Chapter 3 Cosmology

3.1 The Doppler effect

Learning objectives

→ Explain why the wavelength of waves from a moving source depends on the speed of the source.

→ Define Doppler shift.

→ Measure the velocity of the two stars in a binary system.

Doppler shifts

The wavelengths of the light waves from a star moving *towards* the Earth are shorter than they would be if the star was stationary. If the star had been moving *away* from the Earth, the wavelengths of the light waves from it would be longer than if the star was stationary. This effect applies to all waves and is known as the Doppler effect. It is the reason why the siren on an approaching emergency vehicle rises in pitch as the vehicle approaches then falls sharply as it passes you. The pitch is higher as the source approaches and lower as it retreats because the source moves a certain distance each time it emits each cycle of waves.

Consider a source of waves of frequency f moving at speed v. Figure 1 shows wave fronts representing successive wave peaks emitted by the source at time intervals $\Delta t = \frac{1}{f}$.

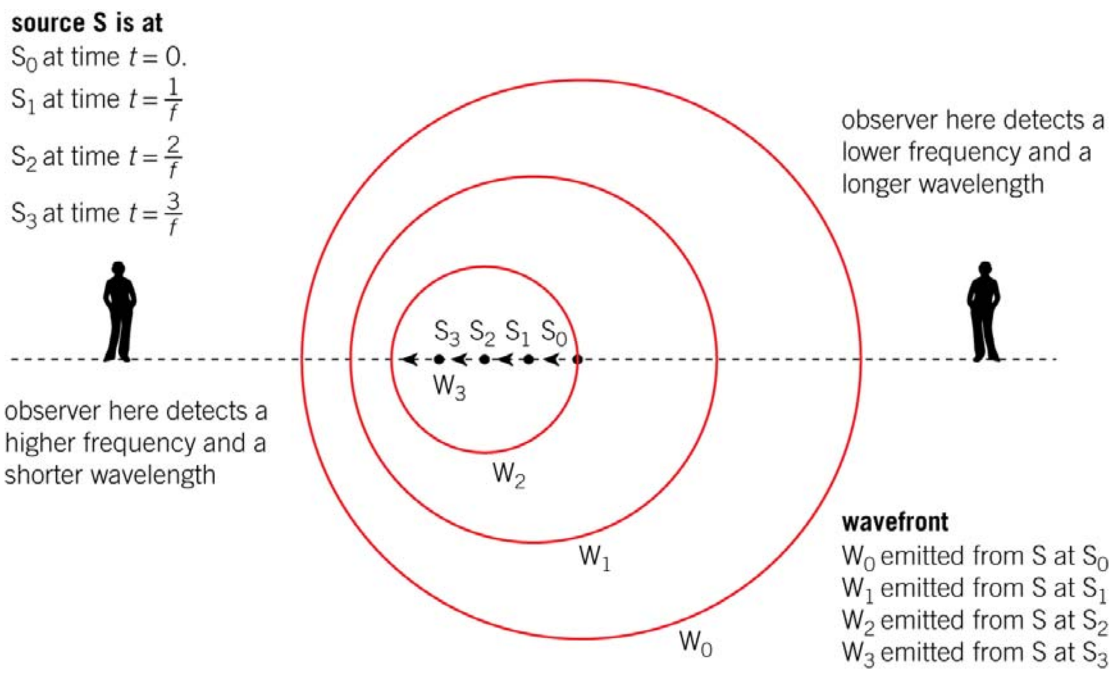


Figure 1 *The Doppler effect*

The distance between successive wave peaks is the wavelength of the waves. In time Δt, each wave peak shown travels a distance $c\Delta t$ ($= \frac{c}{f}$) before the next wave peak is emitted and the source travels a distance $v\Delta t$ ($= \frac{v}{f}$).

- Waves emitted in the opposite direction to the motion of the source (behind the source) are spaced out. If you were in the path of these waves, you would therefore detect waves of longer wavelength and therefore lower frequency. For light, this shift to longer wavelengths is called a **red shift** because it causes the lines of a line spectrum to shift towards the red end of the visible spectrum.
- Waves emitted in the same direction as the motion of the source are bunched together ahead of the source. If you were in the path of these waves, you would therefore detect waves of shorter wavelength and therefore higher frequency. For light, this shift to shorter wavelengths is called a **blue shift** because it causes the lines of a line spectrum to shift towards the blue end of the visible spectrum.

It can be shown that for a source moving at speed v relative to an observer:

towards the observer:

- the change of frequency $\Delta f = \frac{v}{c} f$
- the change of wavelength $\Delta \lambda = -\frac{v}{c} \lambda$

away from the observer:

- the change of frequency $\Delta f = -\frac{v}{c} f$
- the change of wavelength $\Delta \lambda = \frac{v}{c} \lambda$

The **Doppler shift**, z, in frequency (or wavelength) is the fractional change $\frac{\Delta f}{f}$ (or $\frac{\Delta \lambda}{\lambda}$). Mathematically, red shifts and blue shifts are **fractional** changes in frequency or wavelength.

Table 1 summarises the fractional change, z, in frequency and wavelength.

Table 1 Summary of Doppler shifts

Doppler shift, z	Source moves towards observer	Source moves away from observer
in frequency $\frac{\Delta f}{f}$	$+\frac{v}{c}$	$-\frac{v}{c}$
in wavelength $\frac{\Delta \lambda}{\lambda}$	$-\frac{v}{c}$	$+\frac{v}{c}$

Study tip

The frequency f is the frequency of the light *emitted* by the source, which is the same as the frequency emitted by an identical source in the laboratory. The change of frequency Δf is the difference between this frequency and the observed frequency (the frequency of the light from the source as measured by an observer).

Notes

1 The equations above and in Table 1 can only be applied to electromagnetic waves at speeds much less than the speed of light c.

2 A star or galaxy may be moving through space with perpendicular velocity components parallel and at right angles to the line from the Earth to the star. The first component is the star's radial speed, and the second component is the star's tangential speed. Throughout this topic, speed v refers to its radial speed (i.e., the component of the star's velocity parallel to the line between the star and the Earth.

Astronomical velocities

The line spectrum of light from a star or galaxy is shifted to longer wavelengths if the star or galaxy is moving away from you, and to shorter wavelengths if it is moving towards you. By measuring the shift in wavelength of a line of the star's line spectrum, the speed of the star or galaxy relative to Earth can be found. If the star is part of a binary system, its orbital speed can also be found, as explained later below.

In practice, the line spectrum of the star or galaxy is compared with the pattern of the prominent lines in the spectrum according to the star's spectral class. The change of wavelength of one or more prominent lines of known wavelength λ in the spectrum is then measured, and the Doppler shift z (= $\frac{\Delta\lambda}{\lambda}$) is then calculated.

For an individual star or galaxy, the speed v of the star or galaxy relative to a line between Earth and the star is then calculated from $z = \frac{v}{c}$.

The star or galaxy is moving:

- towards the Earth if the wavelength is shortened due to the star or galaxy's relative motion
- away from the Earth if the wavelength is lengthened due to the star or galaxy's relative motion.

For binary stars in orbit about each other in the same plane as the line from the Earth to the stars, the wavelength of each spectral line of each star changes periodically between:

- a minimum value of $\lambda - \Delta\lambda$ when the star is moving towards the Earth
- a maximum value of $\lambda + \Delta\lambda$ when the star is moving away from the Earth.

Worked example

$c = 3.0 \times 10^8$ m s^{-1}

A spectral line of a star is found to be displaced from its laboratory value of 434 nm by +0.087 nm. State whether the star is moving towards or away from the Earth and calculate its speed relative to the Earth.

Solution

The star is moving away from the Earth because the wavelength of its light is increased.

Rearranging $\Delta\lambda = \frac{v\lambda}{c}$ gives $v = \frac{c\Delta\lambda}{\lambda} = \frac{3.0\times10^{8}\times0.087\times10^{-9}}{434\times10^{-9}} = 6.0\times10^{4}$ m s^{-1}

If the two stars cannot be resolved, they are called a **spectroscopic binary**. Each spectral line splits into two after the stars cross the line of sight, then merge into a single spectral line as the two stars move towards the line of sight. Figure 2 shows the idea.

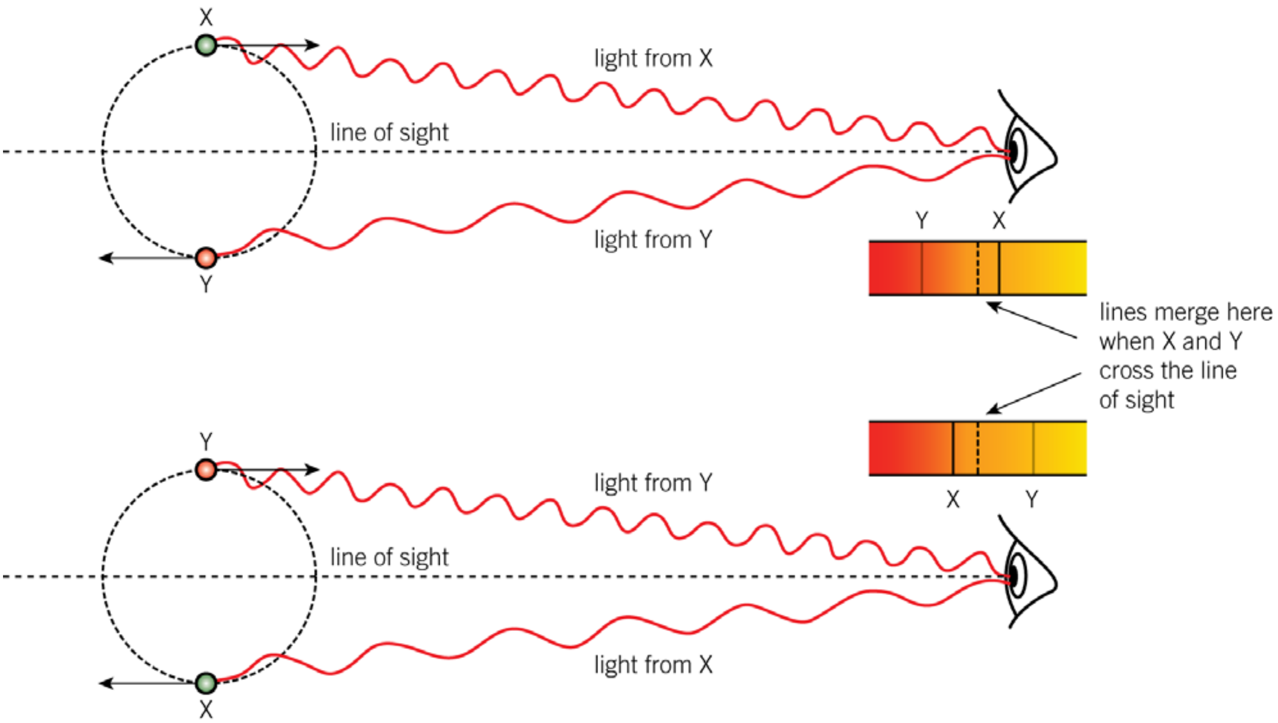


Figure 2 *A spectroscopic binary*

Note If the stars are of different masses, they will move with the same period but at different speeds and orbital radii. The change of wavelength will be greater for the faster star (less massive star) than for the other star.

Worked example

$c = 3.0 \times 10^8$ m s^{-1}

A spectral line of a certain spectroscopic binary merge once every 1.5 years and split to a maximum displacement of 0.042 nm and 0.024 nm from their laboratory wavelength of 486 nm. Calculate:

a the orbital speed of each star

b the radius of orbit of the larger orbit.

Solution

a For the slower star, $\Delta\lambda = 0.024$ nm

Rearranging $\Delta\lambda = \dfrac{v\lambda}{c}$ gives $v = \dfrac{c\Delta\lambda}{\lambda} = \dfrac{3.0 \times 10^8 \times 0.024 \times 10^{-9}}{486 \times 10^{-9}} = 1.5 \times 10^4 \text{ m s}^{-1}$

For the faster star, $\Delta\lambda = 0.042$ nm

Rearranging $\Delta\lambda = \dfrac{v\lambda}{c}$ gives $v = \dfrac{c\Delta\lambda}{\lambda} = \dfrac{3.0 \times 10^8 \times 0.042 \times 10^{-9}}{486 \times 10^{-9}} = 2.6 \times 10^4 \text{ m s}^{-1}$

b The orbital speed of the faster star, $v = \dfrac{2\pi r}{T}$, where r is its radius of orbit and T is the time period.

Therefore, the radius of its orbit $r = \dfrac{vT}{2\pi} = \dfrac{(2.6 \times 10^4 \text{ m s}^{-1}) \times (1.5 \times 365.25 \times 24 \times 60 \times 60 \text{ s})}{2\pi}$

Hence $r = 2.0 \times 10^{11}$ m

Summary questions

$c = 3.0 \times 10^8$ m s^{-1}

1 Explain why the wavelengths of the light waves from a star moving away from the Earth are longer than they would be if the star was stationary relative to the Earth.

2 A spectral line of a star is found to be displaced from its laboratory value of 656 nm by −0.035 nm. State whether the star is moving towards or away from the Earth and calculate its speed relative to the Earth.

3 The spectral lines of a star in a binary system vary in wavelength.

- **a** Explain why this variation is:
  - **i** periodic
  - **ii** over a narrow well-defined range of wavelengths.
- **b** **i** State what measurements can be made by observing the variation in wavelength of a spectral line from such a star.
  - **ii** Explain how the measurements can be used to find the radius of orbit of the star.

4 A spectral line of a certain star in a binary system changes from its laboratory wavelength of 618 nm by ± 0.082 nm with a time period of 2.5 years. Calculate:

- **a** the orbital speed of the star
- **b** its radius of orbit.

3.2 Hubble's law and beyond

Learning objectives

→ State what is meant by the term 'red shift'.

→ Explain why it is thought the Universe is expanding.

→ Discuss the evidence that led to the acceptance of the Big Bang theory.

→ Define dark energy.

Galaxies

The Andromeda galaxy is the nearest large galaxy to the Milky Way. Andromeda can just about be seen by the unaided eye on a clear night. By taking photographs of Andromeda using a large telescope, Edwin Hubble was able to identify Cepheid variable stars in Andromeda. These stars vary in brightness with a period of the order of days and are named after the first one to be discovered, δ-Cephei, the fourth brightest star in the constellation Cepheus. Their significance is that the period depends on the absolute magnitude. Hubble measured the periods of the Cepheid variables in Andromeda he had identified. He then used data obtained on Cepheid variables of known absolute magnitudes to find the absolute magnitude and hence the distance to each Cepheid variable in Andromeda. He found that Andromeda is about 900 kiloparsecs away, far beyond the Milky Way galaxy which was known to be about 50 kiloparsecs in diameter. His result settled the issue of whether or not Andromeda is inside or outside the Milky Way galaxy.

Astronomers realised that many spiral nebulae they had observed, like Andromeda, must also be galaxies. The Universe consists of galaxies, each containing millions of millions of stars, separated by vast empty spaces. Hubble and other astronomers studied the light spectra of many galaxies and were able to identify prominent spectral lines as in the spectra of individual stars but red-shifted to longer wavelengths. Hubble studied galaxies which were close enough to be resolved into individual stars. For each galaxy, he measured:

- its red shift and then calculated its speed of recession (the speed at which it was moving away)
- its distance from Earth by observing the period of individual Cepheid variables in the galaxy.

His results showed that galaxies are receding from us, each moving at speed v, that is directly proportional to the distance, d. This discovery, called **Hubble's law**, is usually expressed as the following equation:

$$v = Hd$$

where H, the constant of proportionality, is called the Hubble constant.

For distances in megaparsecs (Mpc) and velocities in km s^{-1}, the accepted value of H is 65 km s^{-1} Mpc^{-1}.

In other words, the speed of recession of a galaxy at a distance of:

- 1 Mpc is 65 km s^{-1}
- 10 Mpc is 650 km s^{-1}
- 100 Mpc is 6500 km s^{-1}

Figure 1 shows that the pattern of typical measurements of the speed of recession *v* and distance *d* plotted on a graph is a straight line through the origin. The slope of the graph is equal to the Hubble constant *H*.

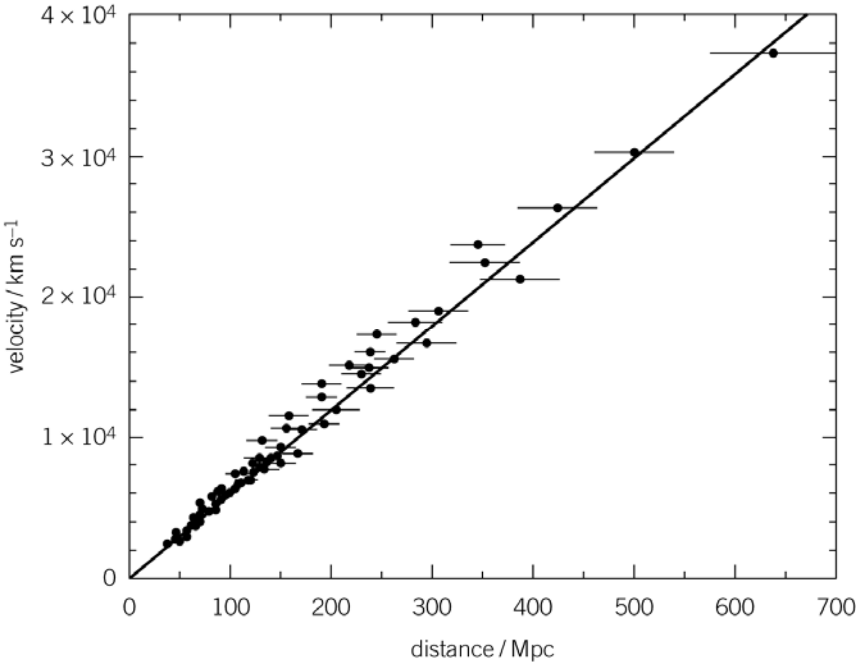


Figure 1 *Speed of recession against distance*

Note: The galaxies local to the Milky Way galaxy such as Andromeda do not fit Hubble's law because their gravitational interactions have affected their direction of motion. Andromeda is known to be on course to collide with the Milky Way galaxy billions of years in the future.

Worked example

$c = 3.0 \times 10^8$ m s^{-1}, $H = 65$ km s^{-1} Mpc^{-1}

The wavelength of a spectral line in the spectrum of light from a distant galaxy was measured at 398.6 nm. The same line measured in the laboratory has a wavelength of 393.3 nm. Calculate:

a the speed of recession of the galaxy

b the distance to the galaxy.

Solution

a $\Delta\lambda = 398.6 - 393.3 = 5.3$ nm

Rearranging $\Delta\lambda = \dfrac{v\lambda}{c}$ gives $v = \dfrac{c\Delta\lambda}{\lambda} = \dfrac{3.0\times10^{8}\times5.3\times10^{-9}}{393.3\times10^{-9}} = 4.0\times10^{6}\,\text{m s}^{-1}$

b Converting *v* to km s^{-1} gives $v = 4.0 \times 10^3$ km s^{-1}

Rearranging $v = H\,d$ gives $d = \dfrac{v}{H} = \dfrac{4.0\times10^{3}\,\text{km s}^{-1}}{65\,\text{km s}^{-1}\,\text{Mpc}^{-1}} = 62\,\text{Mpc}$

The Big Bang theory

Hubble's law tells you that the distant galaxies are receding from you. The conclusion you can draw from this discovery is that the galaxies are all moving away from each other and the Universe must therefore be expanding. At first, some astronomers thought this expansion is because the Universe was created in a massive primordial explosion and has been expanding ever since. This theory was referred to by its opponents as the **Big Bang theory**.

With no evidence for a primordial explosion other than an explanation of Hubble's law, many astronomers supported an alternative theory that the Universe is unchanging, the same now as it ever was. This theory, known as the Steady State theory, explained the expansion of the Universe by supposing that matter entering the Universe at white holes pushes the galaxies apart as the matter enters. But the Big Bang theory was accepted in 1965 when radio astronomers discovered microwave radiation from all directions in space. Steady State theory could not explain the existence of this microwave radiation, but the Big Bang theory could.

Estimating the age of the Universe

The speed of light in free space, *c*, is 300 000 km s^{-1}. No material object can travel as fast as light. Therefore, even though the speed, *v*, of a galaxy increases with its distance *d*, *no* galaxy can travel as fast as light.

The Hubble constant tells us that the speed of a galaxy increases by 65 km s^{-1} for every extra million parsecs of distance or 3.26 million light years. Therefore, a galaxy travelling almost at the speed of light would be almost at a distance of

$\frac{300\,000}{65} \times 3.26$ million light years.

To reach this distance, light would need to have travelled for 15 000 million years. Thus the Universe cannot be older than 15 000 million years.

Note

In mathematical terms, the speed of a galaxy $v < c$

Therefore, using the equation for Hubble's law gives $H\,d < c$ or $d < \frac{c}{H}$

The distance $\frac{c}{H}$ represents the maximum expansion of the Universe, and light could not have travelled further than this distance since the Universe began.

The age of the Universe, *T*, can be estimated by equating the distance travelled by light in time T ($= cT$) to the expansion distance $\frac{c}{H}$. Hence $cT = \frac{c}{H}$ gives $\boldsymbol{T = \frac{1}{H}}$.

Substituting $H = 65\text{ km s}^{-1}\text{ Mpc}^{-1} = 2.1 \times 10^{-18}\text{ s}^{-1}$ (as $1\text{ Mpc} = 3.1 \times 10^{22}$ m)

therefore gives $T = \frac{1}{H} = \frac{1}{2.1 \times 10^{-18}\text{ s}^{-1}} = 4.7 \times 10^{17}\text{ s} = 15\,000$ million years.

Evidence for the Big Bang theory

The spectrum of microwave radiation

The spectrum of microwave radiation from space matched the theoretical spectrum of thermal radiation from an object at a temperature of 2.7 K. Because the radiation was detected from all directions in space with little variation in intensity, it was realised it must be universal or cosmic in origin.

This background cosmic microwave radiation is explained readily by the Big Bang theory as radiation that was created in the Big Bang and that has been travelling through the Universe ever since the Universe became transparent. As the Universe expanded after the Big Bang, its mean temperature has decreased and is now about 2.7 K. The expansion of the Universe has gradually increased the background cosmic microwave radiation to its present range of wavelengths.

Relative abundance of hydrogen and helium

Stars and galaxies contain about three times as much hydrogen by mass as helium. In comparison, other elements are present in negligible proportion. This 3 : 1 ratio of hydrogen to helium by mass means that for every helium nucleus (of mass 4 u approximately) there are 12 hydrogen nuclei (of mass 12 u in total). Thus there are 14 protons for every 2 neutrons (proton: neutron ratio of 7 : 1). This ratio is because the rest energy of a neutron is slightly greater than that of the proton. As a result, when the Universe cooled sufficiently to allow quarks in threes to form baryons, protons formed from the quarks more readily than neutrons. Precise calculations using the exact difference in the rest energies of the neutron and the proton yield a 7 : 1 ratio of protons to neutrons.

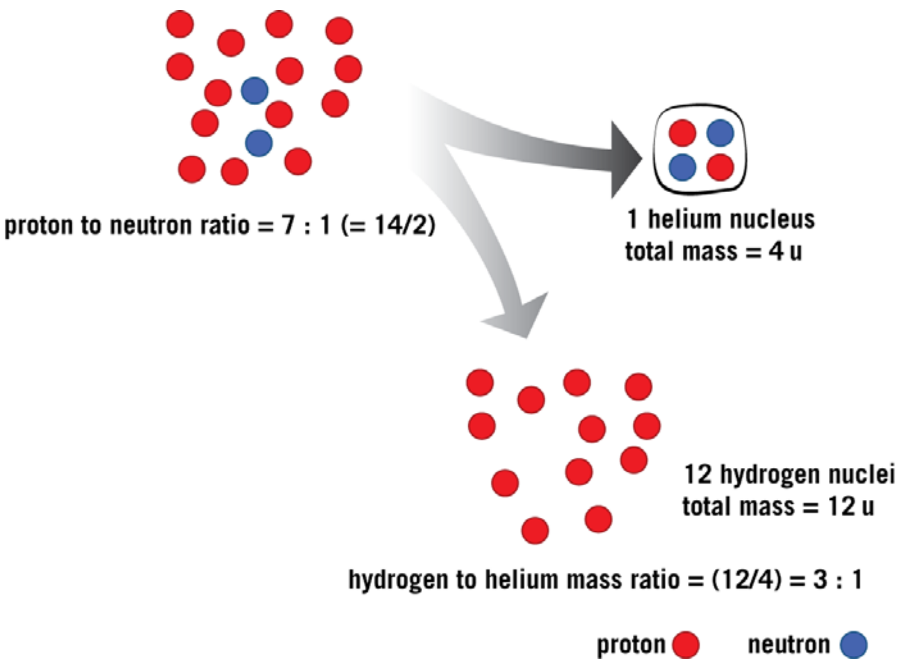


Figure 2 *Formation of hydrogen and helium nuclei*

Dark energy

Astronomers in 1998 studying type Ia supernovae were astounded when they discovered very distant supernovae much further away than expected. To reach such distances, the supernovae must have been accelerating. The astronomers concluded that the expansion of the Universe is accelerating and has been for about the past 5000 million years. Before this discovery, most astronomers expected that the Universe was decelerating because very distant objects would be slowed down by the force of gravity from other galaxies. Many more observations since then have confirmed the Universe is accelerating. Scientists think that no known force could cause an acceleration of the expansion of the Universe and that therefore a previously unknown type of force must be releasing hidden energy called **dark energy**.

Evidence for accelerated expansion of the Universe is based on distance measurements to type Ia supernova by two different methods:

1 The red shift method: measurement of the red shift of each of these distant type Ia supernova and use of Hubble's law gives the distance to each one.

2 The luminosity method: type Ia supernovae at peak intensity are known to be 10^9 times more luminous than the Sun, corresponding to an absolute magnitude of about −18. As you saw in Topic 2.4, type Ia supernovae are distinguished from other types of supernovae by the presence of strong silicon absorption lines in their spectrum. They also have distinctive light curves, as shown in Figure 3, which peak at the same absolute magnitude and decline gradually by about eight magnitudes over one year. They are called **standard candles** because they all have the same peak absolute magnitude of about $M = -19$. The distance to such a supernova can be calculated from its absolute magnitude M and its apparent magnitude m using the equation $m - M = 5 \log \frac{d}{10}$.

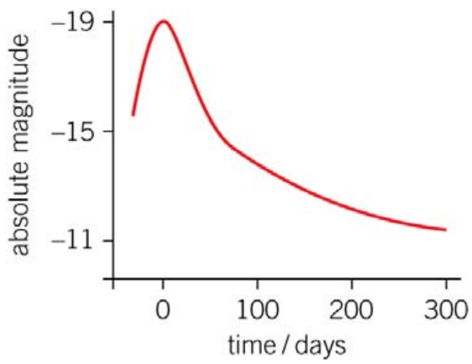


Figure 3 *Light curve of a type Ia supernova*

Link

The inverse square law was looked at in Topic 2.1, Star magnitudes.

The two methods give results that are different and indicate that the distant type Ia supernova are dimmer and therefore further away than their red-shift indicates.

The nature of dark energy is unclear. It is thought to be a form of background energy present throughout space and time. It is more prominent than gravity at very large distances because gravity becomes weaker and weaker with increased distance, whereas the force associated with dark energy is thought to be constant. Current theories suggest it makes up about 70% of the total energy of the Universe. The search for further evidence of dark energy will continue with observations using larger telescopes and more sensitive microwave detectors on satellites.

Summary questions

$c = 3.0 \times 10^8$ m s^{-1}, $H = 65$ km s^{-1} Mpc^{-1}

1 **a** State Hubble's law.

b Explain why Hubble's law leads to the conclusion that the Universe is expanding.

2 The wavelength of a spectral line in the spectrum of light from a distant galaxy was measured at 597.2 nm. The same line measured in the laboratory has a wavelength of 589.6 nm. Calculate:

a the speed of recession of the galaxy

b the distance to the galaxy.

3 State *two* pieces of experimental evidence other than Hubble's law that led to the acceptance of the Big Bang theory of the Universe.

4 A certain type 1a supernova has an apparent magnitude of +24.

a Calculate the distance to the supernova.

Assume the absolute magnitude of any type Ia supernova is −18.

b Outline why measurements on type Ia supernovae have led to the conclusion that the expansion of the Universe is accelerating.

3.3 Quasars

Learning objectives

→ Describe how quasars were discovered.

→ State the characteristic properties of a quasar.

→ Explain why there are no nearby quasars.

The first quasar

The first quasar was announced two years after a previously discovered astronomical radio source, 3C 273, was identified as a dim star in 1962 using an optical telescope. The star presented a puzzle because its radio emissions were stronger than expected from an ordinary star and its visible spectrum contained strong lines that could not be explained. Astronomers in California realised the strong lines were due to a very large red shift of 0.15, corresponding to a light source with speed of recession of 0.15 *c* (i.e., 15% of the speed of light) at a distance of over 2000 million light years away.

Based on this distance, calculations showed that 3C 273 is 1000 times more luminous than the Milky Way galaxy. But variations in its brightness indicated it is much smaller than the Milky Way galaxy. Its variations on a time scale of the order of years or less tell you that its diameter cannot be much more than a few light years.

Astronomers concluded that 3C 273 is more like a star than a galaxy in terms of its size, but its light output is on a galactic scale or even greater. The object was called a *quasi-stellar object* or **quasar**. Many more quasars have been discovered moving away at speeds up to 0.85*c* or more at distances between 5000 and 10 000 light years away. The absence of quasars closer than about 5000 million light years indicates a quasar age that started 2000 to 3000 million years after the Big Bang and lasted about 5000 million years.

Notes

1 To calculate the red shift of a quasar, the change of wavelength of one of its spectral lines of known wavelength λ is measured and then used to calculate the red shift z $(=\frac{\Delta\lambda}{\lambda})$.

2 To calculate the speed of recession v, the equation $v = zc$ may be used only if $v << c$. Otherwise, a relativistic equation relating v and z must be used. You don't need to know about this relativistic equation in your course. Quasars generally have red shifts between 1 and 5 corresponding to speeds from 0.6*c* to about 0.95*c*, which are not insignificant compared with the speed of light, *c*.

Worked example

A certain quasar has an apparent magnitude of +12.8 and a red shift of 0.15.

a Show that the quasar is about 690 Mpc from Earth.

b **i** Estimate the absolute magnitude of the quasar.

ii The absolute magnitude of the Sun is +4.8. Show that the power output of the quasar is about 3 million million times greater than that of the Sun.

Solution

a Speed of recession $v = 0.15c = 0.15 \times 300\,000$ km s^{-1} = 4.5×10^4 km s^{-1}

Using Hubble's law $v = Hd$, the distance to the quasar $d = \frac{v}{H} = \frac{4.5 \times 10^4 \text{ km s}^{-1}}{65 \text{ km s}^{-1} \text{ Mpc}^{-1}} = 690$ Mpc.

b **i** Using $m - M = 5 \log \frac{d}{10}$ gives $M = m - 5 \log \frac{d}{10}$

Hence $M = +12.8 - 5 \log \frac{690 \times 10^6}{10} = +12.8 - 39.2 = -26.4$

ii The difference between the absolute magnitude of the quasar and of the Sun $= (-26.4) - (+4.8) = -31.2$

Each magnitude difference of 1 corresponds to a power ratio of $100^{\frac{1}{5}}$. Therefore for a magnitude difference of −31.2, the power output of the quasar is $100^{\frac{31.2}{5}}$ × the power output of the Sun.

Because $100^{\frac{31.2}{5}} \approx 3.0 \times 10^{12}$, the output power of the quasar is 3.0×10^{12} × the power output of the Sun.

Note: As explained in Topic 2.3, the power output of the Sun is about 4×10^{26} W. So the power output of the quasar in the worked example is about 1×10^{39} W. In the above calculation, $d = 690$ Mpc $\approx 2 \times 10^{25}$ m as 1 pc $= 3.1 \times 10^{16}$ m. Therefore, using the inverse square law for intensity, the intensity of the light from the quasar at the Earth $= \left(\frac{1}{2 \times 10^{25}}\right)^2$ × the power output of the quasar ≈ 10^{-12} W m^{-2}.

Quasar properties

Quasars are among the oldest and most distant objects in the Universe. A quasar is characterised by:

- its very powerful light output, much greater than the light output of a star
- its relatively small size, not much larger than a solar system
- a large red shift indicating its distance is between 5000 and 10 000 light years away.

Many quasars are not like 3C 273 because they do not produce strong radio emissions.

What are quasars? Detailed optical and radio images of quasars indicate fast-moving clouds of gases and jets of matter being ejected. Quasars are found in or near galaxies which are often distorted, sometimes with lobes either side. Such active galaxies are thought to have a supermassive black hole at their centre. As discussed in Topic 2.4, such a black hole could have a mass of more than 1000 million solar masses. With many stars near it, matter would be pulled in and would become very hot due to compression as it nears the event horizon. Overheating would result in clouds of hot glowing gas being thrown back into space. A spinning supermassive black hole would emit jets of hot matter in opposite directions along its axis of rotation.

Many astronomers think that a quasar is formed from an active **supermassive black hole** at the centre of a galaxy. When we observe a quasar, we are looking back in time at a supermassive black hole in action. The action ceases when there are no nearby stars for the black hole to consume. Fortunately, the Milky Way galaxy and Andromeda and other galaxies close to Earth are relatively inactive because each galaxy no longer has many stars left near the supermassive black hole at its centre.

Summary questions

$c = 3.0 \times 10^8$ m s^{-1}, $H = 65$ km s^{-1} Mpc^{-1}

1 State three characteristics of a quasar.

2 Light from a certain quasar was found to contain a spectral line of wavelength 540 nm that had been red-shifted from a normal wavelength of 486 nm.

- **a** Show that the red shift of this quasar is 0.11.
- **b** Calculate the speed of recession of this quasar, assuming its speed is much less than the speed of light. Ignore relativistic effects.

3 **a** What features of the light from a quasar indicate a quasar is much more luminous than a star?

- **b** What feature of the light from a quasar indicates a quasar is much smaller in size than a galaxy?

4 Outline why astronomers think certain galaxies have a supermassive black hole at their centre.

3.4 Exoplanets

Learning objectives:

→ Define an exoplanet.
→ Explain how exoplanets are detected.
→ Describe the features of exoplanets.

The discovery of exoplanets

Many planets outside the Solar System have been discovered. These planets are known as **exoplanets** because they do not orbit the Sun and are outside the Solar System, orbiting stars just like the planets of the Solar System orbit the Sun. The first exoplanet was discovered in 1992 when two large planets were found to be orbiting a pulsar. Three years later, the first exoplanet orbiting a main-sequence star was discovered. By 2014, over 1700 exoplanets had been discovered and investigated. Astronomers now know that:

- most of the known exoplanets are not like the Earth, and many are gas giants like Jupiter. Some exoplanets are thought to be accompanied by other planets orbiting the same star, and a few are known to orbit more than one star.
- some exoplanets orbit within the habitable zone around its parent star. This is the zone in which liquid water may exist on a planet because the temperature at the surface needs to be between 273 K and 373 K. Liquid water cannot exist on a planet that is too close to, or too far from, its parent star.

Detecting exoplanets

Direct imaging of planets orbiting other stars is very difficult because an exoplanet is much fainter than its parent star and is hidden by the glare of the star. The main indirect methods used to detect and study exoplanets are as follows:

The radial velocity method

The radial velocity method involves observing the line spectrum of the light from the star to detect a periodic Doppler shift. A periodic shift in the wavelength of the light from the star would occur where the star and a planet are in orbit around a common centre of mass. Figure 1 shows the idea.

Each time the star moves around its orbit, each spectral line is shifted:

- towards the short wavelength end of the spectrum as the star moves towards the Earth (a blue shift)
- towards the long wavelength end of the spectrum as the star moves away from the Earth (a red shift).

The time period, *T*, of the orbital motion of the star can be found from the time period of the Doppler shift (e.g., the time between successive shifts to minimum wavelength).

The speed, *v*, of the orbital motion of the star is found by measuring the maximum change of wavelength, $\Delta\lambda$, from the mean wavelength λ. The speed *v* is then calculated by using the Doppler equation $v = c\dfrac{\Delta\lambda}{\lambda}$. See Topic 3.1.

The radius, R, of the star's orbit can then be calculated using the equation $v = 2\pi\frac{R}{T}$.

However, this calculation only applies if the line of sight to the star is in the orbital plane of the exoplanet. More generally, if the orbital plane is inclined at angle θ to the line of sight, the orbital speed of the exoplanet is $\frac{v}{\cos\theta}$. This is because the component of velocity in the direction of the Earth (i.e., the radial velocity) is the orbital speed $\times$ cos θ.

If angle θ is not known, the calculation of R using the equation $v = 2\pi\frac{R}{T}$ gives a minimum value of R.

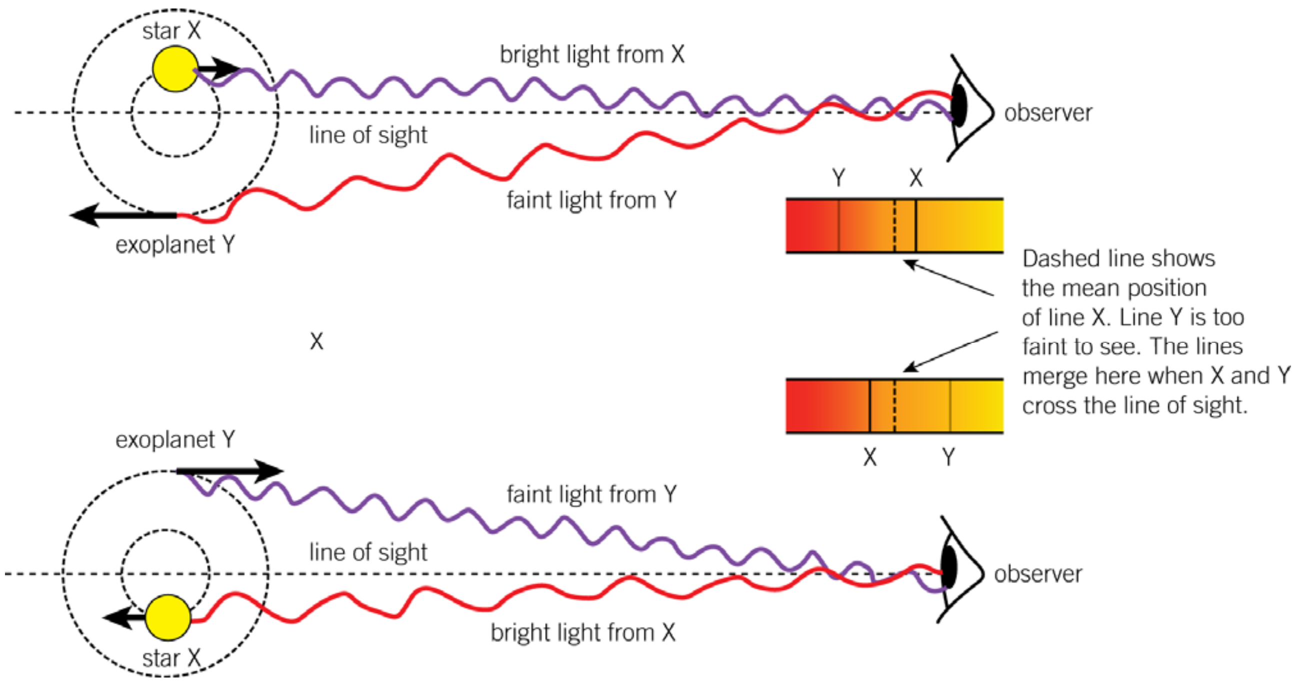


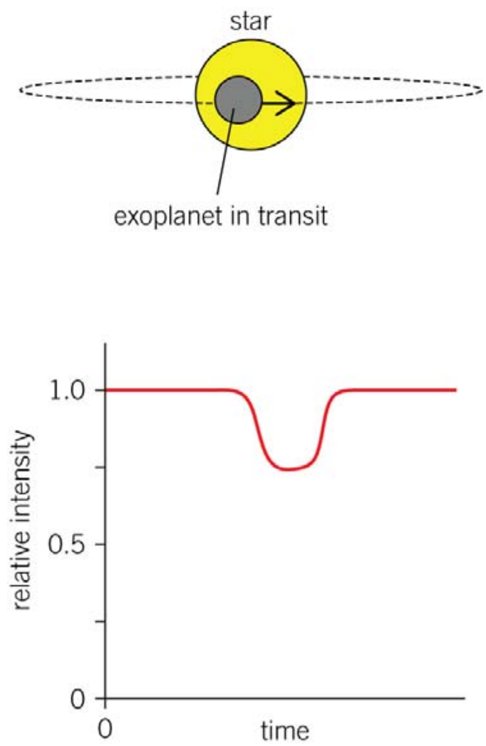
Figure 1 *The Doppler shift caused by an exoplanet*

The transit method

The transit method involves measuring and recording the intensity of the light from the star. If the intensity regularly dips, the likely cause is an exoplanet passing in front of the star – in other words crossing the line of sight to the star. The exoplanet blocks out some of the light from the star. The larger the exoplanet, the greater the dip in intensity. By measuring the dip in intensity, the radius of the exoplanet can be estimated. Figure 2 shows the light curve of an exoplanet transit. The fractional drop of intensity at each dip is equal to the ratio of the area of the exoplanet disc to the area of the star disc. Hence the radius of the exoplanet can be determined if the radius of the star is known. The time period of the planet's orbital motion can also be estimated from the light curve.

Exoplanet transit only occurs if the line of sight to the star is in the plane of the planet's orbit. Most exoplanets have orbits that are inclined to the line of sight, where the planet passes above or below the star when it moves across the line of sight. Transits are more likely for exoplanets with small orbits because most orbits are inclined, and small inclined orbits are more likely to cross the star's disc than large inclined orbits.

Variations in the regularity of the transit times indicate the presence of other planets due to their gravitational effect on the known exoplanet. Neptune and Pluto in the Solar System were both discovered from their gravitational pull on known inner planets.



> **Note:** The *y*-axis may show the change in the apparent magnitude instead of the change of relative intensity. If the magnitude decreases by Δm, $\frac{\text{the dip of intensity}}{\text{the unaffected intensity}} = 100^{\frac{\Delta m}{5}}$.
> See Topic 2.1 if necessary.

Figure 2 *The light curve of an exoplanet in transit*

Exoplanet worlds

Several space telescopes and observatories have been launched since the first exoplanet was discovered. For example, the Kepler space observatory, launched in 2009, is designed to detect exoplanets using the transit method. It is fitted with a photometer to monitor the brightness of many stars in its wide field of view. The data gathered from telescopes and other instruments in space has enabled astronomers to estimate the mass and density of many exoplanets and to draw conclusions about their composition as follows.

- Exoplanets are either low-density gas giants like Jupiter, or rocky planets like Mercury, Venus, Earth, and Mars.
- The surface conditions on rocky planets are likely to depend on how far the exoplanet is from its parent star. This is because the surface temperature on a rocky planet depends on how far the planet is from its star and also whether or not it has an atmosphere.
- The so-called habitable zone around a star is the region where liquid water could exist on a planet. Liquid water can exist only in a limited temperature range (from the freezing point of water to its boiling point). The orbit of the Earth is in the Sun's habitable zone.
- The presence of water molecules in a few exoplanets has been detected by analysing the line spectra of the light reflected from the planet. However, the

presence of water molecules does not necessarily mean liquid water is present.

- Rocky exoplanet and some gas-giant exoplanets are likely to have formed in the same way as the Solar System. The Sun is thought to have formed from swirling clouds of gas and dust in space. The planets are thought to have formed from the matter in the outer parts of these clouds. However, some gas-giant exoplanets may be so-called brown stars, which are small 'stars' in which nuclear fusion failed to start.

QUESTION: State the physical property that determines where the habitable zone is near a star.

Life on an exoplanet

A rocky exoplanet far from its parent star is likely to be a frozen world, whereas a rocky planet very close to its parent star is likely to be hot and dry with no atmosphere (like Mercury). Between these two extremes, surface conditions could be similar to Venus (hot and stormy atmosphere containing clouds of sulphuric acid) or to Mars (cold and windy with an atmosphere consisting mostly of carbon dioxide gas. Fortunately, the Earth orbits the Sun in the Sun's habitable zone, which is between Venus and Mars.

Summary questions

$c = 3.0 \times 10^8$ m s^{-1}, $H = 65$ km s^{-1} Mpc^{-1}

1 State two reasons why exoplanets are difficult to observe directly.

2 Estimate the radius of the exoplanet that caused the intensity dip in Figure 2 in terms of the radius of the parent star.

3 An exoplanet caused a Doppler shift of 0.033 nm in light of wavelength 550 nm from a star. Estimate the radial velocity of the star, assuming the line of sight to the star is in its orbital plane.

4 Explain why the conditions on many rocky exoplanets are likely to be very different to conditions on Earth.