27

Optional topic: Astrophysics

PRIOR KNOWLEDGE

Before you start, make sure that you are confident in your knowledge and understanding of the following points:

- Light is an electromagnetic wave, which travels at a speed of $3.0 \times 10^8\,m\,s^{-1}$ in a vacuum.
- Light is a wave, which shows the wave properties of reflection, refraction, diffraction and interference.
- A lens can be used to refract light.
- Lenses are used to focus light and to produce images of various objects.
- The Universe is made up of billions of stars and galaxies.
- The distance between galaxies is measured in millions of light years.
- The Universe is about 13.8 billion years old.

TEST YOURSELF ON PRIOR KNOWLEDGE

1 A ray of light is incident on one face of a parallel-sided block of glass, at an angle of 30° to the normal. Draw a sketch to show the path of the ray as it passes into and then out of the block of glass.

2 Describe how you would use a laser and an adjustable small slit to demonstrate the diffraction of light in a laboratory.

3 a) A light year is the distance that light travels in one year. Calculate this distance in metres.

b) A distant galaxy is 2 billion light years from Earth. Calculate this distance in metres.

4 a) Astronomers estimate that our Galaxy, the Milky Way, contains about 300 billion stars. They also estimate that the Universe contains approximately 200 billion galaxies. Calculate the number of stars in the Universe, stating any assumptions you make.

b) Our Sun has a mass of 2×10^{30} kg and its mass by composition is 75% hydrogen and 25% helium. Make an estimate of the number of hydrogen atoms (or nuclei) in the Universe, assuming that nearly all the Universe's hydrogen is in stars. State any other assumptions you make. The mass of a hydrogen atom is 1.67×10^{-27} kg.

TIP

If you have studied lenses in your GCSE course, you might be able to move on to the section on telescopes. This section is provided as background for those who are unfamiliar with lenses.

The Milky Way is the name we give our Galaxy. Our Sun is one of about 300 billion stars in the Galaxy. On a dark night the Milky Way is an awe-inspiring sight, which has caused people to wonder with amazement at our world. Babylonian astronomers developed geometry and trigonometry, some four thousand years ago, so that they could measure and plot the positions of the stars that they observed. It is an interesting thought that if we lived on a planet that was covered in dense clouds, and where clear skies and stars were never seen, we might not have trigonometry on the school curriculum and we would have little idea about the origin of our Universe.

Lenses

A convex or **converging lens** is designed so that it can focus light rays to a point. For example, you may have used a converging lens to focus the Sun's rays on to a piece of paper, so that it starts to burn. The principle behind a converging lens is illustrated in Figure 27.1. A ray of light is incident on the lens at an angle *i* to the normal, with an angle of refraction *r*. As the ray leaves the lens, it bends away from the normal, as shown.

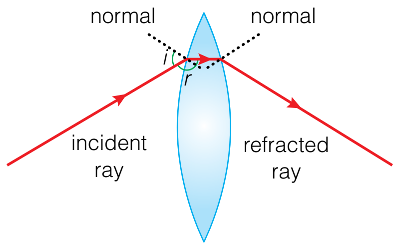


Figure 27.1 The principle behind a converging lens.

Converging lens A converging lens refracts rays of light to a point.

Figure 27.2 shows more about the nature of converging lenses. A lens is constructed to that it is symmetrical about its **principal axis**. A ray that passes along the principal axis passes through the lens undeviated, because it is parallel to the normals on both faces. Rays that are parallel to the principal axis come to a focus at the lens's **focal point**. There are two focal points, one on either side of the lens. The **focal length** of a converging lens is the distance between the centre of the lens and the focal point.

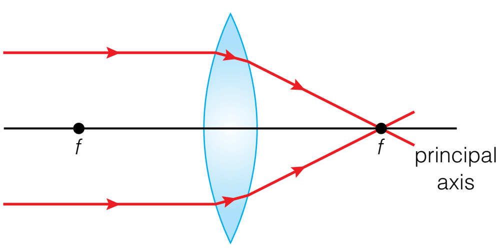


Figure 27.2 Rays parallel to the principal axis meet at the focal point.

The lens in Figure 27.2 has a short focal length because its surfaces have small radii of curvature, and the light is refracted through relatively large angles. The lens in Figure 27.3 is thinner than the lens in Figure 27.2. It is less curved and its focal length is longer.

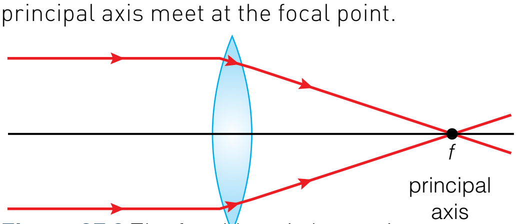


Figure 27.3 The focal lens is longer in a lens that is thinner and less curved.

Construction of ray diagrams

There are three classes of light ray that are used to predict the position of an image formed by a converging lens. These are illustrated in Figure 27.4. (Note that, when we draw a ray diagram for a lens, we simplify the process of refraction by assuming that it happens in just one part of the lens. So the lens is drawn as a thin vertical line. The arrows pointing out from the centre of the lens, at the top and bottom, indicate that this lens is a converging lens. (If the arrows point the other way, it is a diverging lens.)

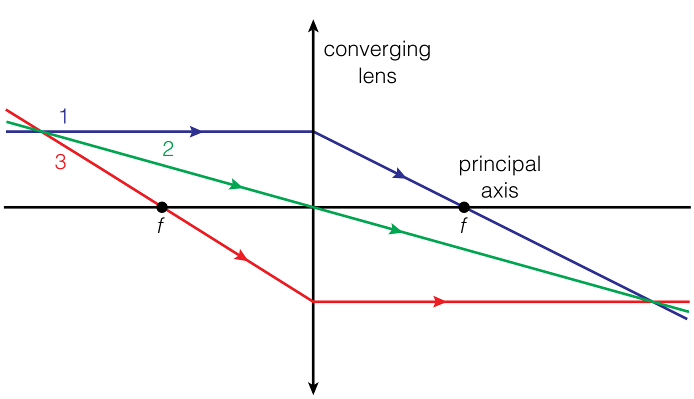


Figure 27.4

1. A ray parallel to the principal axis (on the left side of the lens) is refracted so that it passes through the focal point on the right side of the lens.
2. A ray that passes through the optical centre of the lens is undeviated.
3. A ray that passes through the focal point on the left side of the lens is refracted so that it travels on a line parallel to the principal axis on the right side of the lens.

Projecting an image

Focal length The focal length of a lens is the distance between the centre of the lens and the point at which rays parallel to the principal axis are brought to a focus.

Principal axis The principal axis of a lens is an imaginary line that passes through the centre of a lens and through the centres of curvature of the faces of the lens.

Focal point The focal point of a lens is the point at which rays parallel to the principal axis of the lens are brought to a focus.

Figure 27.5 shows how you can use two of the construction rays to predict where an image will be formed by a converging lens. Provided the object lies outside the **focal length** of the lens, a real image will be formed. The image is real when the rays converge at a point. This image can be focused on to a screen.

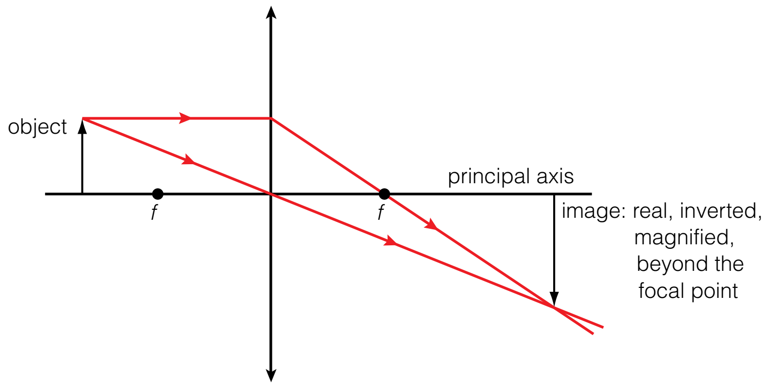


Figure 27.5

Figures 27.6a and b show how two different converging lenses can be used to project an image of a distant object. Light rays from the same point on a distant object arrive at the lens very nearly parallel to each other. So, for example, rays from the top of a distant object arrive at the lens parallel to each other and rays from the bottom of the same object also arrive parallel to each other. Lens B produces a larger image than lens A, because it has a longer focal length. This idea will be used later when we consider the design of an astronomical telescope.

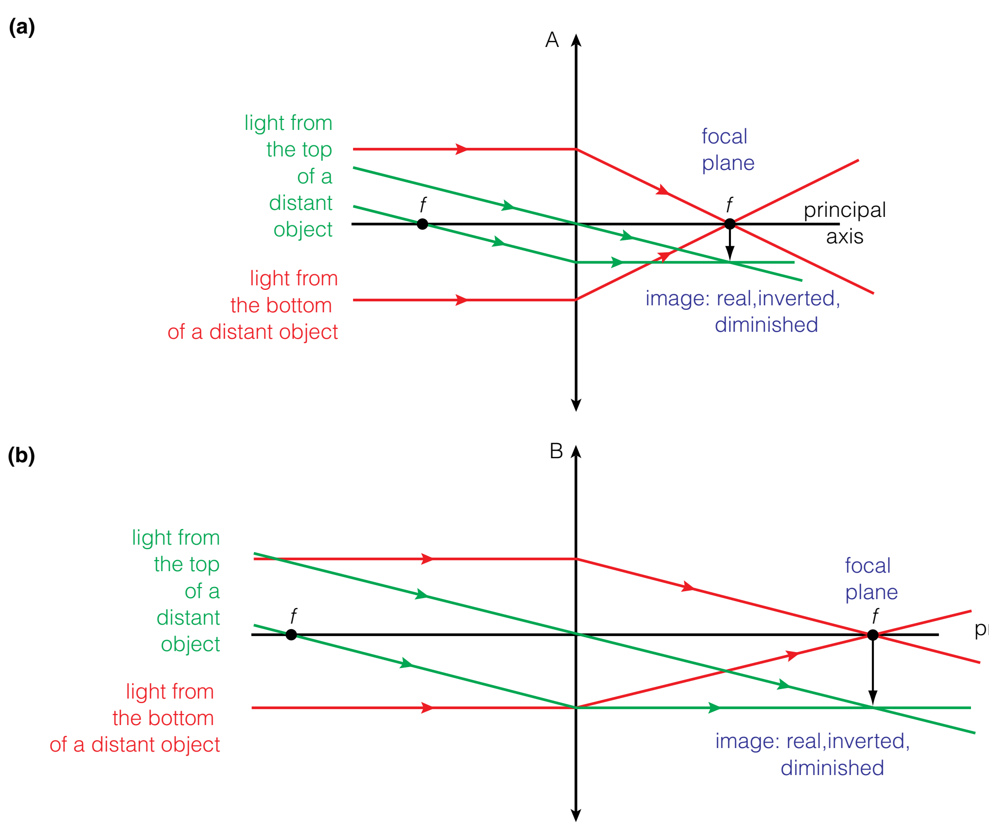


Figure 27.6 A lens with longer focal length projects a larger image of a distant object; the image projected by lens B is larger than the image projected by lens A.

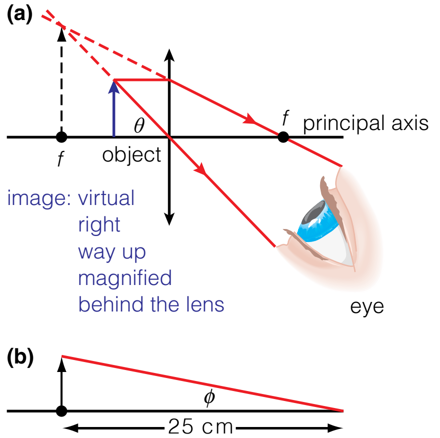


Figure 27.7 (a) An object viewed inside the focal length of a lens produces a virtual magnified image. (b) Without a lens, you can only focus on an object at your near point of vision.

The magnifying glass

Figure 27.7a shows what happens when an object is placed inside the focal length of a converging lens. Rays from the top of the object now diverge, and do not come to a focus. If your eye is placed behind the lens, the object appears to be bigger and further behind the lens. This is a virtual image. It cannot be projected on to a screen and it appears only to the eye on the other side of the lens. When the lens is used like this, it is called a magnifying glass. The object appears bigger because the lens produces a magnified image at your near point. Without the lens, you can only focus on the object at your near point of vision – perhaps 25 cm away, as shown in Figure 27.7b. The lens causes magnification because the angle θ in Figure 27.7a is bigger than the angle ϕ in Figure 27.7b.

Figures 27.8a and b show how two lenses can be used to view an object situated at the focal point of a lens. In both cases, a virtual image is seen at infinity, behind the lens. However, the magnification of lens D is larger than the magnification of lens C, because angle β is larger than angle α. So a converging lens with a short focal length is a more powerful magnifying glass than a converging lens with a longer focal length. This idea is also important when designing an astronomical telescope.

The astronomical telescope

Figure 27.9 shows the principle behind the astronomical refracting telescope. The objective lens (the lens pointing towards the distant object) projects a real image of a distant object such as the Moon. This image is larger for a longer focal length of the objective lens, f_o. The eyepiece is now used to magnify this image. A short focal length eyepiece produces a larger magnification of the telescope.

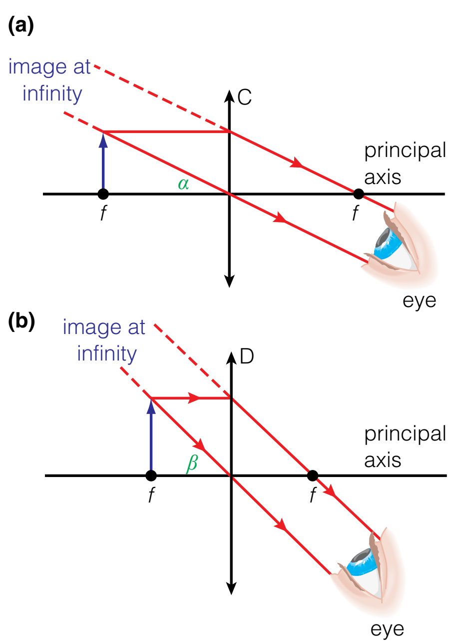


Figure 27.8 A shorter focal length converging lens is a more powerful magnifying glass.

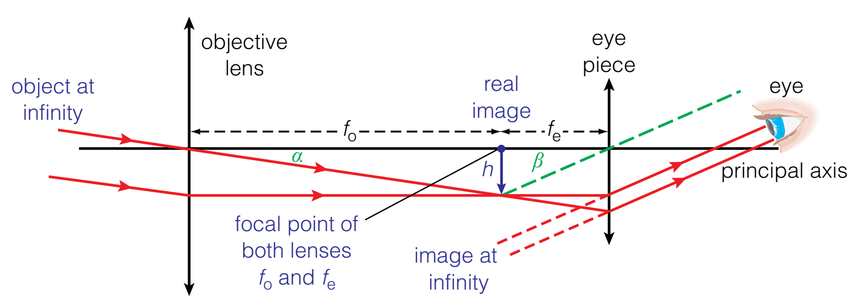


Figure 27.9

Using trigonometry, we can write

$$\tan\alpha = \frac{h}{f_e}$$

$$\tan\beta = \frac{h}{f_e}$$

where h is the height of the real image, f_o is the focal length of the objective lens and f_e is the focal length of the eyepiece lens. But for small angles (expressed in radians)

TIP

The angle subtended by an object is the angle between the rays coming from the extremities of the object to the eyes or telescope lens.

$$\tan\alpha \approx \alpha \quad \text{and} \quad \tan\beta \approx \beta$$

so

$$\alpha = \frac{h}{f_o} \quad \text{and} \quad \beta = \frac{h}{f_e}$$

The angular magnification, M, of the telescope is defined as:

$$M = \frac{\text{angle subtended by image at eye}}{\text{angle subtended by object at unaided eye}}$$

$$= \frac{\beta}{\alpha} = \frac{h}{f_e} \times \frac{f_o}{h} = \frac{f_o}{f_e}$$

TIP

The magnification of an astronomical telescope in normal adjustment is $M = \frac{f_o}{f_e}$

A telescope is described as being in normal adjustment when the real image, produced by the objective lens, is viewed at the focal point of the eyepiece. Under these circumstances, a magnified virtual image is viewed at infinity.

Safety: NEVER look directly at the Sun through a telescope – you will burn your eye.

ACTIVITY

A simple model telescope

Select two converging lenses with different focal lengths – for example, 50 cm and 10 cm. Use modelling putty to stick them on to a metre rule 60 cm apart. You have just made a simple model telescope.

1 Look through the 10 cm lens towards the 50 cm lens and describe what you see.
2 Look at a brick wall through your telescope with one eye, and use the other eye to look directly at the wall. Calculate the telescope's angular magnification.
3 Draw a ray diagram to show the passage of light through your telescope.

TEST YOURSELF

1 a) A man of height 1.7 m stands a distance of 10 m away from you. Calculate the angle he subtends at your eye. Give your answer in radians.
b) The man now moves to a distance of 120 m away. Calculate, in radians, the angle he now subtends at your eye.
c) Is the small-angle approximation, $\tan\alpha = \alpha$, valid in case (a) or case (b) or both cases?

2 Explain why an astronomical telescope should have
a) an objective lens of long focal length
b) an eyepiece with a short focal length.

3 What is the length of an astronomical telescope in normal adjustment, when it has an objective lens of focal length 2.50 m and an eyepiece of focal length 40 mm.

4 The great refractor in the Vienna Observatory has an objective lens with a focal length 10.5 m.
a) Explain why this telescope has an objective lens with this large focal length.
b) The telescope is used with an eyepiece of focal length 50 mm. Calculate the angular magnification of the telescope.

5 Two stars are separated by an angle of 0.05° when viewed directly by eye. What angle do the images of the stars subtend when viewed through an astronomical telescope with an objective lens of focal length 2.4 m and an eyepiece of focal length 40 mm?

Lens aberrations

Although refracting astronomical telescopes are very useful instruments, their effectiveness is reduced to some extent by the limitations of their lenses. Glass lenses have two main types of *aberration*, which limit the sharpness of the image that we see.

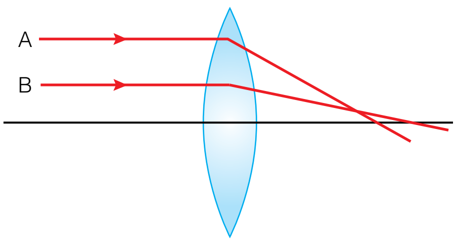


Figure 27.10 Spherical aberration: rays from a distant object are not brought to a focus at a single point.

Spherical aberration

Most lenses are ground into a spherical shape, but this is not quite the ideal shape for a lens. Figure 27.10 shows two rays, parallel to the principal axis of a lens, which come from the same distant object. The two rays refract at different angles, but they do not pass through the same focal point – the ray at the top of the lens, A, comes to a focal point closer to the lens than the lower ray, B. As a result of this there is a slight blurring of the image that we see.

Spherical aberration can be demonstrated easily in the laboratory. A lens is used to project an image of a lamp filament on to a screen. If a card with a small hole is placed in front of the lens, you will see that the image becomes sharper. This is because rays pass through only a small part of the lens.

It is possible to reduce spherical aberration by using a lens with a parabolic shape. However, such lenses are very expensive, and they produce some distortion of the image, except for light exactly parallel to the principal axis.

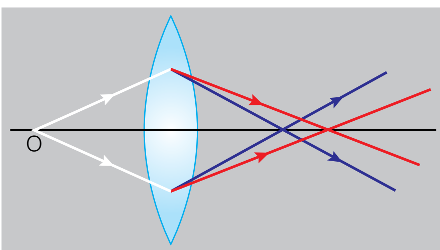


Figure 27.11 Chromatic aberration: different colours of light are refracted by different amounts.

Chromatic aberration

Figure 27.11 shows two rays of white light being refracted by a lens. The speed of light through glass depends on its wavelength. Blue light has a shorter wavelength than red light, and it travels more slowly than red light through glass. Consequently, blue light is refracted more than red light, and there are different points of focus for the two colours. This is called *chromatic aberration*. It is possible to reduce the effects of chromatic aberration, but not to remove it entirely, by constructing a lens using two different types of glass.

Reflecting telescope

Figure 27.12 shows the principle behind the Cassegrain reflecting telescope. Light from a distant object strikes the primary concave mirror, where the light is reflected towards the focal point at F. However, a secondary convex mirror reflects the light again, so that it is focused at F′, where a real image is formed. The observer can then see a magnified image through the eyepiece, which is placed behind a hole in the primary mirror.

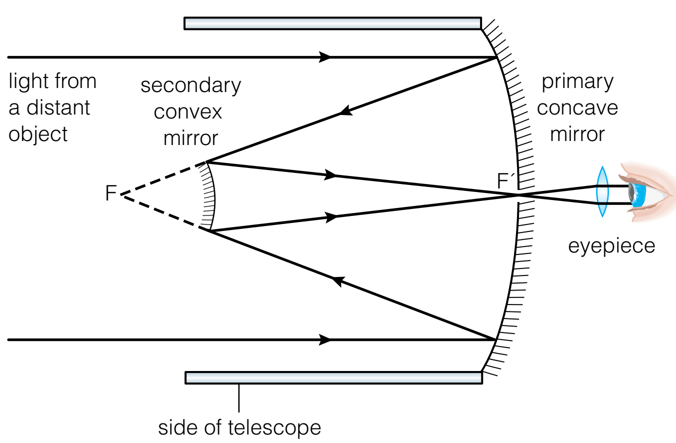


Figure 27.12 Principle of the Cassegrain reflecting telescope.

A reflecting telescope has several advantages over a refracting telescope.

- A good astronomical telescope requires a diameter of about 15 cm or more, so that sufficient light is gathered. It is very difficult to make a high-quality lens of diameter 15 cm, but much easier to make a concave mirror of that size.
- A reflecting mirror has no chromatic aberration, because light is reflected over a metal surface without passing through glass.
- Spherical aberration can be reduced more easily in a reflecting telescope by making the concave mirror parabolic in shape. A parabolic mirror focuses light that is parallel to the principal axis accurately at the focal point.
- It is possible to make reflecting telescopes with larger diameters than refracting telescopes. The world's largest refracting telescope, at the Yerkes Observatory, has a diameter of 1.0 m. There are several reflecting telescopes that have diameters over 8 m – for example, the Subaru Telescope in Hawaii has a mirror of diameter 8.2 m. A glass lens with a diameter of over 1 m begins to sag under its own weight, whereas a mirror can be supported by a strong structure behind it.

Collecting power is a measure of the light intensity gathered by a telescope. This is proportional to the square of the telescope's diameter.

The **collecting power** of a telescope is proportional to its area. Since the area of the telescope mirror is $\frac{\pi d^2}{4}$, where d is its diameter, the collecting power is proportional to the diameter squared, d^2. Larger telescopes are able to show fainter objects, because more light is collected. Images in large telescopes are also less affected by diffraction – this is dealt with in detail in the next section.

EXAMPLE

Comparison of collecting powers

Compare the light gathered by two telescopes – a reflecting telescope that has a mirror with a diameter of 36 cm, and a refracting telescope that has an objective lens with a diameter of 10 cm.

Light gathered by a telescope is measured by the collecting power, which is proportional to the telescope's diameter squared. So:

$$\frac{\text{collecting power of the reflector}}{\text{collecting power of the refractor}} = \frac{(36)^2}{(10)^2}$$

$$= 13 \text{ (2 s.f.)}$$

A refracting telescope does have some advantages over a reflecting telescope.

- The lenses in a refractor are held in place by a metal tube. So little maintenance is required. The mirror in a reflecting telescope is exposed to the air, and might need recoating.
- The mirrors in a small reflector can get out of alignment if the telescope gets knocked. So sometimes the mirrors need adjustment. The strong construction of the refracting telescope makes such misalignment less likely.
- The secondary mirror in a reflecting telescope has the disadvantage of blocking some light from entering the primary mirror.
- The secondary mirror and its supports will cause some diffraction which will degrade the image.

TEST YOURSELF

6 Explain the meaning of the terms:
   a) chromatic aberration
   b) spherical aberration.

7 Explain four advantages that reflecting telescopes have over refracting telescopes.

8 An amateur astronomer uses his 12 cm diameter reflector to take a photograph of Jupiter and its moons. He finds that he needs to expose his photograph for 16 s to get a clear photograph. He visits a friend to take a photograph using her reflecting telescope, which has a diameter of 28 cm.

   What exposure time would you advise for the photograph using the 28 cm reflector? They use the same photographic equipment.

Angular resolution of telescope

You met the idea of the diffraction of light in Chapter 6. To demonstrate the diffraction of light in a laboratory, it is necessary to direct a beam of light through a very narrow slit – then we can see the light spread out. However, the effects of diffraction are apparent when light enters a telescope aperture, even though the telescope has a diameter of many centimetres or even metres.

Figure 27.13 shows how the intensity of light, with wavelength λ, varies after it has been diffracted through a slit of width D. There is an area of high intensity – the central maximum – and the light intensity falls to zero when:

$$\sin\theta = \frac{\lambda}{D}$$

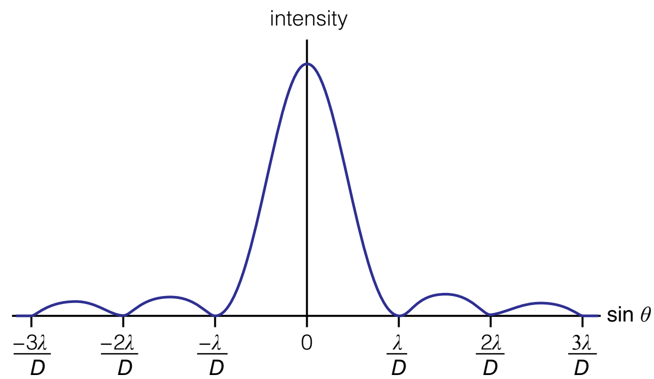


Figure 27.13

MATHS BOX

When light passes through a circular aperture of diameter D, the first minimum occurs at angle θ given by

$$\sin\theta = \frac{1.22\lambda}{D}$$

However, we shall work with the approximation that the minimum occurs for small angles at

$$\theta = \frac{\lambda}{D}$$

Because the angles of diffraction that we shall be dealing with are very small, we can work in the small-angle approximation and say that the first diffraction minimum occurs at an angle of:

$$\theta = \frac{\lambda}{D}$$

So when light from a star passes through a telescope, the image of the star has a measurable width due to diffraction as the light passes through the lens or mirror aperture.

Diffraction affects how well a telescope can resolve fine detail. Figure 27.14 shows the idea. Figure 27.14a shows the diffraction pattern due to two small sources of light, after passing through a narrow aperture. The patterns

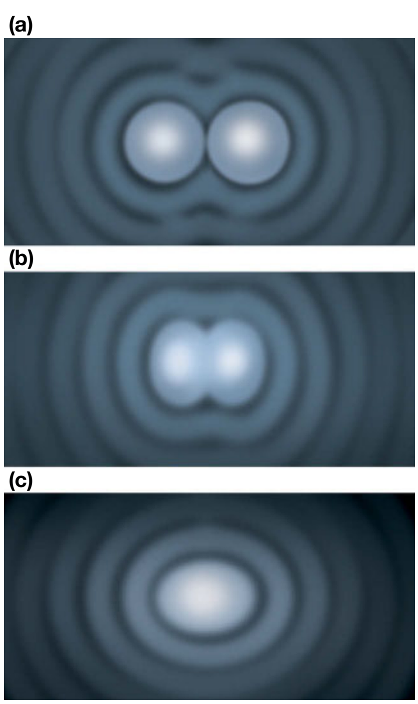


Figure 27.14

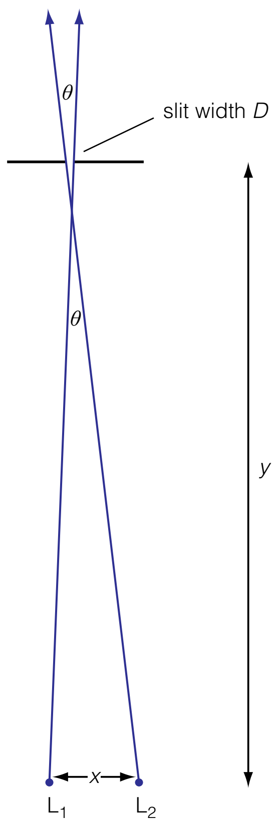


Figure 27.15

overlap, but we can see two separate, distinct patterns. In Figure 27.14b the sources have been moved closer together. Now the patterns merge into each other, but we can still see that there are two sources. We say we can just *resolve* the two sources. In Figure 27.14c the sources are so close together that we cannot distinguish between them – the sources are not resolved.

Rayleigh's criterion

Figure 27.15 shows an arrangement you can use in the laboratory to investigate the resolution of two small filament lamps. The two filaments are arranged so that they are about 1 cm apart (the distance x in the diagram). They are then viewed through a narrow slit, which can be adjusted to be about 0.2 mm (2×10^{-4} m) wide. What do we see when we look at the lamps as we vary their distance, y, from the slit?

Figure 27.16 shows how the intensity will appear for different values of y. In Figure 27.16a the lamps are close to the slit, so their angular separation is relatively large and we see two separate patterns of intensity (this is similar to the photographs in Figure 27.14). In Figure 27.16b the lamps are further away, so that they are just resolved, and in Figure 27.16c the lamps are so far away that the eye cannot see any small dip in intensity between the lamps – so they cannot be resolved.

Figure 27.16b shows the Rayleigh criterion for resolution. When the first minimum of one of the sources coincides with the maximum of the second source, we can just see (resolve) the two separate sources. This rule is only a guide because some people's eyes are better than others.

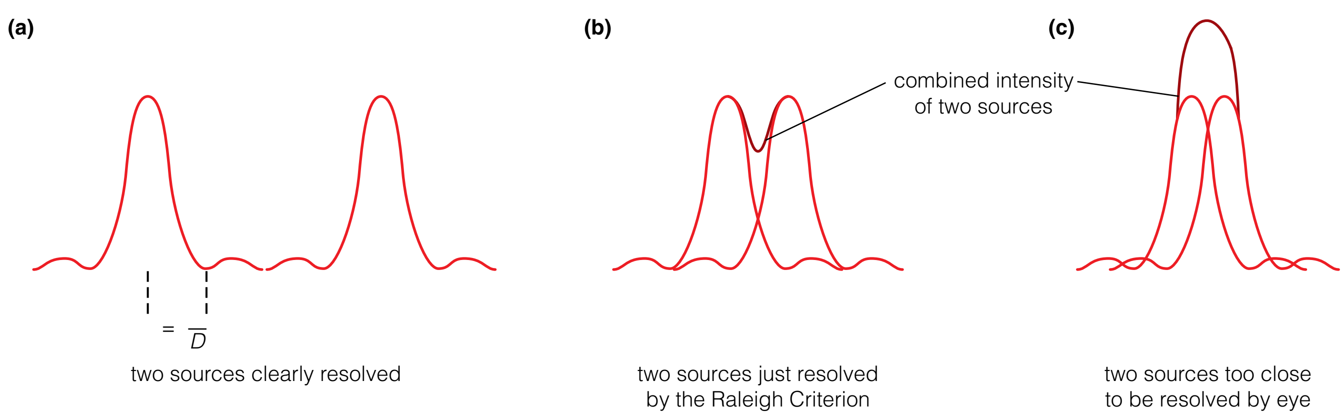


Figure 27.16

Rayleigh's criterion for resolution can be written as follows – when two sources, emitting light of wavelength λ, have an angular separation θ and are viewed through an aperture of diameter D:

- If $\theta > \dfrac{\lambda}{D}$ the sources can be resolved.
- If $\theta \approx \dfrac{\lambda}{D}$ the sources can just be resolved.
- If $\theta < \dfrac{\lambda}{D}$ the sources cannot be resolved.

EXAMPLE

Angular separation of two lamps

Two lamps are separated by a distance of 1.2 cm, and they are placed 4.0 m away from a narrow slit of width 2×10^{-4} m. They are viewed through a blue filter, which allows light of wavelength 4.8×10^{-7} m to pass. Will an observer be able to resolve the two lamps?

Answer

We use the small-angle approximation to calculate the angle between the lamps:

$$\tan\theta \approx \sin\theta \approx \theta = \frac{x}{y}$$

where x is the separation of the lamps, and y is their distance from the slit

So the angular separation of the lamps is

$$\theta = \frac{x}{y} = \frac{1.2\text{cm}}{400\text{cm}} = 3 \times 10^{-3}\ \text{rad}$$

The smallest angle that the observer will be able to resolve is

$$\frac{\lambda}{D} = \frac{4.8 \times 10^{-7}}{2 \times 10^{-4}} = 2.4 \times 10^{-3}\ \text{rad}$$

Because $\theta > \frac{\lambda}{D}$ the lamps may be resolved.

TEST YOURSELF

9 Two small lamps, each with a thin wire filament, are set up with the filaments 1.5 cm apart. They are placed 6.0 m away from a slit of width 0.22 mm. Explain what a student sees when she views the lamps through the slit when the following filters are placed in front of the lamps:

a) a red filter passing light of wavelength 6.5×10^{-7} m

b) a green filter passing light of wavelength 5.4×10^{-7} m

c) a blue filter passing light of wavelength 4.7×10^{-7} m.

10 The presence of turbulence in the atmosphere reduces the resolving power of any telescope by about a factor of 10. What this means is that a large reflecting telescope such as the Subaru Telescope, with a diameter of 8.2 m, is only as effective as a telescope with a diameter of 0.82 m in perfect conditions (in space, for example).

a) The Andromeda galaxy is a distance of 2.2 million light years away from Earth. It is possible to see blue giant stars at this distance, which emit light of wavelength around 4.0×10^{-7} m. What is the minimum separation of two blue giants for the Subaru Telescope to be able to resolve them?

b) The Hubble Space Telescope has the advantage of being above the Earth's atmosphere. It has a mirror diameter of 2.4 m. Repeat the calculation in part (a) for the Hubble Space Telescope.

11 A student draws two black lines 1 mm apart on a piece of paper. She walks away from them until, at a distance of 5 m, she can no longer see them as two separate lines. Another student measures the diameter of the pupil of the eye of the first student, and finds it to be about 3 mm. Make an estimate of the wavelength of light.

Seeing stars

In the days of modern technology, it is easy to think of microscopes, telescopes and cameras, all as excellent optical instruments. However, we must never underestimate the brilliance of our own two eyes. Our eyes and brain process vast amounts of information every second. We can judge depth with binocular vision, and by rapidly looking around we build up an understanding of our surroundings that even the best cameras cannot match. However, optical instruments give us fresh insight into our surroundings, and this is particularly so in the field of astronomy.

The first way we look at stars is to use our eyes, but we see more when we use binoculars or a small telescope. A telescope gathers more light than our eyes, so we see fainter objects, and the larger aperture of the telescope allows us to resolve more detail. However, astronomers realised, around the start of the twentieth century, that even more information could be gathered by using a camera together with a telescope.

By 'driving' a telescope so that it rotates at the same rate as the Earth, it is possible to track stars exactly over a long period of time. Then a very long-exposure photograph can be taken, and the film developed later.

Now, all telescopes used by professional astronomers use cameras with charge-coupled devices (CCDs) to detect the light from stars and galaxies. A CCD is a slice of silicon that stores electrons freed by the energy of incoming photons. The charge on the electrons builds up an image as a pattern of pixels. CCDs are much more sensitive to light than photographic film, and they have the advantage that information can be stored in digital form and processed by computers. Now cameras using CCDs are readily available to us all, and astronomers use high-quality CCDs with hundreds of megapixels to take long-exposure photographs of deep space.

A CCD has a very high quantum efficiency. What this means is that a very high percentage of photons that strike the CCD produce charge carriers, which are then detected. Quantum efficiency is defined:

$$\text{quantum efficiency (QE)} = \frac{\text{number of electrons produced per second}}{\text{number of photons absorbed per second}}$$

The quantum efficiency depends on the frequency of the light incident on the CCD. In Table 27.1 we compare the QEs of our eye, some film and a CCD.

Table 27.1

Device	Quantum efficiency/%
Eye	1–4
Film	4–10
CCD	70–90

As Table 27.1 shows, a CCD has a very high quantum efficiency, so a large telescope equipped with millions of pixels easily outperforms the eye. CCDs can also be designed to be sensitive to other types of electromagnetic radiation, including infrared, ultraviolet and X-rays. So telescopes can be used to investigate waves emitted from stars that lie outside visible wavelengths.

Telescopes beyond the visible range

When astronomers observe the sky, they are not just interested in visible light, because stars and galaxies emit the whole range of electromagnetic radiation from radio waves to X-rays and gamma rays. For example, hot stars emit radiation well into the ultraviolet range, matter close to black holes emits X-rays and colder objects emit infrared radiation and radio waves.

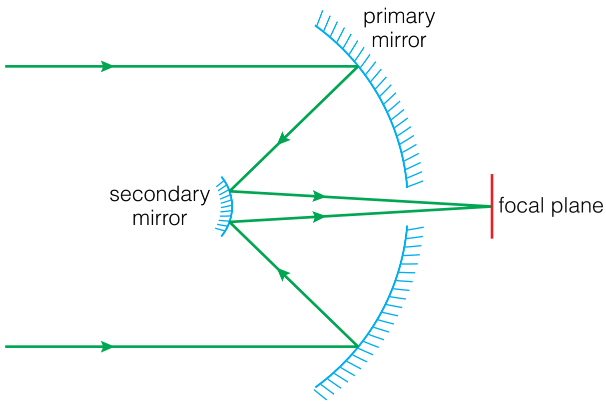


Figure 27.17 Cassegrain reflecting arrangement of mirrors for ultraviolet and infrared radiations, and radio waves.

Telescopes that can detect radiations outside the visible range have many similarities to optical telescopes, but also some important differences. The most obvious difference is that there is no eyepiece because, of course, the eye cannot see infrared, ultraviolet or other radiations. However, for radio waves, infrared and ultraviolet radiations, a Cassegrain reflecting telescope is often used as shown in Figure 27.17. The waves are focused behind the primary mirror: infrared and ultraviolet radiations are detected by CCDs, and aerials can detect radio waves in a radio telescope. Then electrical signals, produced by detectors in the focal plane, are sent to computers which build up colour-coded pictures so that we can 'see' the various intensities of radiations.

Radio telescopes

Figure 27.18 shows a photograph of a radio telescope with its large primary mirror and its secondary mirror, which focuses the waves on to a detector behind the primary mirror. The siting of a radio telescope is not critical because radio waves are not affected by atmospheric conditions – radio waves will still reach the telescope on a cloudy day.

The mirrors or dishes for radio telescopes are very large. To detect radio waves with wavelengths in the range 30 cm to 3 m, dishes are usually larger than 100 m in diameter, but smaller dishes can be effective for shorter-wavelength radio waves. The large-diameter radio dishes mean that the collecting power of the telescope is very high. Often radio telescopes do not have a secondary mirror but position the detector directly at the focal point of the primary mirror.

Figure 27.18 A photograph of a radio telescope

The reason for building such large telescopes is to ensure that it is possible to resolve two close radio sources. You will recall from the work on optical telescopes that the criterion for resolving two sources separated by an angle θ is

$$\theta \approx \frac{\lambda}{D}$$

where λ is the wavelength of the radiation, and D is the telescope diameter.

EXAMPLE

Resolving two radio sources

What is the smallest angular separation of two radio sources emitting radio waves of wavelength 0.3 m that can be resolved by a telescope of diameter 60 m?

Answer

Using the expression from the text

$$\theta \approx \frac{\lambda}{D} = \frac{0.3\,\text{m}}{60\,\text{m}} = 5 \times 10^{-3}\ \text{rad}$$

optical telescopes are able to resolve much smaller angle than this.

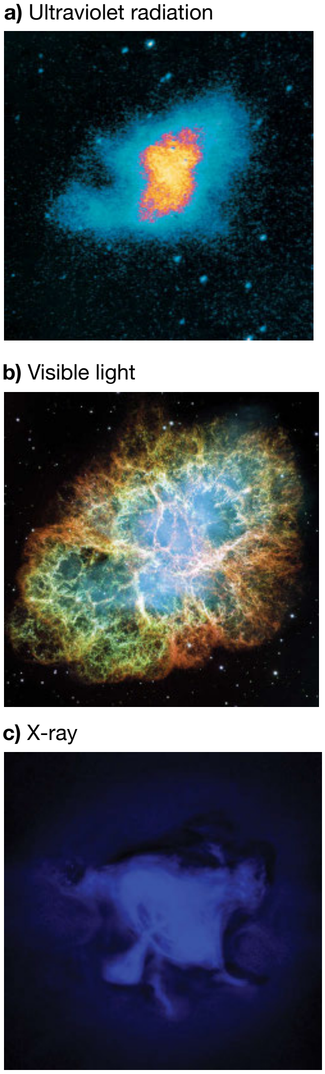


Figure 27.19 Three photographs taken at different wavelengths show the remnants of a supernova explosion seen in 1054. This is known as the Crab nebula.

Ultraviolet and infrared telescopes

The construction of ultraviolet and infrared telescopes is fairly similar to that of an optical telescope, because the wavelengths of the two radiations lie at either end of the visible spectrum. However, careful consideration of the position of these telescopes is essential because of the effect of the atmosphere on ultraviolet and infrared radiations. The majority of ultraviolet radiation is absorbed by the atmosphere, so ultraviolet telescopes are usually in orbit around the Earth in a satellite. Some infrared radiation penetrates the atmosphere, so it is possible to position some infrared telescopes on mountain tops to view specific wavelengths of radiation. Other infrared telescopes are in orbit around the Earth, so that they can detect infrared radiations that do not penetrate the atmosphere.

The collecting power of infrared and ultraviolet telescopes is similar to the that of an optical telescope, because their diameters are similar. However, the resolving power of an ultraviolet telescope is better than for an optical telescope of the same diameter – this is because ultraviolet light has a shorter wavelength than visible light. By contrast, an infrared telescope of the same diameter as an optical telescope does not resolve objects as well as an optical telescope, because the wavelength of infrared radiation is longer than that of visible light. Some telescopes are able to receive near-infrared, visible and near-ultraviolet wavelengths by using a range of CCDs.

Figure 27.19 shows three images of the Crab nebula, taken through different telescopes, detecting three different wavelengths of radiation. The X-ray photograph is able to look through the other layers of the nebula, to detect energy being emitted from a pulsar (a rapidly rotating neutron star) at the centre of the nebula.

X-ray telescopes

X-ray telescopes are also usually situated in space because the atmosphere prevents the majority of X-radiation reaching the Earth's surface. Figure 27.20 shows the design of an X-ray telescope, which is considerably different from the reflecting telescopes discussed above.

X-rays are very penetrating and they are not easily reflected off metal surfaces. You are used to the idea of light being incident on a glass surface. Some light is reflected and some is transmitted by the glass. X-rays behave in this way when incident on a metal surface. However, if X-rays are incident at a very shallow angle, on a highly reflective metal such as iridium, they are all reflected. This is rather like skimming a stone along the surface of water.

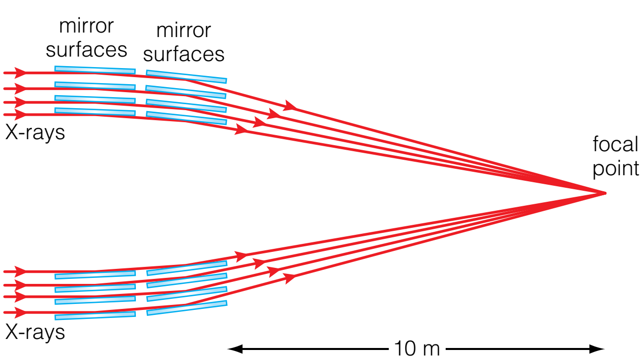


Figure 27.20 X-ray telescopes focus X-rays with very shallow reflections.

In Figure 27.20 X-rays are reflected off a series of mirrors and brought to a focus some 10 m away from the mirrors. Since X-rays have very short wavelengths, 10^{-9} or 10^{-10} m, it is possible to make X-ray telescopes with a small diameter and still produce well-resolved images. The design of telescope shown in Figure 27.20 can also be used to focus some short-wavelength ultraviolet radiations, which are difficult to focus with a conventional telescope.

TEST YOURSELF

12 Explain why radio telescopes have dishes with diameters as large as 100 m.

13 **a)** Describe how the design of an X-ray reflecting telescope differs from that of an optical reflecting telescope. Account for the differences in design.

b) Explain why X-ray telescopes are in orbit around the Earth rather than on the Earth's surface.

14 The table below shows information about two infrared telescopes.

Telescope	Diameter of primary mirror/cm	Wavelength of radiation detected/μm
Wide-field Infrared Survey Explorer (WISE)	40	3–25
Herschel	350	50–670

a) Explain why the Herschel telescope has a larger diameter than the WISE telescope.

b) Calculate the ratio of the collecting powers of the two telescopes.

c) Calculate the smallest angular separation that each telescope can resolve for

i) the shortest wavelength it detects

ii) the longest wavelength it detects.

Classification of stars

Brightness The brightness of a star is a measure of how much visible light from the star reaches our eyes.

Luminosity The luminosity of a star is the energy it emits per second, in all wavelengths.

When you go outside on a dark moonless night, it is a wonderful sight to see the sky illuminated by thousands of stars. In total, there are about 6000 stars that it is possible to see with the unaided eye. However, with binoculars or a telescope, the number of stars we can see rises into the millions. The **brightness** of the stars we see varies considerably, and this is affected by a star's **luminosity** and how far away it is. The luminosity of a star is the amount of energy it emits per second.

Classification by brightness

Hipparchus was a Greek astronomer who lived some 2200 years ago. He was the first person to begin to categorise stars according to their visual brightness in the sky. Hipparchus began by cataloguing all the brightest stars, and these he called first-magnitude stars. Then he listed the next brightest, and called them second-magnitude stars, and so on until he reached sixth-magnitude stars. The sixth-magnitude stars were the faintest stars that Hipparchus could see by eye.

Two thousand years later modern astronomers looked at the Hipparchus scale of brightness and realised that he had produced a logarithmic scale. A first-magnitude star turns out to be about $2\frac{1}{2}$ times the brightness of a second-magnitude star; and a second-magnitude star is about $2\frac{1}{2}$ times the brightness of a third-magnitude star.

Apparent magnitude A star's apparent magnitude is a measure of its brightness as it appears in the sky.

Astronomers settled on the convention that a first-magnitude star is 100 times brighter than a sixth-magnitude star. This led to a modern, more precise, classification of a star's brightness, or **apparent magnitude**, given the symbol m. The modern scale extends below 1 for the very bright stars, and above 6 for dull stars, which we can see using binoculars or telescopes. Table 27.2 shows a list of some bright stars, seen in the night sky.

Table 27.2 Apparent magnitudes of some bright stars visible in the night sky.

Star	Apparent magnitude (2 s.f.)
Sirius	−1.5
Canopus	−0.7
Vega	0.0
Rigel	0.1
Betelgeuse	0.4
Spica	1.0
Antares	1.1
Bellatrix	1.6
Polaris (Pole Star)	2.0
Acrab	2.5

Comparing brightness of stars

Table 27.2 lists the apparent magnitudes of some bright stars. But what do these magnitudes mean in terms of the brightness (or intensity) of light that we see from different stars?

Earlier, you learnt that the ratio of the brightness of a first-magnitude star to a sixth-magnitude star is 100, and that there is a constant ratio (which we shall call r) between each successive magnitude of brightness (about $2\frac{1}{2}$). This leads to two equations:

$$\frac{I_1}{I_6} = 100$$

defining the ratio in brightness between first- and sixth-magnitude stars, and

$$r^5 = 100$$

Therefore, the ratio of brightness between stars that are one magnitude apart in brightness is

$$r = 100^{\frac{1}{5}} = 2.51$$

Referring to Table 27.2, you can see that Vega has an apparent magnitude of 0.0 and Spica an apparent magnitude of 1.0. This means that Vega is 2.51 times brighter than Spica. Since Polaris has an apparent magnitude of 2.0, it means that Vega is $2.51 \times 2.51 \approx 6.3$ times brighter than Polaris.

It is relatively easy to compare the brightness of stars when their apparent magnitudes are whole numbers apart. It is a little more complicated when their apparent magnitudes are not whole numbers.

EXAMPLE

Comparison of apparent magnitudes

Use Table 27.2 to compare the apparent magnitudes of the following pairs of stars: Sirius and Acrab, Canopus and Bellatrix.

Answer

1 Sirius and Acrab
The difference in apparent magnitudes between Acrab and Sirius is
$2.5 - (-1.5) = 4$.

So $\frac{\text{brightness of Sirius}}{\text{brightness of Acrab}} = (2.51)^4 = 39.8 \approx 40$

2 Canopus and Bellatrix
The difference in apparent magnitudes between Bellatrix and Canopus is $1.6 - (-0.7) = 2.3$.

So $\frac{\text{brightness of Canopus}}{\text{brightness of Bellatrix}} = (2.51)^{2.3} = 8.3$

TEST YOURSELF

15 a) Explain what is meant by the term 'apparent magnitude'.
b) Star A has an apparent magnitude of 2.0 and star B an apparent magnitude of 8.0. Which star is brighter?
c) Calculate the relative brightness of star A to star B.

16 Use Table 27.2 to calculate the ratio of the brightness of the following pairs of stars:
a) Rigel to Antares
b) Sirius to Bellatrix.

Distance measurement and absolute magnitude

Distance measurement

You are used to using metres or kilometres to measure distances. However, the distances in space are so huge that we use different units to make the numbers easier to handle, and to enable a more straightforward comparison of distances.

Astronomical unit

The average distance from the Earth to the Sun is called an astronomical unit (AU). This distance is 1.5×10^{11} m to two significant figures. Some examples of average distances in astronomical units are:

- the average Earth–Sun distance is 1.0 AU
- the average distance from the Sun to Jupiter is 5.2 AU
- the average distance from the Sun to Sedna (a minor planet) is 532 AU.

Light year (ly)

A light year is the distance travelled by light in one year. So

$$1 \text{ light year} = \text{speed of light} \times \text{number of seconds in 1 year}$$

$$= 3.0 \times 10^{8}\,\text{m s}^{-1} \times 3.155 \times 10^{7}\,\text{s}$$

$$= 9.46 \times 10^{15}\,\text{m}$$

Parallax Nearby objects appear to move relative to far-away objects, when viewed from a different angle.

Some examples of average distances in light years are:

- the distance to the star Sirius from the Sun is 8.6 light years
- the distance to the Andromeda galaxy from the Sun is 2.5 million light years.

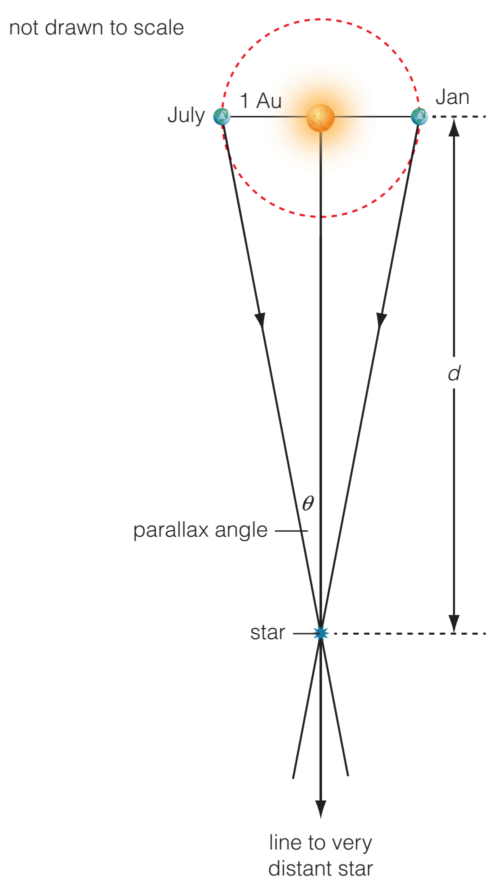


Figure 27.21

Parsec (pc)

When you walk down a street and look at a nearby object such as a lamp post, you will notice that, as you move, the lamp post appears to move relative to more distant objects. This is called **parallax**. We can tell that some stars are closer to us than others because they appear to move slightly as we view them at different times of year. Figure 27.21 (not drawn to scale) shows the idea. In January, for example, we look at a nearby star, then six months later we look at it again. The star appears to have moved relative to more distant stars, which are very far away. The angle shown in the diagram is called the parallax angle. Because even these 'nearby' stars are actually several light years away, this parallax angle is very small.

We can calculate the distance from the Earth to a star:

$$\tan\theta = \frac{1\,\text{AU}}{d}$$

or because θ is very small:

$$\theta = \frac{1\,\text{AU}}{d}$$

$$d = \frac{1\,\text{AU}}{\theta}$$

Remember that θ must be measured in radians. This relationship leads to a new measure of distance, which is directly related to the angle θ. When θ is 1 second of arc, we say that the distance is 1 parsec.

$$1 \text{ second of arc} = \frac{1}{360} \text{degree} = 4.85\times10^{-6} \text{ rad}$$

Therefore

$$1 \text{ parsec} = \frac{1 \text{ AU}}{4.85\times10^{-6}}$$
$$= \frac{1.5\times10^{11} \text{ m}}{4.85\times10^{-6}}$$
$$= 3.09\times10^{16} \text{ m}$$
$$= 3.26 \text{ light years}$$

If the measured parallax angle is smaller, then the distance to the star is further. The distances to galaxies are often expressed in megaparsec (Mpc).

MATHS BOX

Here is a summary of the units used in astronomy and their SI units:

$1 \text{ AU} = 1.50 \times 10^{11} \text{ m}$

$1 \text{ ly} = 9.46 \times 10^{15} \text{ m}$

$1 \text{ pc} = 3.26 \text{ ly}$

$1 \text{ Mpc} = 10^6 \text{ pc}$

TEST YOURSELF

17 This question is about converting astronomical distances expressed in metres into light years and parsecs.

a) The distance from Earth to the star Alpha Centauri is 4.13×10^{16} m and the distance to Beta Centauri is 3.31×10^{18} m. Express these distances in

i) light years

ii) parsecs.

b) The distance from Earth to the Virgo cluster of galaxies is 5.0×10^{23} m and the distance to the Corona Borealis cluster of galaxies is 1.1×10^{25} m. Express these distances in megaparsecs.

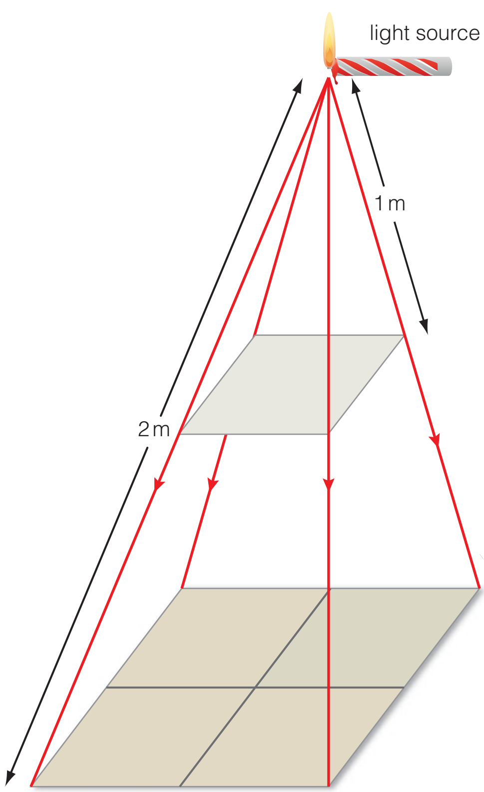


Figure 27.22

Absolute magnitude

Figure 27.22 shows light spreading out from a light source. You can see that, as the light travels further from a source, it spreads over a larger area, so its intensity decreases. When the distance from the source doubles, the intensity of the light reduces by a factor of 4, because the light spreads over four times the area. This is called the inverse square law for intensity:

$$I \propto \frac{1}{d^2}$$

This idea is important when it comes to comparing the brightness of stars. Earlier you met the idea of apparent magnitude – this measures how bright a star appears to be. However, stars appear brighter if they are close to us. So, to compare the brightness of two stars, we need to consider how bright they would appear to be if they were exactly the same distance from us. The distance that is chosen for comparison is 10 parsecs. A star's **absolute magnitude** is the apparent magnitude it would have if it were placed 10 parsecs away from us. In applying the inverse square law for stars, we assume that no light is absorbed by interstellar material such as gas or dust.

Absolute magnitude A star's absolute magnitude is the apparent magnitude the star would have if it were 10 pc away.

The apparent magnitude, m, and the absolute magnitude, M, are linked by the following formula, in which d is the distance of the star from us, measured in parsecs:

$$m - M = 5\log_{10}\left(\frac{d}{10}\right)$$

This formula combines the idea of the inverse square law for light and the standard reference distance of 10 pc. You do *not* need to be able to derive this formula (it is very hard to do), but for interested mathematicians the derivation is shown online with our free resources.

EXAMPLE

Calculation of absolute magnitude

Alpha Centauri has an apparent magnitude of 0.0 and is 1.34 pc from the Sun. Calculate the absolute magnitude of Alpha Centauri.

Answer

Using the formula from the text

$$m - M = 5\log_{10}\left(\frac{d}{10}\right)$$

we obtain

$$M = m - 5\log_{10}\left(\frac{d}{10}\right)$$
$$= 0.0 - 5\log_{10}\left(\frac{1.34}{10}\right)$$
$$= 0.0 - 5\times(-0.87)$$
$$= +4.4$$

TEST YOURSELF

18 a) P Cygni is a star with an apparent magnitude of 4.8. It is a distance of 1800 pc from Earth. Calculate P Cygni's absolute magnitude.

b) The Sun has an apparent magnitude of −26.7. It is 4.8×10^{-6} pc from Earth. Calculate the Sun's absolute magnitude.

19 Canopus has an absolute magnitude of −5.0 and is a distance of 70 pc from Earth. Calculate the apparent magnitude of Canopus.

20 Capella and Vega are two bright stars, clearly visible in the night sky. Capella has an apparent magnitude of 0.1 and Vega has an apparent magnitude of 0.0. Capella is 42 light years from Earth and Vega 25 is light years from Earth.

a) Calculate the absolute magnitude of each star.

b) Show that Capella emits approximately twice as much visible light as Vega per second.

Figure 27.23 This star cluster is called the Jewel Box. Most of the brightest stars you can see are blue, but there are also some bright red stars.

Classification of stars by temperature

Stars can be put into different categories according to their temperature, colour and the total amount of radiation they emit per second. Blue stars are very hot and bright, so we can see a lot of these by eye (Figure 27.23). Red stars are cooler than blue stars, but some red stars appear bright in the sky because they are very large. These ideas are explained further below.

Black-body radiation

Black-body radiation is the type of electromagnetic radiation that is emitted by a black or a non-reflective body, which is held at a constant uniform temperature.

Black-body radiation has a characteristic wavelength spectrum, which depends only on the absolute temperature of the body. The spectrum peaks

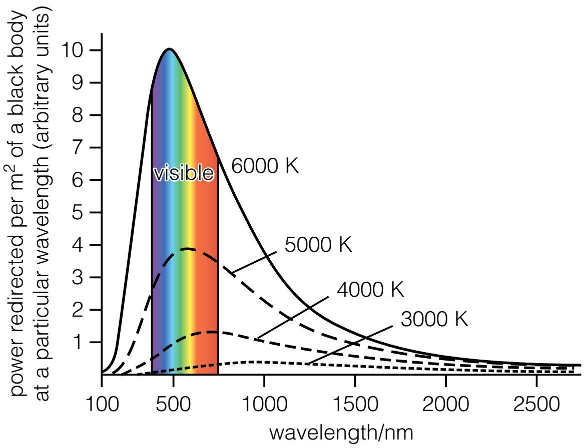


Figure 27.24

at a wavelength that shifts to shorter wavelengths at higher temperatures. Figure 27.24 shows some spectra for black bodies at different temperatures.

The curves in Figure 27.24 show these two important trends.

- As the body gets hotter, more radiation is emitted. The total power emitted by the body is proportional to the area under the graph. So you can see that at 6000 K a black body radiates much more energy than the body at 4000 K.
- The intensity of radiation peaks at a shorter wavelength at higher temperatures. You can see that the peak wavelength corresponds to red light when the temperature of the black body is 4000 K. At 5000 K the peak corresponds to green-yellow light. At 6000 K the peak corresponds to blue-green light.

The term 'black-body radiation' was originally used to describe the spectrum of infrared radiation emitted by hot bodies on the Earth. However, the term also applies to hot bodies such as stars, which emit visible light and also ultraviolet and X-radiation. The shape of the black-body spectra illustrated in Figure 27.24 applies to the stars, and enables us to understand why they have differing absolute magnitudes.

Laws of black-body radiation

There are two laws that summarise the information shown in Figure 27.24.

Stefan's law

Stefan's law states that the total power, P, radiated by a black body of surface A is

$$P = \sigma A T^4$$

where T is the surface temperature of the body (absolute temperature, in K), and σ is the Stefan constant, which is equal to $5.7 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$. The total power radiated by a star is called its *luminosity*, L.

Wien's law

Wien's law states that, for a black-body spectrum, the product of the peak wavelength, λ_{max}, and the absolute temperature of the body, T, is a constant:

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

EXAMPLE

Sun's luminosity and peak wavelength

The surface temperature of the Sun is 5780 K and its radius is 7.0×10^5 km.

1 Calculate the Sun's luminosity.

Answer

Luminosity $= \sigma A T^4$

$= 5.7 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}} \times 4\pi \times (7.0 \times 10^8\,\mathrm{m})^2 \times (5780\,\mathrm{K})^4$

$= 3.9 \times 10^{26}\,\mathrm{W}$

$= 4 \times 10^{26}$ W to 1 s.f.

2 Calculate the peak wavelength of the radiations emitted.

Answer

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

$$\lambda_{max} = \frac{2.9 \times 10^{-3}\,\mathrm{m\,K}}{5780\,\mathrm{K}}$$

$$= 5.0 \times 10^{-7}\,\mathrm{m}$$

$$= 500\,\mathrm{nm}$$

This wavelength is in the blue-green area of the visible spectrum.

TIP
Although the peak wavelength of light from the sun is in the blue-green area of the spectrum, Figure 27.24 shows that all visible wavelengths are emitted and so the light from the sun is a mixture of all colours and is actually white.

Giant stars

The constellation of Orion has two very luminous stars. Rigel is a blue giant with a surface temperature of about 11 800 K and a radius of 54×10^6 km. Betelgeuse is a red giant with a surface temperature of about 3300 K and a radius of 7.7×10^8 km. We can use this information to compare the brightness of these stars with the Sun's brightness.

Rigel

$P = \sigma AT^4$

$= 5.7 \times 10^{-8}\,\text{W m}^{-2}\,\text{K}^{-4} \times 4\pi \times (5.4 \times 10^{10}\,\text{m})^2 \times (11\,800\,\text{K})^4$

$= 4.0 \times 10^{31}\,\text{W}$

$\approx 10^5$ times more luminous than the Sun

Betelgeuse

$P = \sigma AT^4$

$= 5.7 \times 10^{-8}\,\text{W m}^{-2}\,\text{k}^{-4} \times 4\pi \times (7.7 \times 10^{11}\,\text{m})^2 \times (3300\,\text{K})^4$

$= 5.0 \times 10^{31}\,\text{W}$

$\approx 1.3 \times 10^5$ times more luminous than the Sun

Although Betelgeuse is a relatively cool star, its radius is over 1000 times larger than that of the Sun. It is because its surface area is so large that Betelgeuse is one of the most luminous stars in the sky.

Luminosity and brightness

It is important not to confuse *luminosity* and *brightness*.

- Luminosity is the total power emitted by a star in all wavelengths.
- Brightness is a measure of what we can see, and therefore is a measure of the visible light emitted by a star.

For example, a star with a surface temperature of 20 000 K has a peak wavelength, λ_{max}, of about 150 nm, which is well into the ultraviolet spectrum. Such a hot star emits much more of its power outside the visible spectrum.

TEST YOURSELF

21 What are the two factors that affect the luminosity of a star?

22 a) Polaris has a surface temperature of 6015 K, and a radius of 3.2×10^7 km. Calculate its luminosity.

b) Mintaka is a star with a luminosity of 3.6×10^{31} W. Its radius is 1.1×10^7 km. Calculate its surface temperature.

c) 61 Cygni is a star with a surface temperature of 3900 K, and a luminosity of 4×10^{25} W. Calculate the star's radius.

23 A star has a surface temperature three times that of the Sun, and its radius is four times that of the Sun. Calculate how many times bigger the star's luminosity is than the Sun's.

24 Barnard's star is a red dwarf star about 6 light years away from the Sun. The star's surface temperature is 3100 K and its luminosity is 1.4×10^{24} W.

a) Calculate the radius of Barnard's star.

b) Calculate the peak wavelength of the radiation from Barnard's star. In what part of the spectrum does this wavelength lie?

c) Explain why this star has a very low visual brightness.

Stellar spectra

The magnitude of a star and its colour have proved useful for learning about the luminosity and temperature of the star. We can also learn about a star by observing the spectrum of the light that it emits.

Figure 27.25 shows a spectrum of the light emitted from the Sun, when it is viewed through a diffraction grating. The continuous spectrum of light is crossed by dark absorption lines, called Fraunhofer lines. Such absorption lines are produced when light passes through the cooler gases in the outer atmosphere of the Sun.

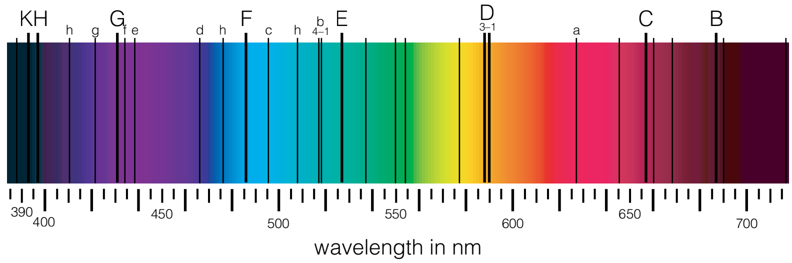


Figure 27.25

Figure 27.26 helps to explain how the process works. The diagram shows an energy level diagram for a hydrogen atom. When a photon has an energy exactly equal to the energy difference between levels 1 and 2, $E_2 - E_1$, the photon can be absorbed by an electron in energy level 1, which is promoted to level 2. Similarly, if there is an electron in level 2, it can move to level 3 if it absorbs a photon of energy $E_3 - E_2$. When light is absorbed in this way, the intensity of these wavelengths is reduced, so black lines appear across the spectrum.

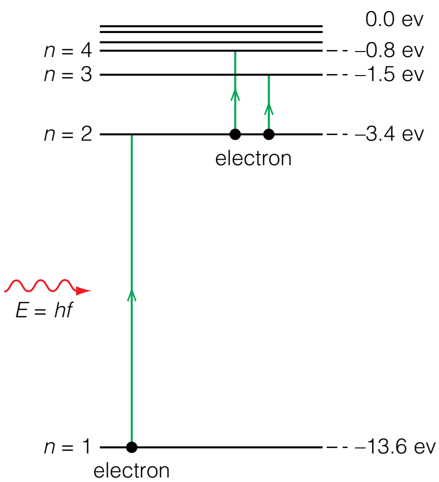


Figure 27.26

Each element or compound has a unique set of energy levels. These energy levels lead to a unique **absorption spectrum**. Therefore, it is possible to see which elements are present in a star's atmosphere by analysing the absorption lines in its spectrum.

Absorption spectrum This spectrum is seen as a series of dark lines in a continuous spectrum, when some elements absorb specific wavelengths of light.

Spectral classes

When the spectra of a large number of stars were studied, it was realised that stars could be divided into a number of *spectral classes*. These classes were based on which elements were most prominent in the spectra of stars – and these elements varied considerably from star to star.

Originally it was thought that the observation of prominent elements related closely to the chemical composition of the star. However, although there are differences in stellar chemical composition, the most important factor in spectral classes is the star's temperature.

The reason why temperature is very important in determining the spectral class of a star is as follows. For a particular absorption line to be observed, there must be atoms present with an electron in the correct energy level. Hydrogen is the most abundant element in all stars. It is therefore no surprise that we see hydrogen absorption lines in stellar spectra, but we see different patterns of absorption at different temperatures.

When a hydrogen atom is relatively cold, its one electron will lie in its ground state, $n = 1$, nearest the nucleus. Therefore, this electron can be excited to the $n = 2$ level by a photon of the correct energy. Such photons lie in the ultraviolet part of the spectrum, so we do not see these lines when a star is viewed in visible light. These ultraviolet lines are more visible in a star with a surface temperature of about 8000 K than in a star with a lower temperature of, for example, 5000 K, because the hotter star emits more ultraviolet light. However, hydrogen lines are not the most prominent lines seen in cooler stars, because other elements absorb more light than hydrogen.

Table 27.3 lists the various spectral classes of stars, with their most prominent absorption lines.

Table 27.3

Spectral class	Intrinsic colour	Temperature/K	Prominent absorption lines
O	blue	25 000–50 000	He^+, He, H
B	blue	11 000–25 000	He, H
A	blue-white	7500–11 000	H (strongest) ionised metals
F	white	6000–7500	Ionised metals
G	yellow-white	5000–6000	Ionised and neutral metals
K	orange	3500–5000	Neutral metals
M	red	<3500	Neutral atoms, TiO

At higher temperatures, some electrons in atoms move into higher states. At temperatures between about 7500 K and 25 000 K, hydrogen has a significant number of atoms with electrons in the n= 2 state. These temperatures correspond to the A and B spectral types. In these stars, we see prominent hydrogen absorption lines in the visible part of the spectrum. The electron in the n = 2 level is able to absorb photons to lift it to the n = 3, n = 4, n = 5 levels and so on. This series of lines is called the Balmer series, after the scientist who discovered them.

In the hottest stars, the most prominent absorption lines come from He and He^+. In the cooler stars, absorption lines are seen from ionised and neutral metals. In the coolest stars, with surface temperatures below 3500 K, titanium oxide produces prominent absorption lines.

TEST YOURSELF

25 What is meant by the 'ground state' of an atom?

26 Explain how an absorption spectrum is produced in a star's continuous spectrum.

27 What is the Balmer series?

28 This question refers to Figure 27.26.

a) Calculate the wavelength of a photon that is absorbed when an electron is excited from the n = 1 level to the n = 2 level. In what part of the spectrum does this wavelength lie?

b) Calculate the wavelength of a photon that is absorbed when an electron is excited from the n = 2 to n = 4 level. In what part of the spectrum does this wavelength lie?

(You may need to refer back to Chapter 3 to remind you of how to do these calculations.)

29 Explain why different absorption lines are seen in stars with different temperatures.

The Hertzsprung–Russell diagram

In common with all stars, our Sun was formed from a giant cloud of gas. Figure 27.27 shows part of the Orion nebula, in which stars are being formed.

Figure 27.27 The Orion nebula is a large cloud of hydrogen gas, which is collapsing to form new stars.

This nebula is made mostly of cold hydrogen gas. Over millions of years, gravity acts to coalesce the gas. This collapse warms the gas. As the atoms fall towards each other, potential energy is transferred into kinetic energy, which is then transferred to heat energy as the atoms crash into each other. Because the mass of all the hydrogen atoms is so great, and the distances fallen by the atoms so enormous, the temperature in the middle of such a ball of gas rises to about 15 000 000 K. At this temperature, thermonuclear fusion takes place and hydrogen nuclei (protons) fuse together into helium nuclei, and a star is born. The energy released in the fusion process is emitted as electromagnetic radiation from the star's surface.

A star is a battleground in which competing forces act, as shown in Figure 27.28. The pull of gravity acting inwards is balanced by the outward pressure from the hot core. The pressure at the centre of a star can be billions of times larger than atmospheric pressure on the Earth.

When a cloud of gas collapses, the stars that are formed may be of considerably different masses (Figure 27.29). Stars range in mass from about 100 times the Sun's mass, down to about 0.1 of the Sun's mass. Stars much above 100 solar masses are unstable, and stars below about 0.1 solar masses are too small to start the thermonuclear fusion of hydrogen nuclei.

Main sequence star A star in which hydrogen 'burning' takes place. This is the thermonuclear fusion of hydrogen nuclei into helium nuclei.

Most stars are **main sequence stars**, which means that the star is fuelled by the fusion of hydrogen. The more massive stars are much more luminous than the smaller stars. This is because the gravitational forces that tend to collapse a star increase with mass. So for the star to be in in equilibrium, it means that the outward pressure from the core must be larger. Therefore the nuclear reactions must run at a higher rate generating more power, which leads to the star having a higher luminosity.

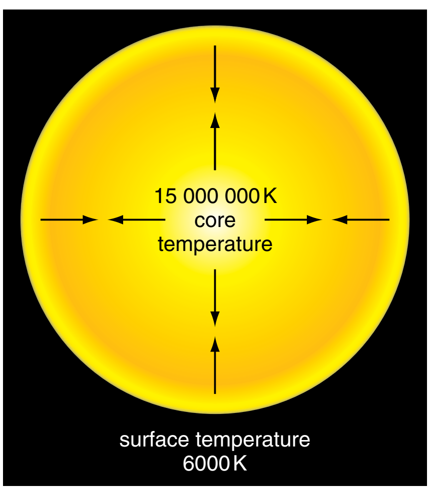


Figure 27.28

Stars vary in luminosity from being about 10^6 times more luminous than the Sun (absolute magnitude about −10) to being about 10^4 times less luminous than the Sun (absolute magnitude about +15). The variation in the luminosity of stars is displayed in the Hertzsprung–Russell diagram, as shown in Figure 27.30. The main sequence of stars runs in a diagonal line from the top left-hand corner. At the top left of the diagram are the bright O class stars with absolute magnitudes of −10 and surface temperatures of 50 000 K; at the bottom right of the diagram, are dull M class stars with absolute magnitudes of +15 and surface temperatures of about 2500 K.

Our Sun is a G class star with a surface temperature of about 5780 K and an absolute magnitude of +4.6. The Sun is a significant star in that it is more luminous than 95% of all stars. The best-known stars are the brightest ones, but there are billions of very small, dull stars that cannot be seen by the unaided eye.

The Hertzsprung–Russell diagram also contains further types of stars in the giant and dwarf branches, which will be discussed later on.

The lifetimes of stars

The bright O class stars are very rare because they only live for a short time. Our Sun will exist for a total of about 10^{10} years. It is about 4.6 billion years old, so the Sun is about halfway through its life. A star that is about 100 times more massive than the Sun is about 10^6 times more luminous. So although it has more nuclear fuel, it uses it very quickly. So the brightest stars have lifetimes of the order of a few million years, whereas the dullest stars can live for 10^{12} years or more (which is about 100 times longer than the Universe has been in existence).

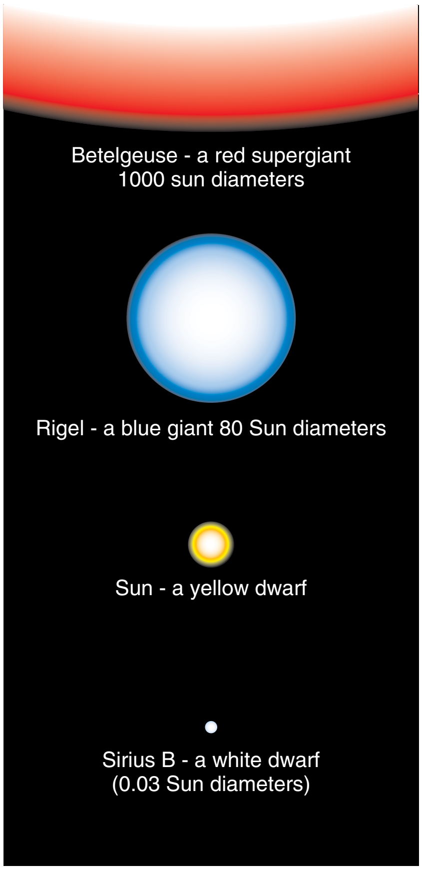


Figure 27.29 Stars come in all sizes.

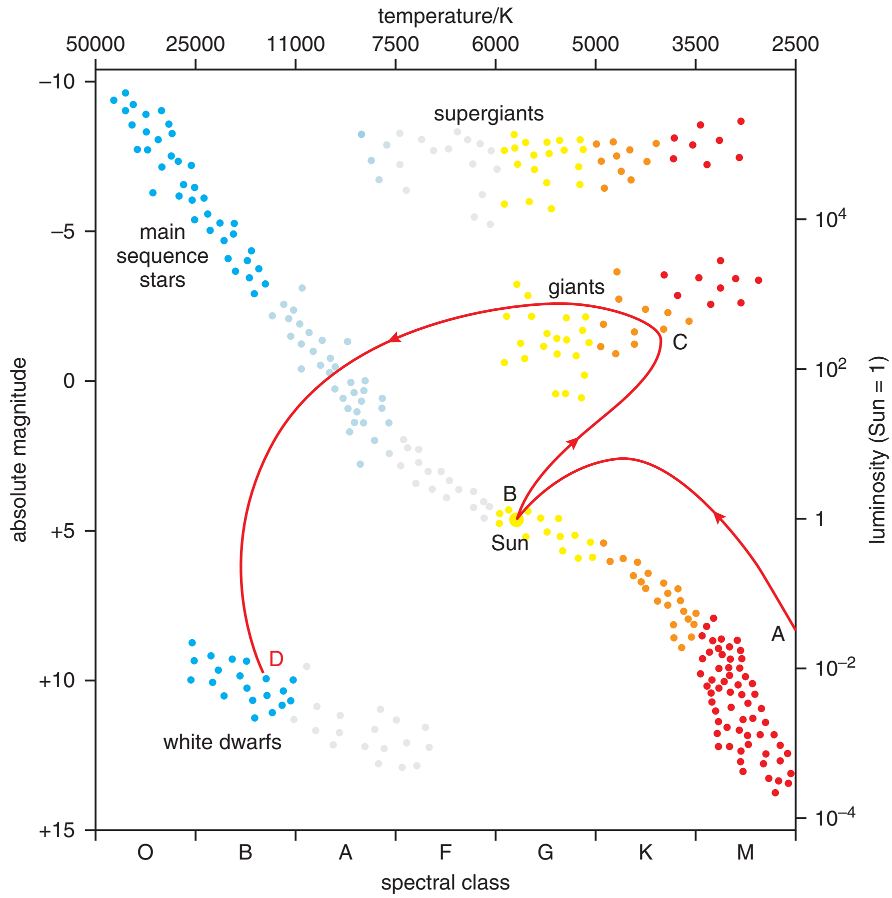


Figure 27.30 The Hertzsprung–Russell diagram.

TEST YOURSELF

30 Explain what is meant by each of these terms:

a) main sequence star

b) red giant star

c) white dwarf star.

31 Explain why stars with very high luminosities are short-lived.

32 Sirius B is the closest white dwarf to us. It has a luminosity of 7.6×10^{23} W, and its surface temperature is 25 200 K.

a) Use Stefan's law to calculate the surface area of the star (the Stefan constant is $5.7 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$).

b) Calculate the radius of Sirius B.

33 Sirius B has approximately the same mass as the Sun, 2×10^{30} kg. Calculate the density of Sirius B, using the result from question 32. Comment on your answer.

The Sun's evolutionary path

The red line ABCD in Figure 27.30 shows the evolutionary path of a star, similar to the Sun, on the Hertzsprung–Russell diagram. As described earlier, the star collapses from a cold cloud of gas and reaches its position on the main sequence, where it remains for about 10 billion years, path A to B. After that time the star will have exhausted its supply of hydrogen, which will have been turned into helium. At that point the process of nuclear fusion stops, the pressure inside the core of the star reduces, and the gravitational forces begin to collapse the star. The collapse of the star causes the core to heat up even further, to temperatures in the region of 100 million kelvin (10^8 K).

At that temperature the helium nuclei have enough energy to overcome the repulsive electrostatic forces between them, and to come into contact. Once the helium nuclei get into contact, some of them will fuse into more massive nuclei such as beryllium, carbon and oxygen.

This further nuclear reaction reignites the star. However, the massive temperature causes the star to expand into a red giant, which could be 100 times the current diameter of the Sun. Although the star's surface temperature will be lower, at about 3000 K, the giant's extreme surface area causes it to be much more luminous. The star moves along the path B to C into the giant branch of the stars.

TIP

This section is not required by the specification, so you could skip it. But we hope it provides some background material for the interested reader.

Further nuclear reactions can occur in stars much larger than the Sun, which takes them into the supergiant branch on the Hertzsprung–Russell diagram. However, the Sun is not massive enough to move into the supergiant branch.

There comes a time when the supply of helium runs out in the star. At this point in a star of the Sun's mass, nuclear fusion stops and the star collapses into a dwarf. Calculations suggest that white dwarfs of the Sun's mass have about the same volume as the Earth. So a white dwarf is extremely dense. The surface temperature of a white dwarf can be 10 000 K, which is much hotter than the Sun's surface. However, because the dwarf star has such a small surface area, it has a low luminosity. The dwarf star is powered by the gravitational potential energy released as it slowly contracts. After a very long time, this energy will run out and the star will become a black dwarf. It is thought that no black dwarfs exist yet because the process takes a longer time than the current age of the Universe.

Nuclear fusion in large stars

Nuclear fusion between nuclei only happens at high temperatures, when the average kinetic energy of particles is very high. Figure 27.31 explains why. In Figure 27.31a, two protons approach each other at a low temperature and they repel each other and do not collide. In Figure 27.31b, at a higher temperature, the protons get close enough for the strong nuclear force to act, and the two protons fuse to form deuterium and a positron.

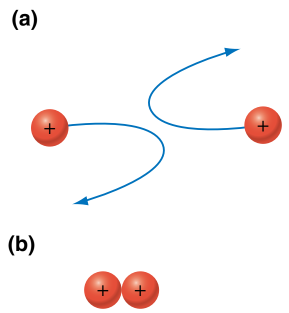


Figure 27.31 (a) At low temperatures (less than 15 million kelvin), two protons repel each other. (b) At high temperatures, two protons have enough kinetic energy to overcome the electrostatic repulsion of their charges, and fusion takes place.

In stars that have cores much hotter than the Sun, the fusion of larger nuclei can take place. Higher temperatures are necessary for such fusions to occur because the larger positive charges on their nuclei result in stronger electrostatic repulsions.

Our Sun will expand into a red giant at the end of its life (in about 5 billion years' time). The Sun is not large enough to progress beyond the helium fusion stage, in which helium fuses to form carbon and oxygen. However, very large stars (about 8 times the mass of the Sun) can progress as far as fusing silicon into larger elements. While a large star lives for millions of years, the silicon fusion stage of its life lasts a matter of only a few days. In a large star there is a lot of helium and larger elements are built up by a process of fusion with helium as follows:

$${}^{28}_{14}\text{Si} + {}^{4}_{2}\text{He} \rightarrow {}^{32}_{16}\text{S}$$

$${}^{32}_{16}\text{S} + {}^{4}_{2}\text{He} \rightarrow {}^{36}_{18}\text{Ar}$$

$${}^{36}_{18}\text{Ar} + {}^{4}_{2}\text{He} \rightarrow {}^{40}_{20}\text{Ca}$$

$${}^{40}_{20}\text{Ca} + {}^{4}_{2}\text{He} \rightarrow {}^{44}_{22}\text{Ti}$$

$${}^{44}_{22}\text{Ti} + {}^{4}_{2}\text{He} \rightarrow {}^{48}_{24}\text{Cr}$$

$${}^{48}_{24}\text{Cr} + {}^{4}_{2}\text{He} \rightarrow {}^{52}_{26}\text{Fe}$$

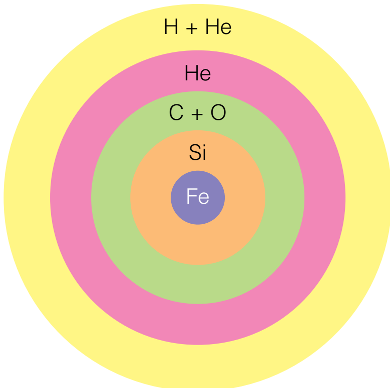
$${}^{52}_{26}\text{Fe} + {}^{4}_{2}\text{He} \rightarrow {}^{56}_{28}\text{Ni}$$

TEST YOURSELF

34 a) Explain why nuclear fusion only occurs at very high temperatures.

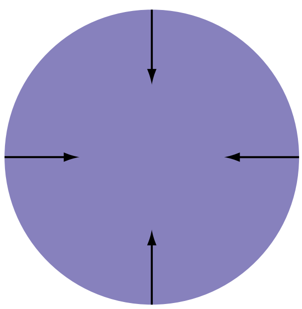
b) Why is a higher temperature required to fuse two helium nuclei than two hydrogen nuclei?

c) Explain why the fusion of a helium nucleus with a silicon nucleus is much more likely to happen than the fusion of two silicon nuclei directly.



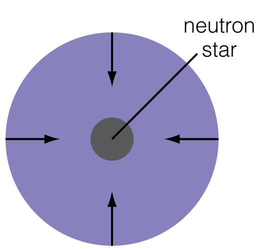
(a)

(a) A large star, more than eight solar masses, has a layered structure, with iron at its core.



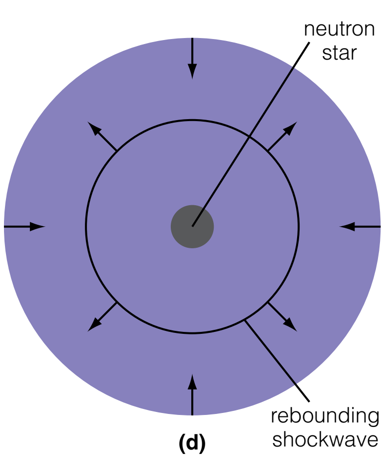
(b)

(b) The core begins to collapse as the nuclear fuel runs out.



(c)

(c) The rapid collapse produces a core of neutrons.



(d)

(d) A shock wave rebounds off the neutron core.

Figure 27.32

The nucleus $^{56}_{28}\text{Ni}$ is the end point of nuclear fusion because the fusion into larger nuclei does not release energy. Rather, larger amounts of energy must be supplied to create heavier nuclei. However, $^{56}_{28}\text{Ni}$ decays by positron decay as follows:

$$^{56}_{28}\text{Ni} \rightarrow \, ^{56}_{27}\text{Co} + \, ^{0}_{1}\text{e} \qquad \text{half-life 6 days}$$

$$^{56}_{27}\text{Co} \rightarrow \, ^{56}_{26}\text{Fe} + \, ^{0}_{1}\text{e} \qquad \text{half-life 77 days}$$

The nucleus $^{56}_{26}\text{Fe}$ is one of the most stable nuclei, which is why it is present inside very large stars.

Supernovae – glorious endings

As explained in the previous section, nuclear fusion does not continue beyond the elements iron and nickel. Figure 27.32a shows a large star towards the end of its life. Owing to the various stages of nuclear fusion, the star is layered like an onion with shells of different nuclei – iron in the centre, with helium and hydrogen in the outer layers.

In Figure 27.32b, which shows the core of the star, the nuclear fuel has just been exhausted, and without the outward pressure from the thermonuclear fusion process, the pull of gravity begins to collapse the star. Under the intense gravitational forces, the core collapses in a matter of seconds. The outer part of the core can reach speeds as high as 20–30% of the speed of light, and the centre of the core rises to temperatures as high as 100 billion kelvin (10^{11} K). At these temperatures, the iron nuclei begin to dissociate into helium nuclei, protons and neutrons.

In such high temperatures and pressures, protons and electrons can combine, in a reverse beta decay, to form neutrons and neutrinos:

$$^{1}_{1}\text{p}^{+} + \, ^{0}_{-1}\text{e}^{-} \rightarrow \, ^{1}_{0}\text{n} + \nu$$

In this way the centre of the core turns into a ball of neutrons, which will become a neutron star, Figure 27.32c. At this point the core collapses no further and the infalling matter rebounds, producing a shock wave, which spreads outwards as shown in Figure 27.32d.

The extremely high temperature in the centre of the star restarts the nuclear reactions in the outer layers of the star and a huge amount of energy, perhaps 10^{46} J, is produced in a few seconds. The shock wave moving out from the centre of the star blows the outer layers apart, and energy moves out into space at an enormous rate. This is a supernova (a *type 2 supernova*).

Supernovae are amongst the brightest objects in the sky. They outshine an entire galaxy and in a matter of a few seconds emit more energy than the Sun does in its entire lifetime. Supernovae are colossal events and highly significant for our existence. The energy produced in a supernova explosion produces heavy elements beyond iron, and it is from the remnants of a supernova that our Sun and our Solar System formed.

In 1987 astronomers saw a supernova explosion in the Large Magellanic Cloud, which is a small galaxy (visible from the southern hemisphere) about 170 000 light years from us. Some 20 hours prior to the supernova being seen, scientists detected a burst of neutrinos that had come from the star. These neutrinos were produced in the core as protons and electrons formed neutrons. The neutrinos were able to pass through the outer layers of the star, before the shock wave blew it apart. The supernova was visible to the naked eye, with an apparent magnitude of about +3. Supernovae are characterised by a rapid increase in absolute magnitude, followed by a decay in luminosity over a period of months.

EXAMPLE

Calculation of absolute visual magnitude

Using the information given in the text, calculate the absolute visual magnitude of SN 1987A at its peak brightness.

Answer

SN 1987A is about 170 000 light years from Earth, which is 170 000/3.26 = 52 000 pc. So

$$M = m - 5\log\left(\frac{d}{10}\right)$$

$$= 3 - 5\log\left(\frac{52000}{10}\right)$$

$$= 3 - 5 \times 3.71$$

$$= -15.5$$

The apparent magnitude of a full Moon is about −12.7, so a supernova placed a distance of 10 pc from us would appear about 3 magnitudes brighter than the full Moon, which is about $(2.5)^3$ or about 16 times brighter. So a supernova at that distance would cast very strong shadows at night.

Neutron stars and black holes

Neutron star A collapsed star made of neutrons. It has a very high density.

After a massive star has blown itself apart in a supernova explosion, a **neutron star** is often left at the star's core. Neutron stars are even more dense than white dwarfs, as they are made only from highly dense nuclear material. A neutron star of mass about 1.5 times that of the Sun has a radius of only about 12 km.

Black hole A highly condensed state of matter that has an escape velocity higher than the speed of light.

Some very massive stars (in the region of 20 solar masses) collapse at the end of their lives in an even more spectacular fashion. As their nuclear fuel runs out, the speed of that collapse is so fast that the gravitational tide even manages to collapse the neutrons at its core. Under these circumstances a **black hole** is formed. A black hole is so dense that not even light can escape from it, because its escape velocity is higher than the speed of light.

Gamma-ray bursts

Neutron stars spin very rapidly on their axes. Many such stars spin round several hundred times a second. These rapidly spinning stars are known as pulsars because they emit radiation along their axes of rotation.

Gamma-ray burst A brief intense emission of gamma rays from a collapsing supergiant star.

Figure 27.33 A rapidly collapsing supergiant emits high-powered short bursts of gamma rays.

As supergiant stars collapse into neutron stars or black holes, they emit **gamma-ray bursts**. As matter collapses into the centre of a very massive star, collisions between particles produce very energetic gamma rays, which are emitted along the axis of rotation of the star (Figure 27.33). It is thought that the most energetic gamma-ray bursts are produced when a supermassive star (of some 50 solar masses) collapses into a black hole. The fact that gamma-ray bursts last for a few seconds (or at the most a few minutes) indicates how rapidly larger stars collapse.

A gamma-ray burst produced by a supergiant star, close to the Earth, could have catastrophic consequences. The radiation dose, on the side of the Earth facing the star could be lethal for all animals. The fossil record shows that there was a mass extinction of animals on the Earth some 450 million years ago. One possible explanation is that this was caused by a gamma-ray burst.

Schwarzschild radius

The *event horizon* for a black hole can be described as 'the point of no return', that is the boundary beyond which the gravitational pull becomes so big that escape becomes impossible. So if you are in a spacecraft just outside the event horizon of a black hole you could escape with very powerful rockets. However, once inside the event horizon the escape velocity is higher than the speed of light, and a spacecraft would be trapped (and of course torn apart by the immense gravitational forces).

We can calculate the approximate radius of the event horizon using Newton's law of gravitation. The gravitational potential energy of a spacecraft, of mass m, at a distance R from the centre of a black hole of mass M, is given by

$$E_p = -\frac{GMm}{R}$$

If the spacecraft is to escape, its kinetic energy, $\frac{1}{2}mv^2$, must satisfy the relationship

$$\frac{1}{2}mv^2 - \frac{GMm}{R} > 0$$

or

$$\frac{1}{2}mv^2 > \frac{GMm}{R}$$

Schwarzschild radius The radius of a black hole's event horizon. Light cannot escape from inside a black hole's event horizon.

The radius of the event horizon is known as the **Schwarzschild radius**, R_s, at which point the escape velocity is the speed of light, c. So

$$\frac{1}{2}mc^2 = \frac{GMm}{R_s}$$

and

$$R_s = \frac{2GM}{c^2}$$

EXAMPLE

Radius of event horizon

Calculate the radius of the event horizon for a black hole of mass 20 solar masses. (A solar mass is 2×10^{30} kg.)

Using the formula in the text

$$R_s = \frac{2 \times 6.7 \times 10^{-11}\,\mathrm{N\,m^2\,kg^{-2}} \times 40 \times 10^{30}\,\mathrm{kg}}{(3 \times 10^8\,\mathrm{m\,s^{-1}})^2}$$

$$= 6 \times 10^4\,\mathrm{m}$$

$$= 60\,\mathrm{km}$$

Observations of stars at the centre of our Galaxy, the Milky Way, suggests that millions of stars are contained in a very small volume. Astronomers calculate that there is a supermassive black hole at the galactic centre, with a mass of about four million times that of the Sun.

Type 1a supernovae

Many stars exist as binary stars, which means that two stars rotate about a common centre of gravity. Such stars can coexist in stable orbits for millions of years. However, if the stars are of different masses, they evolve at different rates.

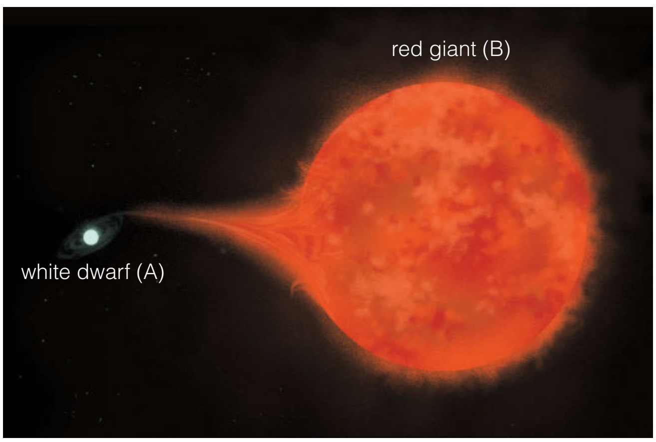


Figure 27.34

Figure 27.34 shows a pair of stars that are a little more massive than the Sun. The star A has passed through the main sequence and red giant stages and is now a white dwarf. Later, star B moves into the red giant stage, and as it expands matter is pulled into the white dwarf.

If the mass of the white dwarf grows to be larger than 1.4 solar masses, the star collapses. At this point carbon and oxygen in the white dwarf suddenly begin to undergo nuclear fusion. Such a rapid collapse, followed by the re-ignition of nuclear fusion, can trigger a supernova explosion.

Type 1a supernovae are easily identified by astronomers for two reasons. First, they have approximately the same absolute magnitude, because they always occur in stars with about 1.4 solar masses. Secondly, the rapid onset of fusion in the collapsing star produces the nuclear isotope $^{56}_{26}\mathrm{Ni}$. As explained earlier, this isotope decays to cobalt-56 with a half-life of 6 days, and then cobalt-56 decays to iron-56 with a half-life of 77 days. So type 1a supernovae have a characteristic light curve (Figure 27.35), which decays on a time scale governed by the half-lives of the isotopes $^{56}_{26}\mathrm{Ni}$ and $^{56}_{26}\mathrm{Co}$. As the two isotopes decay, massive numbers of high-energy photons are emitted, which power the light emitted by the remnants of the expanding supernova.

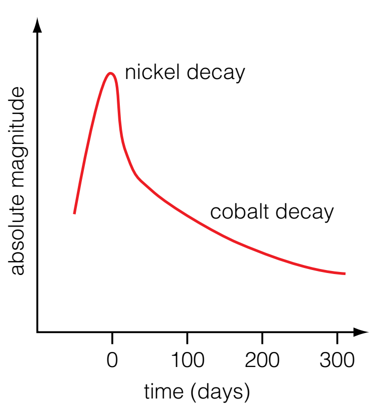


Figure 27.35 All type 1a supernovae produce light curves of a characteristic shape.

Because type 1a supernovae have a characteristic absolute magnitude, they are used as **standard candles**. This means that astronomers can calculate the distance of a galaxy from Earth by measuring the apparent magnitude of a type 1a supernova in the galaxy.

Standard candle A star or supernova of known brightness that can be used to calculate galactic distances.

The use of type 1a supernovae has led to a controversial result. Measuring the distance to very distant galaxies has led cosmologists to the conclusion that the Universe was expanding more slowly in the past. For a long time it was assumed that the action of gravity would cause the expansion of the Universe to slow down. The idea of a Universe with accelerating expansion is a most controversial idea. There is no firm explanation for this theory yet, but cosmologists suggest that some 'dark energy' in the Universe may be responsible for an accelerating expansion.

TEST YOURSELF

35 Calculate the density of a neutron star with mass 4×10^{30} kg and a radius of 14 km.

36 The supermassive black hole at the centre of a galaxy has a mass of 100 million solar masses. Calculate its Schwarzschild radius. The mass of the Sun is 2×10^{30} kg.

37 Explain the meanings of the following terms:
a) neutron star
b) black hole
c) standard candle
d) gamma-ray burst
e) supernova.

38 Explain why type 1a supernovae always have
a) similar shapes of light curves
b) similar absolute magnitudes.

39 A type 1a supernova is seen in a distant galaxy by an astronomer who measures its apparent magnitude to be +11 at its peak of brightness. It is known that a type 1a supernova has an absolute magnitude of about −19, at its peak. Show that the galaxy is about 10 Mpc away

Cosmology

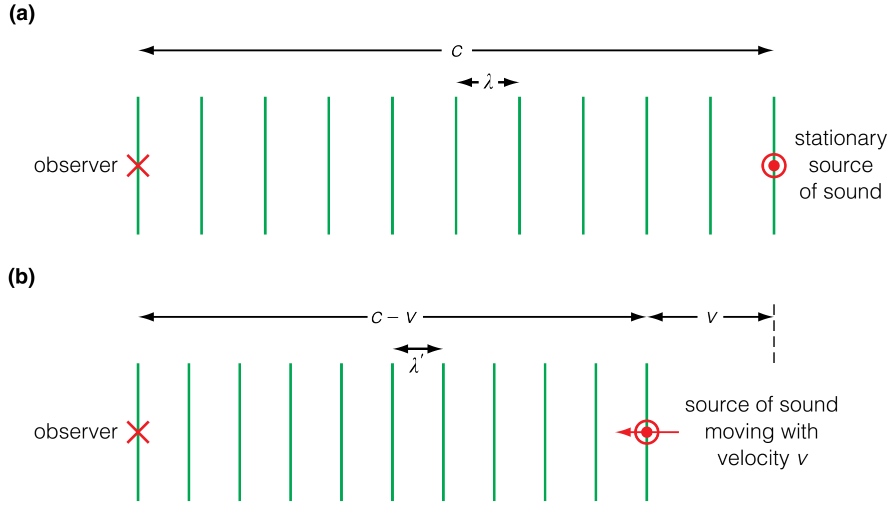
Cosmology is the study of the origin, evolution and eventual fate of the Universe. A detailed understanding of the Universe has been gained by mapping the positions and relative motion of the many groups of galaxies that lie in deep space. You learnt in the previous section that the distance from Earth to galaxies can be estimated using the light seen from type 1a supernovae. Below, you will learn how the Doppler shift in the light seen from galaxies can be used to measure their velocity – and then also deduce the distance of galaxies that are very far away.

Doppler effect

You will be familiar with the Doppler effect. This is the name given to the apparent change in the frequency, or wavelength, of a moving source of sound (or other type of wave). When you hear the siren from a fire engine as you stand in a street, you hear one pitch (frequency) of sound as the fire engine approaches you, and a lower pitch of sound after the fire engine passes you and goes away in the opposite direction. Figure 27.36 helps you to understand why the sound changes pitch.

In Figure 27.36a a stationary source of sound is emitting waves, which are heard by the observer, who is a distance c metres away from the source, where c is the speed of sound in m s^{-1}. So a 1 s burst of sound stretches from the source to the observer. In Figure 27.36b the source is moving towards the observer with a velocity v. Now the 1 s burst of sound is squashed into a length $c - v$ metres. This means that the wavelength is reduced (from λ to λ'), and the observer hears a higher frequency. If the source moves away from the observer, the waves are stretched out into a length of $c + v$ metres. The wavelength is increased and the observer hears a lower frequency.

Figure 27.36



From Figure 27.36 you can see that

$$\frac{\lambda'}{\lambda} = \frac{c-v}{c}$$

but $\lambda' = \lambda - \Delta\lambda$, where $\Delta\lambda$ is the change in wavelength. So

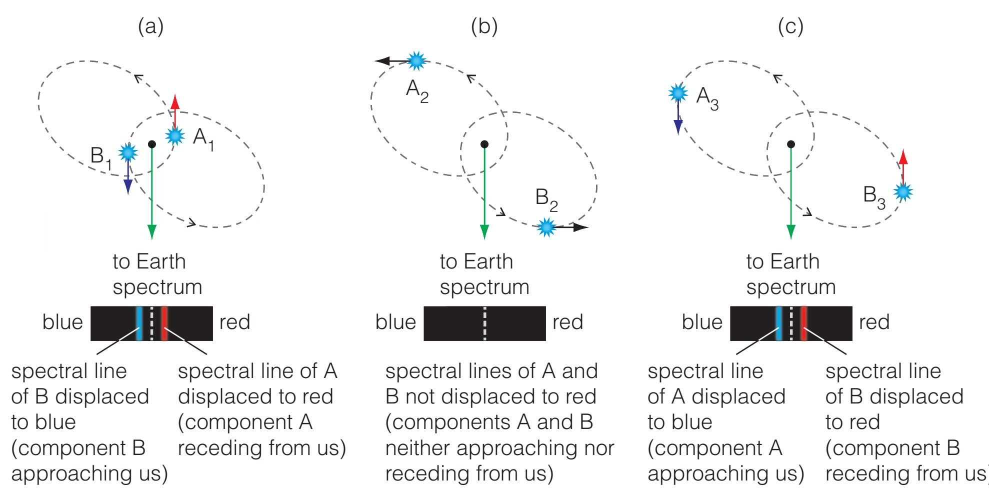
$$\frac{\lambda - \Delta\lambda}{\lambda} = \frac{c-v}{c}$$

$$\frac{\Delta\lambda}{\lambda} = -\frac{\Delta f}{f} = \frac{v}{c}$$

Note that if the source moves away from the observer then the wavelength increases, and the frequency decreases.

Light also shows a Doppler effect or shift when a source is moving. This has proved to be a very successful way of investigating the orbits of binary stars. Figure 27.37 shows a pair of stars that orbit around a common centre of gravity. When a star is moving towards the Earth, the wavelength of the light decreases, and it is shifted towards the blue end of the spectrum. When a star is moving away from the Earth, the light it emits appears to be shifted towards the red end of the spectrum. The spectrum of light emitted from stars are crossed with absorption lines (see Figure 27.25). The shift of these absorption lines towards the red or blue end of the spectrum enables astronomers to calculate the velocity of the stars.

Figure 27.37



The Doppler shift has also shown that galaxies are moving away from us. The *redshift* in the spectral lines emitted from galaxies has proved an invaluable tool in mapping the Universe. The redshift of a spectral line is sometimes expressed as a fraction. For example, if the redshift is 0.1, it means the wavelength has shifted by 10%. Since

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

we can see that the galaxy is receeding at 10% of the speed of light.

TEST YOURSELF

40 An absorption line in the hydrogen spectrum has a wavelength of 656.3 nm. In the spectrum of a star, which is one of a binary pair, the wavelength of the absorption line changes between 655.9 nm and 656.7 nm.

a) Explain why the wavelength of the spectral line appears to change.

b) Calculate the maximum velocity of the star away from the Earth.

41 A spectral line in a galaxy is observed to be shifted from 486 nm to 541 nm. Calculate the velocity of the galaxy.

42 A motorist is in court having been accused of driving through a red light. In his defence he explains to the magistrate that the light looked green as he went past it because he was moving. Discuss whether or not this is a good defence. The wavelength or not of red light is 650 nm, and the wavelength of green light is 530 nm.

Hubble's law

Our Galaxy, the Milky Way, is not alone in space. It is part of a group of some 50 galaxies that we call the Local Group. The largest two galaxies in the Local Group are the Milky Way and the Andromeda galaxy. Our Local Group of galaxies is a very small group and one of billions of such groups. Figure 27.38 shows the distribution of groups or galaxies within 600 million light years of us.

Cepheid variable A bright star whose intensity varies over a matter of days. The period of the variation of intensity is linked directly to the absolute magnitude of the star.

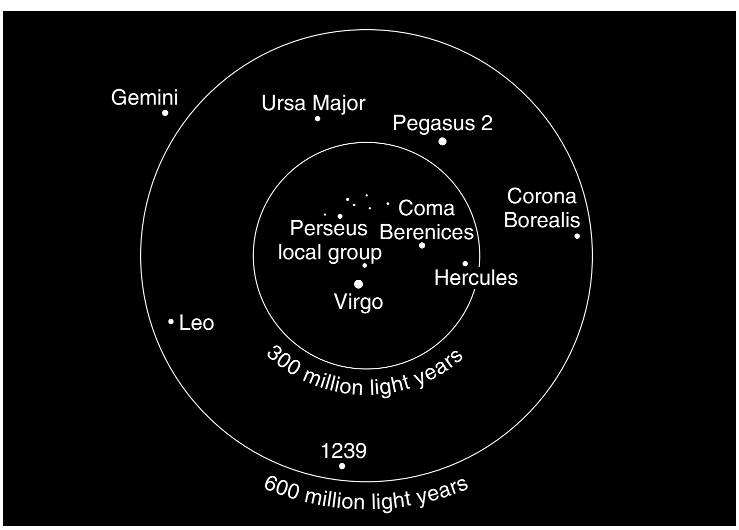


Figure 27.38 This map show groups of galaxies in the vicinity of our Local Group of galaxies.

In the 1920s the American astronomer Edwin Hubble began to plot the positions and distances of galaxies from Earth. He calculated the distance of galaxies using standard candles called **Cepheid variable** stars. Hubble used Cepheids as his standard candles, in the same way as type 1a supernovae are used today. Hubble compared the distances of galaxies with their redshifts, and established that the distance a galaxy is away from us is proportional to its redshift or its velocity of recession. Figure 27.39 shows this linear relationship, which leads to Hubble's law:

$$v = Hd$$

where v is the speed of recession of a galaxy, d is its distance away from us and H is Hubble's constant, which is $67.8\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ or $20.7\,\mathrm{km\,s^{-1}\,Mly^{-1}}$.

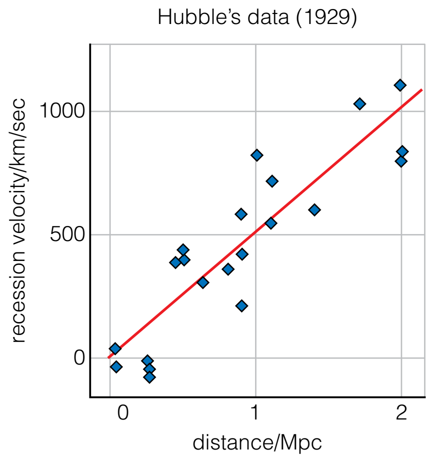


Figure 27.39

> **TIP**
> The Hubble constant is not well known and values given in data and questions can vary. Often a figure of $70\,\text{km s}^{-1}\,\text{Mpc}^{-1}$ is used.

Hubble's constant tells us that if a galaxy is 1 Mpc away from us its velocity is about $70\,\text{km s}^{-1}$, and if a galaxy is 10 Mpc away from us then its velocity is about $700\,\text{km s}^{-1}$.

> **EXAMPLE**
>
> **The Hubble constant**
>
> Express the Hubble constant in units of s^{-1}.
>
> **Answer**
>
> From earlier in this chapter, 1 pc = 3.26 ly, so
>
> $$1\,\text{Mpc} = 3.26\,\text{Mly}$$
> $$= 3.26 \times 10^{6} \times 3 \times 10^{8}\,\text{m s}^{-1} \times 365 \times 24 \times 3600\,\text{s}$$
> $$= 3.1 \times 10^{22}\,\text{m}$$
>
> So
>
> $$H = \frac{67.8 \times 10^{3}\,\text{m s}^{-1}}{3.1 \times 10^{22}\,\text{m}}$$
> $$= 2.2 \times 10^{-18}\,\text{s}^{-1}$$

The Big Bang theory

Hubble's law led to the idea of the Big Bang theory. Figure 27.40 shows a region of space, with an observer O at its centre. The observer sees galaxies in every direction. Galaxies that are a distance r from O travel with a speed v. Galaxies that are a distance $2r$ from O travel with a speed $2v$. Therefore, it is argued, at some point in the past all the galaxies must have been at the same point.

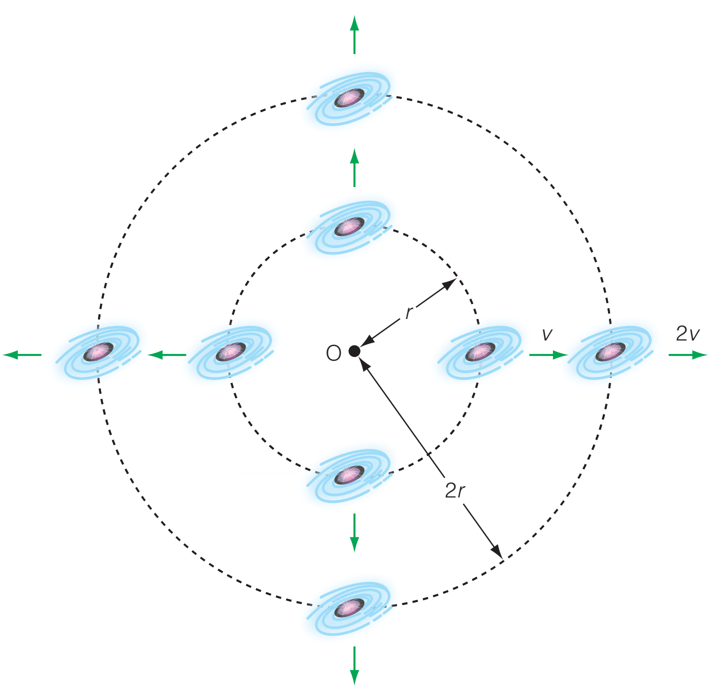


Figure 27.40

Cosmologists now accept the Big Bang theory, which suggests that the Universe originated about 13.8 billion years ago. All the matter we see in the Universe exploded at one point and has been travelling outwards ever since. In the first few seconds after the Big Bang, the Universe was extremely hot, with temperatures in excess of 10^{11} K. As the Universe cooled, atoms of hydrogen and helium were formed. Over billions of years, the force of gravity acted on this matter to pull it together into the stars and galaxies that we see today.

Calculations on the early state of the Universe lead us to think that, in the time between 10 seconds and 20 minutes after the Big Bang, the temperature of the Universe was hot enough to fuse hydrogen into helium, in the same way that fusion takes place in stars. These calculations suggest that the early Universe was composed of about 75% hydrogen and 25% helium, together with traces of other elements, such as deuterium, ${}^{2}_{1}\text{H}$, and lithium, ${}^{7}_{3}\text{Li}$. Observation of some of the Universe's older objects have confirmed that hydrogen and helium are present in the ratio of 75% to 25%, providing support for the Big Bang theory.

Cosmic microwave background radiation

A further piece of evidence to support the Big Bang theory was provided by the discovery of background radiation, which comes uniformly from all directions. After about 350 000 years the Universe had cooled to a temperature of about 3000 K. So the Universe was full of black-body radiation associated with matter at that temperature. As the Universe expanded, it cooled, and the wavelength of that background radiation has shifted to much longer wavelengths. The background radiation peaks at a wavelength of 1.8 mm, which corresponds to a background temperature of space of about 2.7 K.

Age of the Universe

If we assume that the Universe has been expanding at a constant rate, we can use Hubble's constant to estimate its age. The distance a galaxy has travelled since the origin of the Universe is given by

$$\text{distance} = \text{speed} \times \text{time}$$

or

$$d = vt$$

(assuming that the speed has been constant). But Hubble's law says that

$$v = Hd$$

or

$$d = v \times \frac{1}{H}$$

So the age of the Universe is approximately $t = \frac{1}{H}$.
Because $H = 2.2 \times 10^{-18}\,\text{s}^{-1}$, the age of the Universe is

$$t = \frac{1}{H} = \frac{1}{2.2 \times 10^{-18}\,\text{s}}$$
$$= 4.5 \times 10^{17}\,\text{s}$$
$$= 14.46 \text{ billion years}$$

The accepted value of the Universe's age is 13.8 billion years.

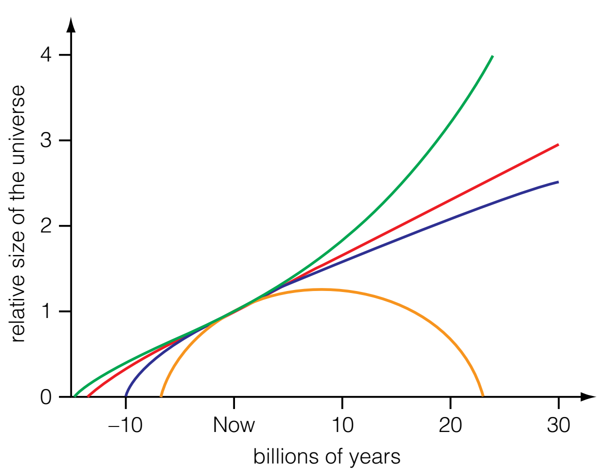


Figure 27.41

The expansion of the Universe is not in question but the rate of expansion is still uncertain and depends on the amount of matter present in the Universe. Observations seem to suggest that while the rate of expansion of the early Universe was slowed because of gravity, the rate of expansion now and in the future is uncertain. If there is enough matter in the Universe, it will reach a maximum size, slow down and reverse, shown by the yellow curve in Figure 27.41. Recent observations indicate this is not the case. If the density of the Universe is a critical density then the rate of expansion will gradually slow down until the expansion stops. In Figure 27.41 the blue curve showing this will gradually get ever closer to horizontal. Slightly less than the critical density and the rate of expansion of the Universe will slow down over a longer period of time and may never stop. This is shown by the red curve in Figure 27.41. However, as suggested previously, some of the most recent measurements show that the rate of expansion of the Universe is increasing and it is suggested that some form of energy, known as Dark Energy, that is part of the fabric of space, is responsible. This is shown by the green curve in Figure 27.41. As yet we do not know the form of this Dark Energy or, indeed, if it exists. Whatever the future expansion of the Universe, the Figure 27.41 shows why the value for the age of the Universe obtained from the Hubble constant is not quite accurate because the calculation using the Hubble constant assumes a steady rate of expansion.

TEST YOURSELF

43 Outline the evidence for the Big Bang theory.

44 a) A group of galaxies lies at a distance of 200 Mpc from the Earth. Calculate the speed of recession of the group. Hubble's constant = 67.8 km s^{-1} Mpc^{-1}.

b) A group of galaxies is receding from Earth at a speed of 120 000 km s^{-1}. Calculate the distance of the group from Earth.

45 A group of galaxies has a redshift of 0.22.

a) Calculate the speed of recession of the group.

b) Calculate the distance of the group away from Earth using the value of Hubble's constant = 20.7 km s^{-1} Mly^{-1}.

Quasars

Quasar A small, very distant object, which emits as much power as a large galaxy.

In the 1960s astronomers discovered a new type of object in the sky. It was given the name **quasar**, which is short for quasi-stellar radio sources. The first quasars we were first discovered because they were very intense sources of radio waves. Quasars puzzled astronomers because they appeared to be very luminous indeed and among the most distant objects in the Universe (because large redshifts were measured in their spectra), yet they appeared to be points of light – just like a star. Figure 27.42 shows a photograph of the nearest known quasar, 3C 273, taken through the Hubble Space Telescope. Although the quasar looks like a point when viewed directly through a telescope, its brightness causes a large image to be formed when a photograph is taken.

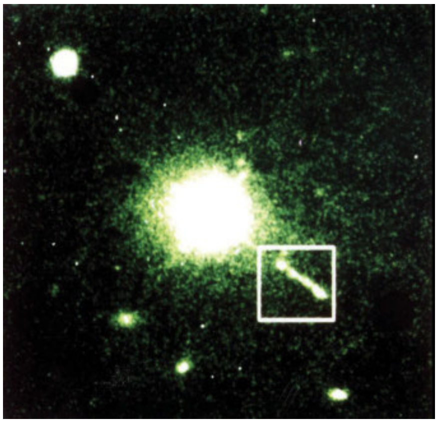


Figure 27.42 Quasar 3C 273 lies a distance of 1000 Mpc away from Earth, yet it outshines galaxies that lie about 20 Mpc from Earth, which you can see in the same photograph.

The lines in the photograph are caused by diffraction effects. The photograph also reveals a jet from the quasar pointing towards the bottom right hand corner.

Quasars are the most luminous objects seen in the sky. The apparent magnitude of 3C 273 is +13, yet its absolute magnitude is –27. This means that if 3C 273 were at a distance of 10 pc from us, it would appear about as bright as the Sun. 3C 273 emits much more light than a large galaxy such as the Milky Way, which contains 200–400 billion stars.

Although the nature of quasars was a mystery for a number of years, astronomers are now convinced that they are caused by massive black holes as large as 10^8 or 10^9 solar masses. The radius of the event horizon of such a massive black hole is the same order of magnitude as our Solar System. Some quasars are so distant (right at the limit of the visible

Universe) that we are seeing them as they were shortly after the Big Bang. They are young galaxies in the making. The density of matter in a quasar is so high that a black hole has formed, and the gravitational pull is so strong that matter is being swallowed up at a great rate. It is calculated that the brightest quasars are swallowing mass equivalent to 110 solar masses per year. As stellar matter falls into the black hole, the gravitational potential energy of the matter is transferred into electromagnetic waves. A black hole tearing up matter releases energy into electromagnetic waves at a much faster rate than thermonuclear fusion does in stars. Quasars are strong emitters of all wavelengths of electromagnetic waves, from radio waves through to X-rays and gamma rays.

Quasars do not live for long – we see quasars as they were billions of years ago. Once a quasar has devoured most of the matter in its vicinity, it then acts as a stable centre of an ordinary galaxy. The Milky Way has an enormous black hole at its centre, which provides a central massive area of gravitational attraction, which helps to keep stars such as our Sun in its stable orbit around the galactic centre.

TEST YOURSELF

46 Explain the origin of the name 'quasar'.

47 List three characteristics of quasars.

48 a) The quasar 3C 273 has an apparent magnitude of +13 and is 1000 Mpc from the Earth. Use the equation

$$M = m - 5\log\left(\frac{d}{10}\right)$$

to confirm that the absolute magnitude of 3C 273 is –27.

b) The absolute magnitude of a large galaxy such as the Andromeda galaxy, which contains over 10^{12} stars, is about –22. Compare the luminosity of 3C 273 with that of the Andromeda galaxy.

49 A large quasar has a mass of 10^{39} kg and an event horizon of radius 3×10^{12} m.

a) i) Show that the gravitational potential close to the event horizon is $-2 \times 10^{16}\,\text{J kg}^{-1}$.

ii) Now show that when a star with the mass of the Sun, 2×10^{30} kg, falls into the quasar from a large distance, the gravitational potential energy lost is about 4×10^{46} J.

b) i) On average, matter equivalent to 20 solar masses falls into the quasar each year. Assuming that 30% of the potential energy of the matter is transferred into electromagnetic waves, calculate the luminosity of the quasar in watts.

ii) The Sun has a luminosity of 4×10^{26} W. Compare the luminosity of the quasar with that of the Sun.

Exoplanets – are we alone?

It is difficult to know exactly how many galaxies there are in the Universe, but current estimates put that number at about 100 to 200 billion. Because each galaxy has hundreds of billions of stars, it is likely that the Universe contains more than 10 000 billion billion, or 10^{22}, stars. There are many stars like our Sun and it is estimated that there are billions of planetary systems similar to ours. Since the laws of physics hold everywhere in the Universe, it is highly probable that somewhere there is another Earth-like planet – but whether there are any life forms there is another question, to which we shall never know the answer.

Discovery of exoplanets

Exoplanet A planet outside our Solar System, in orbit around another star.

Exoplanet is the name given to a planet that lies outside our Solar System. An exoplanet is in orbit around another star. In recent years, new technologies have enabled the discovery of thousands of planets in orbit around other nearby stars. However, only a very small number of giant planets (of Jupiter's size or more) have been observed directly, because planets are much less bright than the stars they orbit. Most exoplanets that have been discovered have been detected by indirect means.

Variation in Doppler shift

Figure 27.43 shows (not to scale) a giant planet and a star. We usually say that planets orbit stars, but it is more accurate to say that a giant planet and a star orbit around a common centre of gravity. If a giant planet has a mass of about 0.001 times the mass of the star, the centre of gravity is likely to lie outside the star. Then there are times when the star will be moving towards the Earth, and times when the star will be moving away from the Earth. So there will be small changes to the spectrum of the star, which will be seen as a small redshift or a small blueshift.

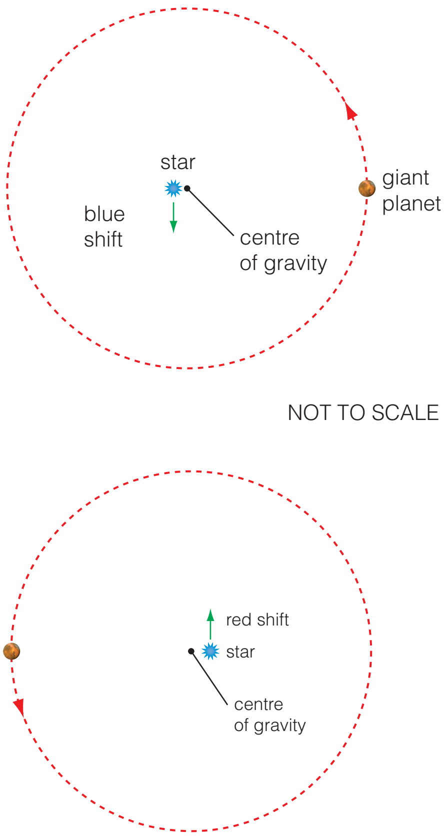


Figure 27.43

This method detects the presence of large planets near to stars, but it does not enable the mass of the planet to be calculated, as we do not know its distance from the star.

Planetary transits

If an exoplanet crosses in front of a star's surface, then the brightness we see will drop by a small amount (Figure 27.44). For example, if a planet covers an area of 5% of the star's disc, then the light intensity would drop by 5%. A planetary transit is the most common method for an astronomer to detect a new exoplanet.

The light curve allows a rough estimate to be made of the planet's radius, and then the planet's mass – if we make some assumptions about its likely composition and density.

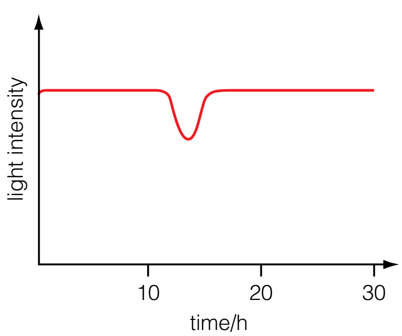


Figure 27.44 A light curve for a typical exoplanet transit across the surface of its parent star.

Direct imaging of exoplanets

HR 8799 is a young (30 million years old) main sequence star, located about 39 pc away from the Earth. It is about 1.5 times as massive as the Sun and 5 times as luminous. Figure 27.45 shows a direct image of an exoplanetary system – you can see four planets in orbit around the star. The light from the star has been digitally removed to enhance our view of the planets. All four planets in view are huge gas giants with approximately 10 times the mass of Jupiter. The inner planet, HR 8799e, takes about 45 Earth years to orbit the star and the outer one, HR 8799b, takes about 460 Earth years to orbit the star.

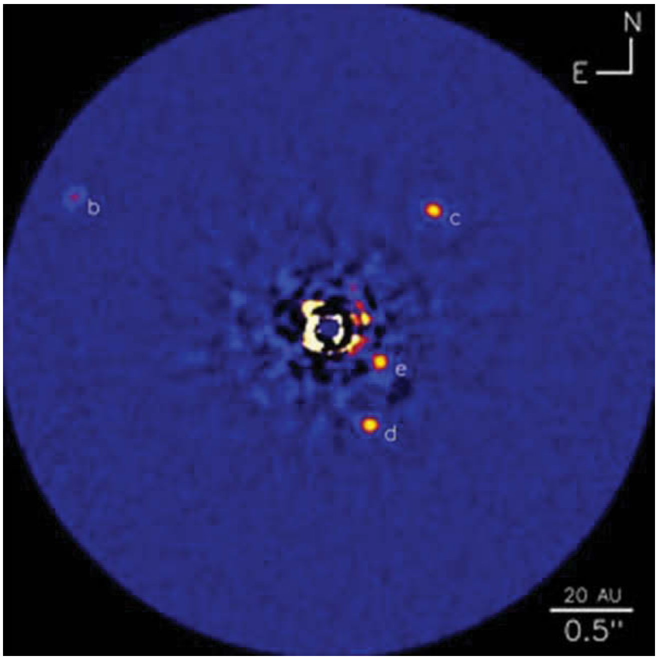


Figure 27.45 A rare direct image of exoplanets.

TEST YOURSELF

50 a) Give an account of three ways in which exoplanets can be detected.

b) Explain why the exoplanets detected are usually larger than the planet Jupiter.

51 When an exoplanet crosses in front of a star, the star's light intensity falls to 96% of its peak value. Calculate the ratio

$$\frac{\text{radius of exoplanet}}{\text{radius of star}}$$

52 The inner planet HR 8799e of the HR 8799 system orbits the star at a distance approximately 15 times the radius of Earth's orbit around the Sun. Discuss what other types of planet may yet be discovered in this system.

Practice questions

1 A reflecting telescope has an objective lens of focal length 120 cm and a diameter of 24 cm. The telescope eyepiece has a focal length of 2.4 cm and a diameter of 1.2 cm. The magnification of the telescope is

A 5 **C** 20

B 10 **D** 50

2 Deneb is a bright star that is 800 pc from Earth. It has an apparent magnitude of 1.2. Its absolute magnitude is

A −13.3 **C** −4.3

B −8.3 **D** −1.3

3 Merak and Ankaa are two stars that have the same black-body luminosities. Ankaa has a surface temperature of 4500 K and a radius $16R_s$, where R_s is the radius of the Sun. Merak has a surface temperature of 9000 K. What is Merak's radius in terms of R_s?

A $2R_s$ **C** $4R_s$

B $3R_s$ **D** $6R_s$

4 A crater on the Moon has a diameter of 500 m. The Moon is 400 000 km distant from Earth. What is the smallest telescope that will be able to resolve this crater, when viewed with light of wavelength 500 nm? Assume perfect viewing conditions.

A 4.0 m **C** 0.40 m

B 2.4 m **D** 0.024 m

5 A star has a surface temperature of 2800 K. The peak intensity of the radiation emitted from the star's surface will be in which part of the spectrum?

A infrared **C** green light

B red light **D** ultraviolet

6 A galaxy has a redshift of 0.185. Hubble's constant is $67.8\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$. The distance of the star away from us is

A 1200 Mpc **C** 820 Mpc

B 950 Mpc **D** 570 Mpc

7 Radio telescope A has a diameter of 64 m, and radio telescope B has a diameter of 45 m. The ratio $\frac{\text{gathering power of A}}{\text{gathering power of B}}$ is

A 1.2 **C** 2.0

B 1.4 **D** 2.4

Use the following information to answer questions 8, 9 and 10.

The table gives the surface temperature and luminosity of five stars; the luminosity listed is given in units relative to the Sun's luminosity.

	Surface temperature/K	Luminosity $\frac{L_{star}}{L_{Sun}}$
A	22000	0.026
B	40000	2×10^5
C	10000	90
D	3500	4000
E	2500	0.05

8 Which star has the smallest diameter?

9 Which star has the largest diameter?

10 Which star has an O class spectrum?

11 A refracting telescope is made from two lenses, an objective lens and an eyepiece.

a) Figure 27.46a shows light arriving at the objective lens of a refracting telescope. Copy and complete the diagram to show how a real image is formed in the focal plane of the lens. *(2)*

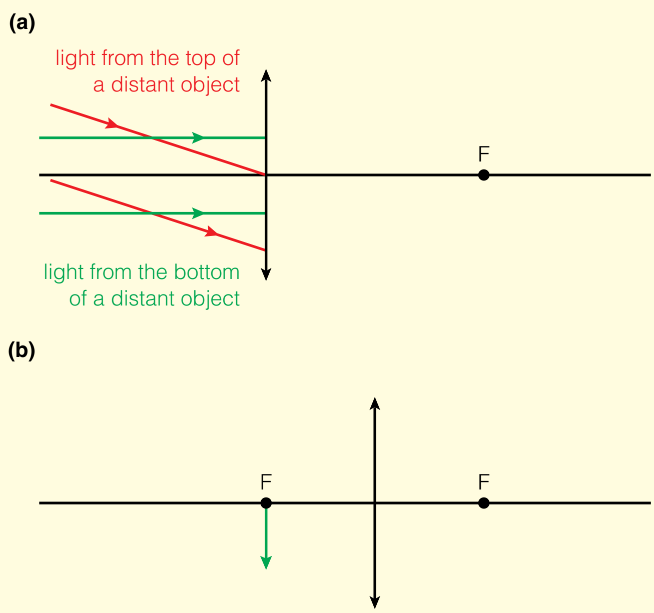


Figure 27.46

b) Figure 27.46b shows a real image in front of the eyepiece of the refracting telescope. Copy and complete this ray diagram to show how a virtual image is seen at infinity. Mark in the position of the eye to see this image. *(3)*

c) The telescope has a length of 2.28 m. Calculate the focal length of the eyepiece that would give the telescope a magnification of 75. *(2)*

d) Refracting telescopes tend to be affected by chromatic aberration. Explain what causes chromatic aberration. *(2)*

12 a) Draw the ray diagram for a Cassegrain telescope. Your diagram should show the paths of two rays, initially parallel to the principal axis, as far as the eyepiece. *(2)*

b) i) Chromatic aberration can be a problem when you use a refracting telescope. Why does a reflecting telescope reduce problems from chromatic aberration? *(1)*

ii) Spherical aberration can be a problem if a reflecting telescope has a concave spherical mirror. Draw a diagram to illustrate spherical aberration caused by a spherical mirror. *(1)*

iii) Explain how telescope makers avoid the problem of spherical aberration. *(1)*

c) A reflecting telescope has a primary mirror with a diameter of 0.30 m. Calculate the minimum angular separation that could be resolved by this telescope when observing point sources of light of wavelength 670 nm. *(2)*

d) This is a gap between the A and B rings in Saturn's ring system. This is called the Cassini division after its discoverer. The division is 4800 km wide, and Saturn is about 1400×10^6 km from Earth. What minimum diameter of telescope do you need to see the Cassini division clearly? *(3)*

13 a) Copy the axes in Figure 27.47 and add to them a sketch of the Hertzsprung–Russell diagram. In your sketch show the main sequence stars, giant stars and white dwarf stars. On the *y*-axis mark in an appropriate scale for the absolute magnitude of stars. *(3)*

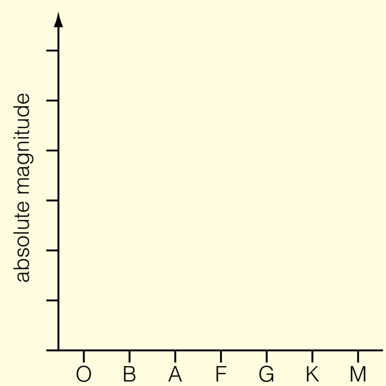


Figure 27.47

b) i) Alioth is a bright star in the constellation Ursa Major. The black-body radiation curve for Alioth shows a peak at a wavelength of 2.7×10^{-7} m. Calculate Alioth's black-body temperature. *(2)*

ii) Alioth has a luminosity 110 times that of the Sun. Calculate the radius of Alioth. The Sun's surface temperature is 5800 K, and the Sun's radius is 6.96×10^8 m. *(3)*

c) The spectrum of Alioth contains hydrogen Balmer absorption lines. Describe how hydrogen Balmer lines are produced in the spectrum of a star. *(6)*

14 Some galaxies, known as Seyfert galaxies, have very active centres. These are very similar to quasars, because astronomers think that they have supermassive black holes at their centres.

a) Explain what is meant by the 'event horizon' of a black hole. *(1)*

b) i) A black hole has a mass 8×10^7 times that of the Sun. Calculate the radius of the event horizon. *(2)*

ii) Calculate the average density of matter inside the event horizon. *(2)*

15 Alnilam and Betelgeuse are bright stars in the constellation of Orion. Some properties are summarised in the table below.

Star	Alnilam	Betelgeuse
Absolute magnitude	−6.4	−6.1
Apparent magnitude	1.7	0.4
Black-body temperature/K	26 200	3300

a) Explain what is meant by the terms

i) apparent magnitude *(1)*

ii) absolute magnitude. *(1)*

b) Which of the two stars is closer to Earth? Explain your answer. *(1)*

c) i) Calculate the wavelength of the peak intensity in the black-body radiation curve of Alnilam. *(2)*

ii) Sketch the black-body curve for Alnilam, using relative intensity on the *y*-axis and wavelength in nm on the *x*-axis. Label the *x*-axis with a suitable scale. *(3)*

d) Analysis of the light from both stars shows prominent absorption lines in their spectra.

i) To which spectral class does Alnilam belong? *(1)*

ii) The spectrum of Alnilam shows prominent Balmer absorption lines due to hydrogen. State the other element responsible for prominent absorption lines in the spectrum for Alnilam. *(1)*

iii) Explain why Betelgeuse does not show Balmer lines in its spectrum. *(1)*

e) Betelgeuse and Alnilam have very similar absolute visual magnitudes, as shown in the table above. However, Alnilam has a luminosity (power) 375 000 times that of the Sun, in comparison with Betelgeuse's luminosity, which is 120 000 times that of the Sun. Account for the differences between the luminosities and visual magnitudes of the stars. *(2)*

16 Reflecting telescopes are now more commonly used by professional astronomers than refracting telescopes. Explain what advantages reflecting telescopes have over refracting telescopes. (6)

17 Different types of telescope are used to detect different parts of the electromagnetic spectrum, from radio waves to X-rays. Discuss with reference to three parts of the electromagnetic spectrum the factors that should be taken into account when deciding where to position the telescope and when deciding on the size of the telescope. *(6)*

18 3C 48 is a quasar that lies in the constellation of Triangulum.

a) 3C 48 has a redshift of 0.367. Calculate the distance of 3C 48 from Earth, stating an appropriate unit. Hubble's constant is $65\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$. *(4)*

b) i) The first quasars were discovered in the 1960s. What property of quasars led to their discovery? *(1)*

ii) Quasars are the most luminous objects in the Universe. Explain the nature of quasars and why they are so luminous. *(3)*

19 A group of galaxies seen in the constellation of Hydra shows a redshift of 0.048.

a) i) Explain what is meant by 'redshift'. *(1)*

ii) Calculate the velocity of the galaxies in Hydra. *(2)*

iii) Estimate the distance from Earth of the galaxies using Hubble's law. *(1)*

b) A type 1a supernova was detected recently in one of the galaxies. Figure 27.48 shows the typical light curve for a type 1a supernova.

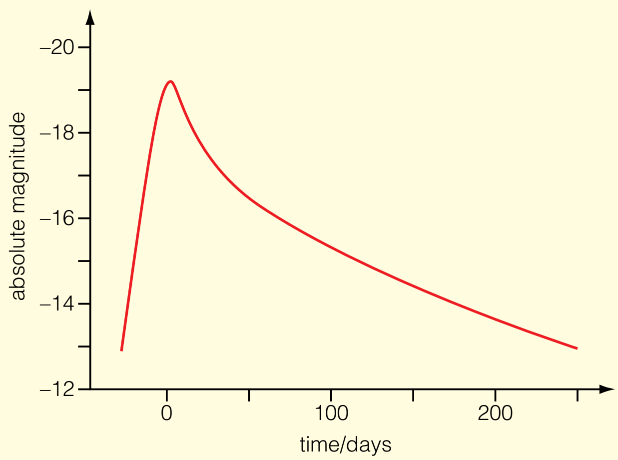


Figure 27.48

i) With reference to Figure 27.48, explain why type 1a supernovae may be used as standard candles to determine distances. *(2)*

ii) The peak value for the apparent magnitude of the supernova was 17.3. Use this information to calculate the distance to the galaxies from Earth. *(3)*

20 **a)** Draw a ray diagram for an astronomical refracting telescope in normal adjustment. Your diagram must show the paths of three non-axial rays through both lenses. *(3)*

b) A refracting telescope has a length of 2.05 m and an angular magnification of 40. Calculate the focal lengths of the eyepiece and of the objective lens. *(2)*

c) Jupiter has a diameter of 7.0×10^4 km and is a distance of 7.8×10^8 km from the Earth. Calculate the angle subtended by Jupiter when viewed through this telescope. *(2)*

d) Refracting telescopes can suffer from chromatic aberration. Draw a ray diagram to show how chromatic aberration can occur when light passes through a lens. *(2)*

21 Albireo A and Allbireo B form a bright double star in the constellation Cygnus. Allbireo A is a red giant star and Albireo B is a green-blue main sequence star. The table below summarises some of the properties of the stars.

Star	Albireo A	Albireo B
Absolute magnitude	−2.5	−0.3
Apparent magnitude	3.1	5.3
Diameter/10^3 km	50 000	2000
Black-body temperature/K	4300	12 900

a) Explain the terms 'main sequence star' and 'red giant'. *(2)*

b) Calculate the distance from Earth to Albireo, giving an appropriate unit. *(3)*

c) By using Stefan's law, show that the ratio below is about 8. *(3)*

$$\frac{\text{luminosity of Albireo A}}{\text{luminosity of Albireo B}}$$

d) Show that your answer to (c) is consistent with the stated absolute magnitudes of the stars. *(2)*

22 Figure 27.49 shows a computer-coloured image of radio emissions from Cygnus A, which is one of the strongest radio sources in the sky. Two jets emerge from either side of a giant black hole at the centre of the galaxy. These jets probably extend beyond the width of the host galaxy. When material from the jets is slowed down by the surrounding medium, radio waves are emitted. The strongest areas of emission are seen as the bright lobes on either side of the image. The radio telescopes that recorded this image detected waves with a wavelength of 0.15 m.

a) Use the scale on the diagram to determine the smallest distance that you can resolve in the image. Express your answer in Mly. *(1)*

b) The galaxy is about 600 Mly from Earth. Use your answer to part (a) to determine the smallest angle that the radio telescope can resolve at this wavelength. *(2)*

c) The resolution of radio telescopes can be improved by connecting together two or more telescopes separated by a large distance. Use your answer to part (b) to estimate the effective diameter of the radio telescopes used to produce this image. *(2)*

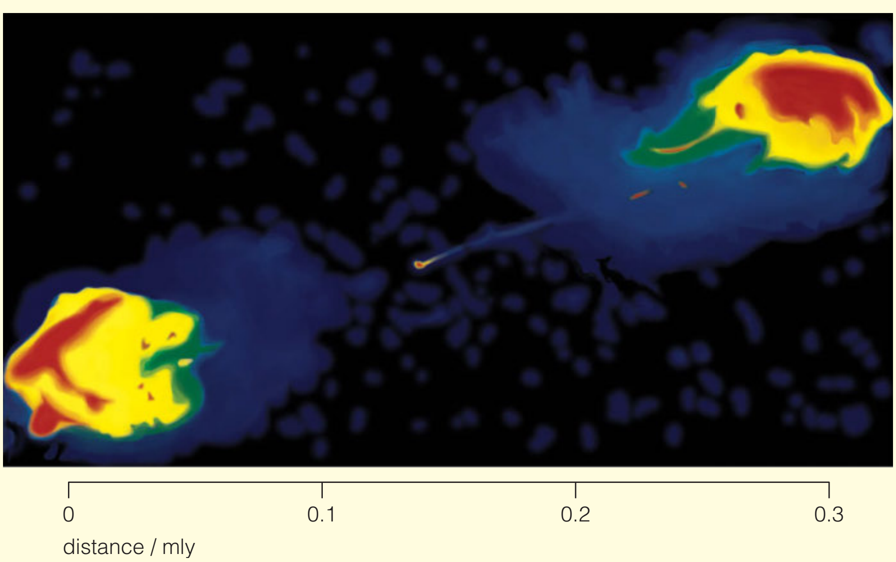


Figure 27.49 Radio emissions from Cygnus A.

Stretch and challenge

23 A red giant has a radius 200 times that of the Sun, and a surface temperature half that of the Sun.

a) Use Stefan's law to show that the luminosity of the red giant is 2500 times that of the Sun.

b) The absolute magnitude of the Sun is +4.6. Calculate the absolute magnitude of the red giant.

24 When a galaxy is moving away from us close to the speed of light, the wavelength of light, λ_0, that we observe is given by

$$\lambda_0 = \lambda_S \frac{\left(1 + \frac{v}{c}\right)}{\left(1 - \frac{v^2}{c^2}\right)^{\frac{1}{2}}}$$

where λ_s is the wavelength of the light emitted by the galaxy, v is the speed of the galaxy and c is the speed of light.

Show that the redshift $z = \frac{\Delta\lambda}{\lambda_S}$ is given by

$$z = \frac{\left(1 + \frac{v}{c}\right)}{\left(1 - \frac{v^2}{c^2}\right)^{\frac{1}{2}}} - 1$$

The largest redshift seen for a quasar is about 7. Calculate the speed of recession of such a quasar.