critical density.
- However, the latest measurements on the red-shifts from distant supernovae provide strong evidence that the universe has been expanding at an increasing rate for about half of its lifetime. As mentioned before, this has led to the proposal of dark energy permeating all space.
- All of these possible futures for the universe can be represented on graphs of cosmic scale factor against time.
- From Wien's law we know that $\lambda_{max} \propto 1/T$ and as the age of the universe increases, space expands, λ_{max} increases and the cosmic scale factor R increases in proportion, so that $T \propto 1/R$. The average temperature of the universe multiplied by the cosmic scale factor is a constant.
- Fluctuations in the CMB (anisotropies) have been the focus of much research in recent years. Although these variations are tiny, they provide important evidence about the early stages of the universe and the origin of galaxies.
- The COBE, WMAP and Planck missions have provided an ever-improving bank of data on which astronomers are building an impressive understanding of the universe. Apart from information about anisotropies, this includes the latest estimates for the critical density and the age of the universe, plus estimates of the proportions of observable mass, dark matter and dark energy in the universe.

Examination questions – a selection

Paper 3 IB questions and IB style questions

Q1 **a** **i** What is the main energy source of a star? (1)
ii Explain how it is possible for a main sequence star to remain stable for billions of years. (2)
b **i** Define the luminosity of a star. (1)
ii Explain why main sequence stars can have very different luminosities. (2)
c **i** Define the apparent brightness of a star. (2)
ii Give two reasons why stars may have different apparent brightnesses. (2)
d Antares is a red supergiant 170 pc from Earth. Its luminosity is 2.5×10^{31} W and its surface temperature is 3400 K.
i Calculate the apparent brightness of Antares as seen from Earth. (2)
ii Explain what is meant by the term *red supergiant*. (2)
iii At what wavelength is the maximum intensity of the spectrum from Antares? (2)

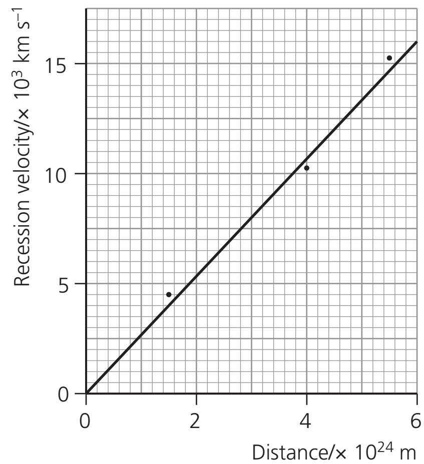
Q2 This question is about cosmic microwave background radiation. The graph shows the spectrum of the cosmic microwave background radiation.



The shape of the graph suggests a black-body spectrum, i.e. a spectrum to which the Wien displacement law applies.
a Use the graph to estimate the black-body temperature. (2)
b Explain how your answer to **a** is evidence in support of the Big Bang model. (2)
c State and explain another piece of experimental evidence in support of the Big Bang model. (2)

Q3 This question is about the mass–luminosity relation and also the evolution of stars.
The mass–luminosity relation for main sequence stars is assumed to be $L \propto M^{3.5}$, where L is the luminosity and M is the mass. Star X is 8×10^4 times more luminous than the Sun and 25 times more massive than the Sun.
a Deduce that star X is a main sequence star. (2)
b Outline with reference to the Oppenheimer–Volkoff limit, the evolutionary steps and the fate of star X after it leaves the main sequence. (3)

Q4 This question is about Hubble's law and the expansion of the universe.
a The spectrum of the cluster of galaxies Pegasus I shows a shift of 5.04 nm in the wavelength of the K-line. The wavelength of this line from a laboratory source is measured as 396.8 nm. Calculate the velocity of recession of the cluster. (2)
b The graph shows the recession velocities of a number of clusters of galaxies as a function of their approximate distances.



i State *one* method by which the distances shown on the graph could have been determined. (1)
ii Use the graph to show that the age of the universe is about 10^{17} s. (2)

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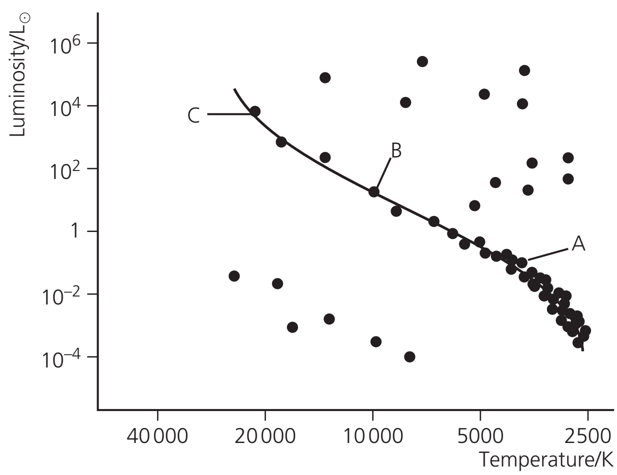
Q5 This question is about stellar evolution.
The diagram below represents a Hertzsprung-Russell (HR) diagram. The three identified stars (A, B and C) are all on the main sequence.



a Explain which of these stars is most likely to evolve to a white dwarf star.
b Draw and label the evolutionary path of the star as it evolves to a white dwarf star.

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Q6 **a** Explain how the cosmic scale factor is used by astronomers to represent the expansion of the universe. (2)
b If at some time, $+\Delta t$ in the future, the redshift of a distant galaxy is determined to be 0.020 calculate the cosmic scale factor at that time, compared with the present value of 1.00. (1)
c Suggest a possible value for the cosmic scale factor at a time $-\Delta t$ in the past. Explain your answer. (3)

Higher Level only

Q7 **a** What is a supernova? (1)
b Distinguish between the origins of type Ia supernovae and type II supernovae. (2)
c Explain why type Ia supernovae are considered to be 'standard candles'. (3)
d Describe the *r process* in supernovae, which results in the creation of heavy elements. (2)

Q8 **a** Explain why stars can only be formed from nebulae of sufficient mass (the Jeans mass). (2)

b Explain why more massive stars have shorter lifetimes on the main sequence. (2)

c **i** If a star has a mass five times greater than the Sun, estimate its main sequence lifetime (compared with the Sun). (2)

ii What will happen to this star after its time on the main sequence? (2)

Q9 **a** Show that the speed of rotation of a star at a relatively close distance of 4 kpc from the centre of a rotating galaxy of average density $1 \times 10^{-20}\,\mathrm{kg\,m^{-3}}$ is approximately $200\,\mathrm{km\,s^{-1}}$. (2)

b Sketch a graph to show how the rotational speeds of stars within the galaxy vary with distance from the centre. (3)

c Explain how your graph indicates the existence of dark matter within the galaxy. (2)

d State one possible origin of dark matter. (1)

Q10 **a** Explain what is meant by the Cosmological Principle. (2)

b Observation of the night sky indicates that more stars can be seen in some directions than in other directions. Discuss whether this contradicts the Cosmological Principle. (2)

Q11 **a** Explain the concept of the critical density of the universe. (2)

b Determine a value for the critical density of the universe in $\mathrm{kg\,m^{-3}}$ if the Hubble constant has a value of $70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. (2)

c **i** Express the critical density in terms of nucleons per cubic metre. (1)

ii Use your answer to estimate an average distance between nucleons at the critical density. (1)

d The actual average density of the universe is believed to be close in value to the critical density. However, the expansion of the universe is believed to be accelerating. Outline:

i the experimental evidence for this accelerating expansion (2)

ii how the proposed existence of dark energy may explain the expansion. (2)