Collins

Student Book

endorsed for edexcel

EDEXCEL INTERNATIONAL GCSE (9-1) PHYSICS

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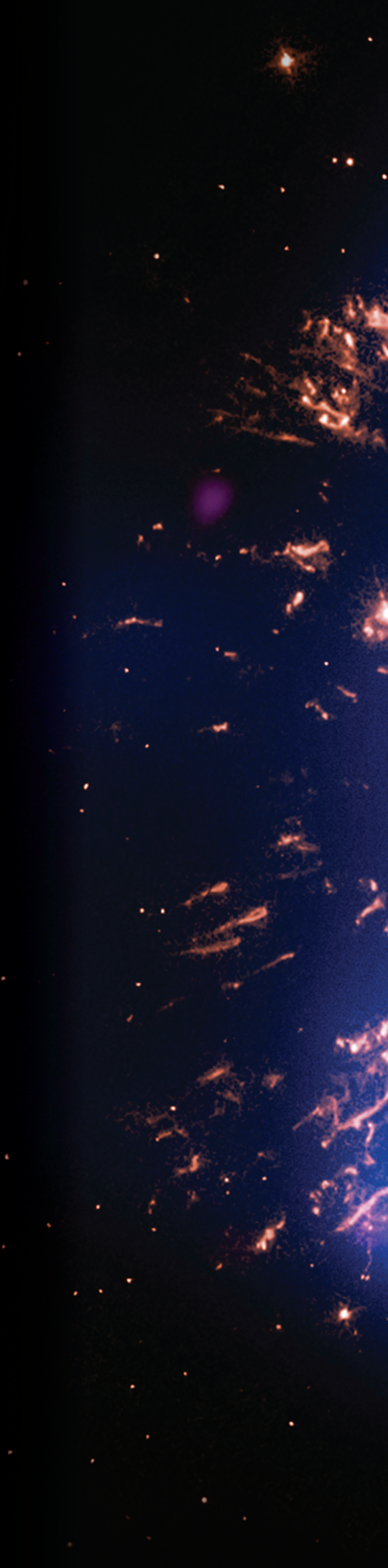
Contents

From simple viewing of the night sky to breathtaking images from the Hubble Space Telescope, humans have tried to make sense of what they see beyond the Earth. Many theories have been developed and many have been questioned and discarded as new evidence comes to light. This progress has been partly driven by new technologies from telescopes to space travel. But humans are very curious about our sky and that curiosity is unlikely to diminish.

You have met forces before and we will consider their effects on the movement of the planets, including Earth, and other celestial bodies. The vast amounts of energy released by nuclear fusion in stars must come to an end when temperatures and pressures are no longer great enough to sustain fusion reactions, and so a star's life cycle must come to an end. The wavelengths of light emitted by stars and the microwave radiation coming from every direction in space provide evidence for how the Universe began.



STARTING POINTS

1. What is the Solar System made of?

2. What are the differences between galaxies and stars, a red giant and a white dwarf?

3. What is the Universe and how might it have started?

4. What is meant by the life cycle of a star?

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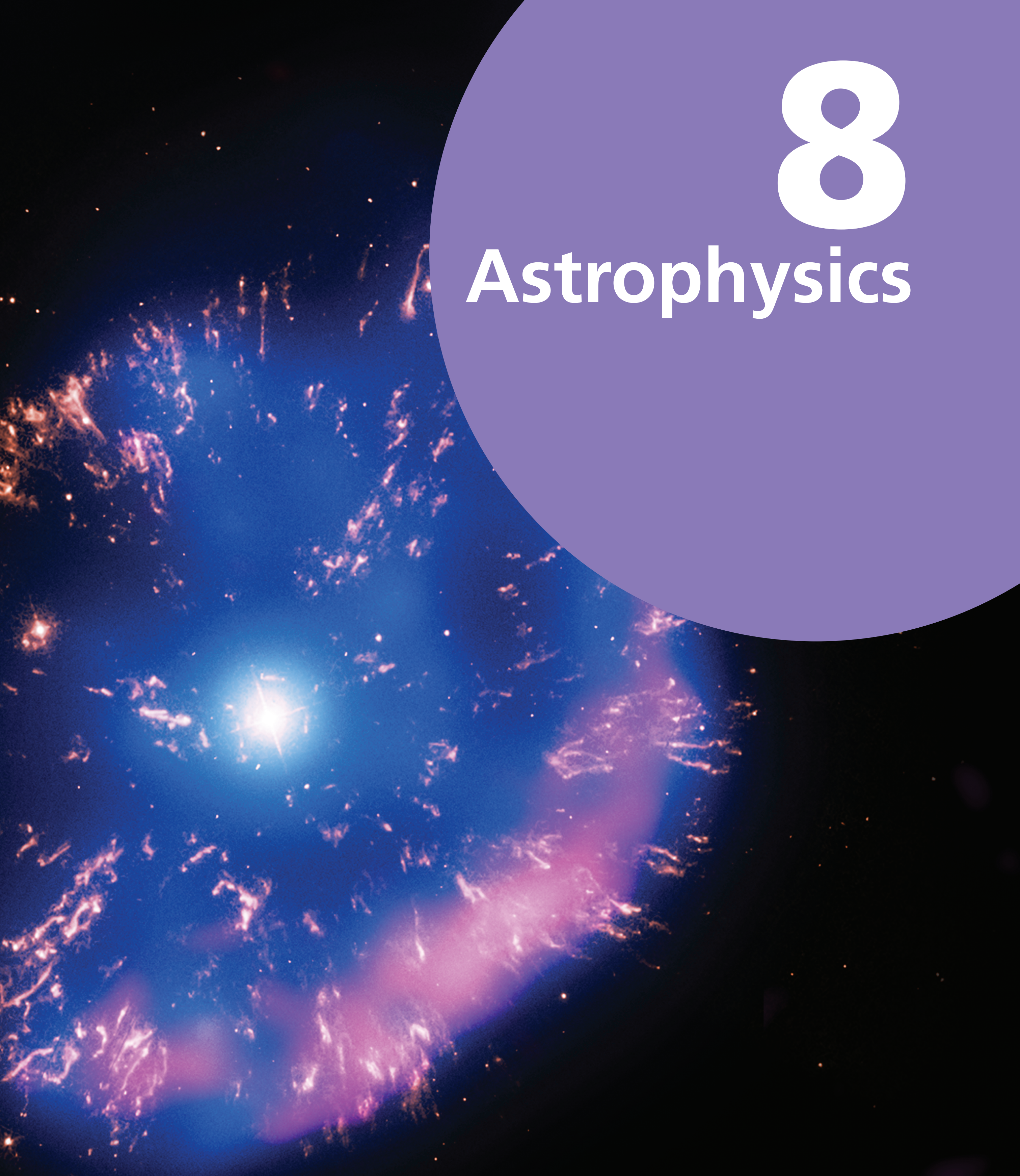
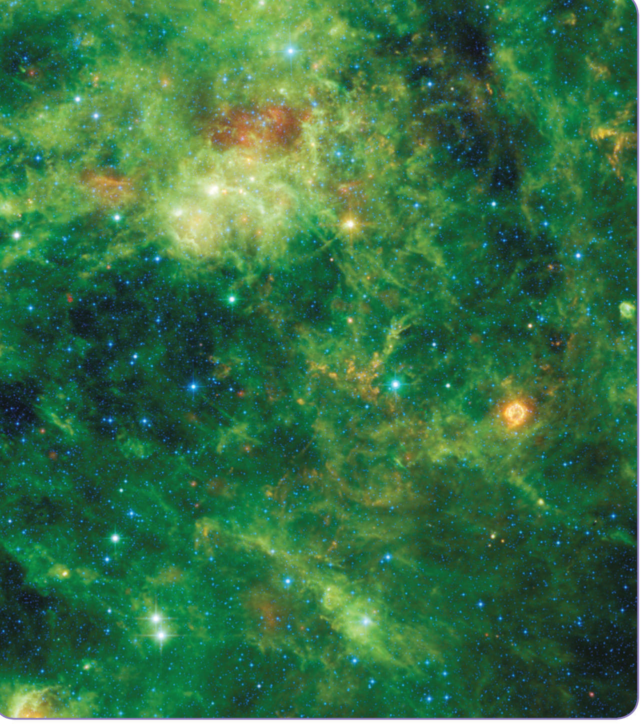


Δ More than 100 years ago in 1901, an ordinary star suddenly became one of the brightest stars in the sky. This image combines data from NASA's Chandra X-ray Observatory with radio and optical telescope data to look at the supernova it left. These pictures give insight into how scientists can study the birth, life and death of stars. Even stars that exploded years ago.



Δ Fig. 8.6 Cassiopeia A, a star in the constellation Cassiopeia, is a remnant of a supernova and appears as a shell of expanding material.

Stellar evolution

INTRODUCTION

When you look at the stars on a clear night you can see up to about 5000 without a telescope or binoculars. Most stars are larger than our Sun despite being visible only as tiny specks of light. Our Sun is much closer to the Earth than any other star so it seems larger. It takes about 8 minutes for light to reach us from the Sun. Our next nearest star is about 4 light years away. This is the distance that light travels in four years. Given that light travels at 300 000 000 metres every second, the nearest star is about $60 \times 60 \times 24 \times 365.25 \times 4 \times 300\,000\,000$ m away from us, or about 3×10^{16} m.

The sky and its stars stay much the same for long periods of time. But the sky does change and some stars are being made and some are ending their existence – sometimes in spectacular fashion.

KNOWLEDGE CHECK

✓ Know that the energy in stars is produced by nuclear fusion.
✓ Know that the Universe is massive and consists mainly of space.
✓ Know that the Universe changes over time.

LEARNING OBJECTIVES

✓ Understand how stars can be classified according to their colour.
✓ Describe the evolution of stars of similar mass to the Sun through the following stages:
- nebula
- star (main sequence)
- red giant
- white dwarf.

✓ Describe the evolution of stars with a mass larger than the Sun.
✓ Understand how the brightness of a star at a standard distance can be represented using absolute magnitude.
✓ Draw the main components of the Hertzsprung–Russell diagram (HR diagram).

COLOURED STARS

When we first look at stars, they all seem white. If you look for a while longer, you will see that some are slightly blue or red. When we heat a metal bar with a Bunsen burner it will glow red-hot. This indicates the frequency of the radiation that is emitted at this temperature. If we heated the bar with an acetylene torch it would become hotter and the light from it would be slightly blue. This relationship between the metal bar's colour and its temperature is also shown by stars. Cool stars appear red as most of the radiated energy is in the red to infrared range of the electromagnetic spectrum. Hot stars appear white or blue as most of their radiated energy is in the blue to ultraviolet range of the electromagnetic spectrum.

The colour of a star is related to its surface temperature and scientists use this to group stars into different types. Our Sun is a G type star.

Type of star	Colour	Approximate surface temperature (K)
O	blue	> 25 000
B	blue	11 000–25 000
A	blue	7500–11 000
F	white to blue	6000–7500
G	yellow to white	5000–6000
K	red to orange	3500–5000
M	red	< 3500

QUESTIONS

1. Stars can be classed as anything between blue ➔ white ➔ yellow ➔ orange ➔ red.

a) Explain and describe what causes the different colours of the stars.

b) Draw a table showing the type, colours, and approximate surface temperature in K for stars.

BRIGHTNESS OF STARS

The colours of stars are important as we have seen. It is also important to look at the brightness of stars.

The two main ways of describing the brightness of a star or galaxy are **apparent magnitude** and **absolute magnitude**.

The **apparent magnitude** is how bright the object is when seen by an observer on Earth. This can depend on two factors:

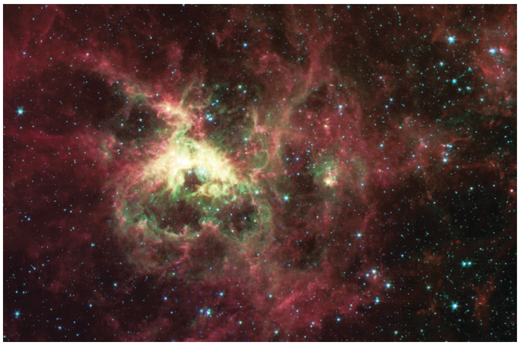
1. the amount of energy the star radiates per second (its **luminosity**)
2. the distance of the star from Earth.

The distance of stars from the Earth varies greatly. Therefore, very bright but distant stars can have a lower apparent magnitude than a less bright, nearby star.

The **absolute magnitude** of a star depends only on its luminosity. Absolute magnitude is the apparent magnitude of an object if it was a standard distance from the Earth. In this way, we can compare the actual brightness of stars regardless of how distant they are. The standard distance for absolute magnitude is 32.6 light years (about 3×10^{17} m). There is no need to travel to a distance of 3×10^{17} m from a star to measure its luminosity as there is a formula which relates the apparent magnitude to absolute magnitude, if its distance is known. This is based on the fact that light follows an inverse square law. This law simply means that when the light source is twice as far away, it will appear four times less bright.

EVOLUTION OF A STAR

A star is formed from a huge cloud of dust and gas called a **nebula**.



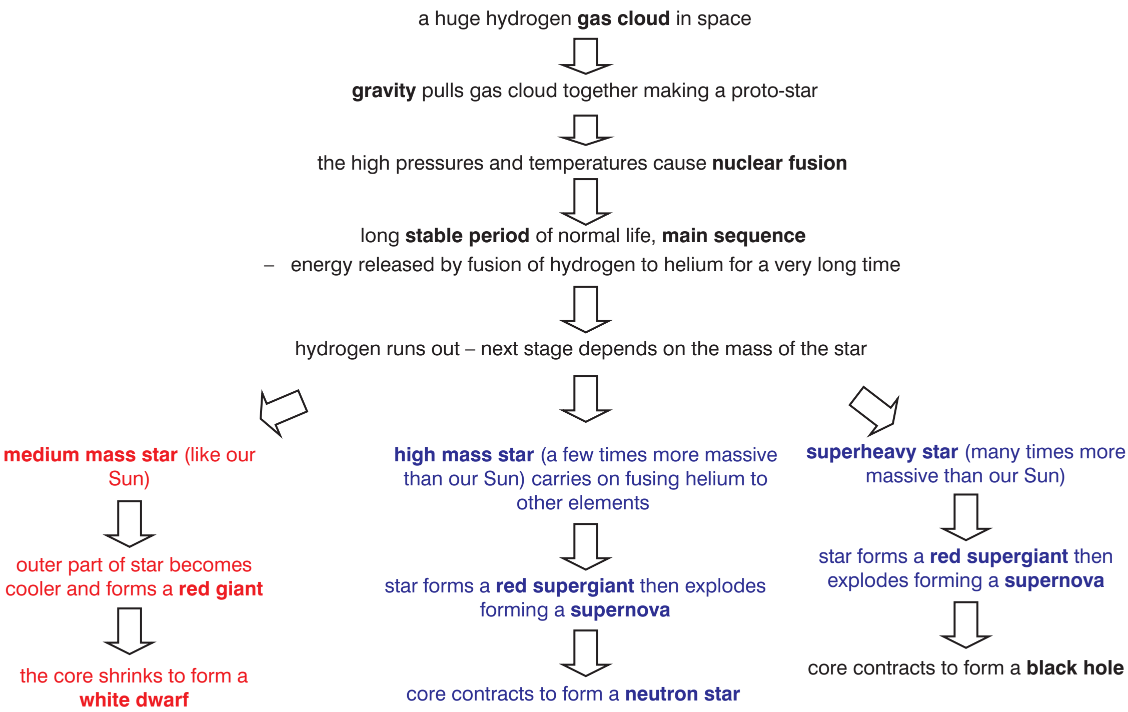
Δ Fig. 8.7 The Tarantula Nebula is a star-forming region in the Large Magellanic Cloud, the nearest galaxy to our own Milky Way. The most dense areas of gas and dust will be the birthplace of future generations of stars.

The gas clouds in a nebula contain hydrogen gas. The gas particles are gradually pulled in towards the centre of the nebula by gravitational attraction. The nebula becomes a much more dense structure called a proto-star. Compression causes the gas molecules to increase speed and the gas becomes very hot, up to about 15 million °C. Eventually, the great pressures involved also force the hydrogen nuclei together. This initiates a **nuclear fusion** reaction, fusing hydrogen nuclei to form helium. A very large amount of thermal energy is released. The thermal energy generated prevents the proto-star shrinking any more.

The star then continues fusing hydrogen into helium for many millions of years until the hydrogen starts to run out. What happens next depends on the star's mass. Our Sun is in this steady phase of fusion (**main sequence star**) and it has about 5 billion years left before the next stage.

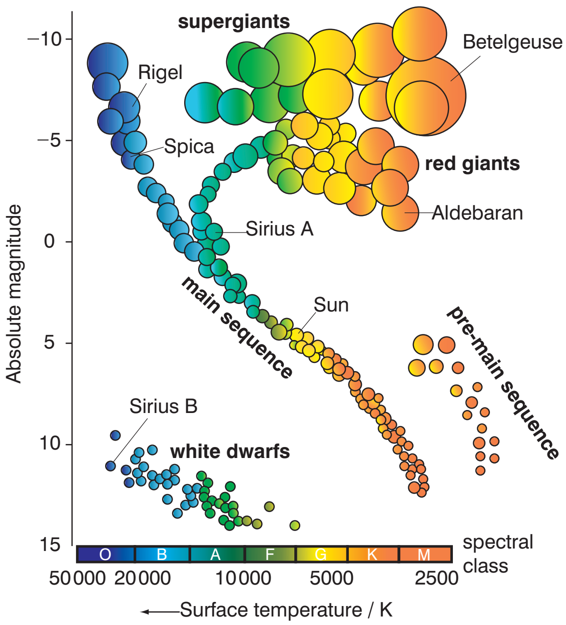
When stars with a similar mass to our Sun start to run out of hydrogen they start fusing helium. The core of the star gets much hotter and expands. The star is no longer on the main sequence. The star appears red because the observed surface temperature of the star decreases as the outer layers spread out, so it is called a **red giant**. When fusion ends, the outer layers are pushed away and the hot, small core of the star collapses to become a **white dwarf**.

The Sun, although it appears large to us, is in fact a relatively small star. When stars with a mass larger than the Sun run low on hydrogen they start fusing helium to carbon. The star gets hotter and hotter and expands, leaving the main sequence. It becomes a **red supergiant**. Eventually this massive star explodes as a **supernova**. The explosion blows the outer layers of the star into space. The remaining core of the star contracts and may form an extremely dense **neutron star** or, if the original star was massive enough, even a **black hole**. Black holes are small, very dense massive concentrations of matter. Their gravitational pull is huge. The gravity is so great that even light cannot escape from it.



Δ Fig. 8.8 Stars are 'born', have a finite 'life' and eventually 'die'. This is the life-history of a star.

HERTZSPRUNG-RUSSELL (HR) DIAGRAM



Δ Fig. 8.9 The Hertzsprung-Russell diagram, showing examples of different types of star.

The **Hertzsprung–Russell (HR) diagram** is a graph that shows the luminosity of a star plotted against its surface temperature. When the data for many stars are plotted, they are not randomly scattered but fall into distinct groups. The majority of stars are shown as a curved band. These are the main sequence stars. Stars on the main sequence towards the lower right are cooler (reddish) and dimmer and stars at the upper left are hotter (blue) and more luminous. Other groups are the red giants and white dwarfs. The HR diagram is useful to scientists as it shows what stage a star is at in its life cycle, from its position on the diagram.

QUESTIONS

1. Black holes and neutron stars are not shown on the HR diagram. Suggest a reason why.

2. a) Where are hot, bright stars found on the HR diagram?

b) What will happen to these hot, bright stars in the future?

c) Where will these hot bright stars move to on the diagram in the future?

3. Our Sun is a medium temperature and brightness star. What will happen to the Sun and its position on the diagram in the future?

End of topic checklist

A **nebula** is a huge gas cloud in space that is pulled together by gravity to form a star.

Nuclear fusion is the energy source for all stars.

In the **main sequence** stage of a star it spends a long time in a stable state undergoing fusion of hydrogen and producing a steady output of energy.

A **red giant** forms from a low mass star after the energy output from fusion of hydrogen ends and the star expands to a much greater size.

A **white dwarf** forms from a low mass star after a red giant cools and contracts.

High mass stars can explode as a **supernova** after which they can form a **neutron star** or **black hole**.

A **Hertzsprung–Russell (HR) diagram** is a diagram that shows the luminosity of a star plotted against the surface temperature.

The **absolute magnitude** is the apparent magnitude of an object if it was a standard distance from the Earth.

The facts and ideas that you should understand by studying this topic:

- ❍ Understand how the temperature of stars can affect their colour.
- ❍ Know how stars are formed and how they end.
- ❍ Describe the differences in the life cycle of a star similar in size to our Sun and of a star much larger than our Sun.
- ❍ Understand how fusion drives the energy output of stars.

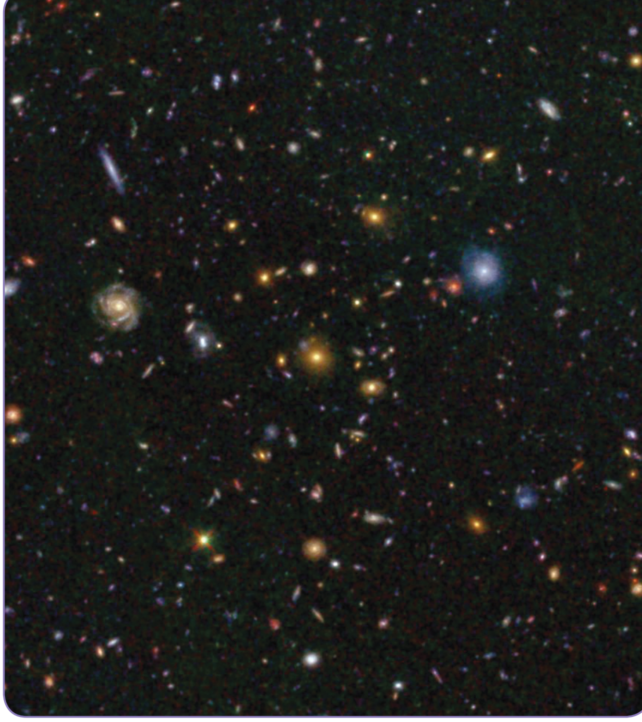
End of topic questions

1. Describe the life cycle of a small star about the size of our Sun.
2. Describe the life cycle of a star with a mass much greater than the Sun.
3. Why are black holes difficult for scientists to detect?
4. Describe, using a diagram, the nuclear fusion reaction that takes place in stars.
5. Explain how a HR diagram can be useful to scientists.
6. What is meant by the term 'apparent magnitude of a star'?
7. Explain why the absolute magnitude of a star can often be more useful to scientists than its apparent magnitude.

Cosmology

INTRODUCTION

Cosmology is the study of the Universe. So you might think that it covers all topics in physics, chemistry and biology. If that was the case cosmology would be the biggest subject of them all. The Universe itself being infinite would mean that its subject matter would be infinite too! Luckily cosmology confines itself to the big picture view of the Universe: how it began, how it has evolved and how it will change in the future.



Δ Fig. 8.10 This image from NASA's Hubble space telescope shows one of the most distant galaxies we know. It dates from 750 million years after the Big Bang that created our Universe. The light took 12.9 billion years to reach us.

KNOWLEDGE CHECK

✓ Know about the Doppler effect and how movement of a light source relative to an observer can affect the wavelength and frequency of waves detected by the observer.
✓ Know that theories and models change as scientists to try to explain new evidence.

LEARNING OBJECTIVES

✓ Be able to describe the past evolution of the Universe and the main arguments in favour of the Big Bang.
✓ Be able to describe evidence that supports the Big Bang theory (red-shift and cosmic microwave background (CMB) radiation).
✓ Be able to describe that if a wave source is moving relative to an observer there will be a change in the observed frequency and wavelength.
✓ Be able to use the equation relating change in wavelength, wavelength, velocity of a galaxy and the speed of light:

$$\frac{\text{change in wavelength}}{\text{reference wavelength}} = \frac{\text{velocity of a galaxy}}{\text{speed of light}}$$

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

✓ Be able to describe the red-shift in light received from galaxies at different distances away from the Earth.
✓ Be able to explain why the red-shift of galaxies provides evidence for the expansion of the Universe .

THE BIG BANG

One theory which tries to explain the origin of the Universe is known as the **Big Bang theory**. The basic idea is that all the matter in the Universe was originally concentrated in one extremely small, dense place. This matter began to expand very rapidly because of a very hot explosion.

In time the Universe continued to expand but also cooled down. The matter in the Universe then started to group together or coalesce into many large gas clouds. These were then subject to gravitational forces and then galaxies, stars and planets were eventually formed.

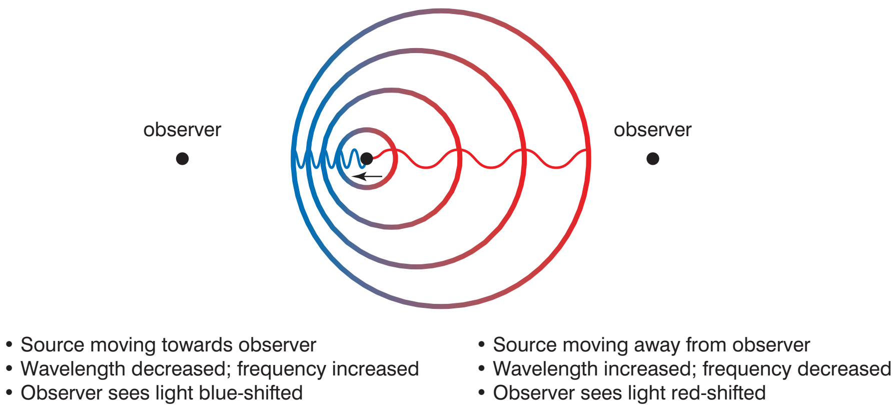
The Universe is older now but it is still expanding today. But what is the evidence that supports this theory? Without evidence to back it up it would just be an idea or an opinion and few would be convinced by it.

Supporting evidence: Red-shift

Scientists can observe the Universe as it is today. They look at other galaxies in space. Scientists observe light from other galaxies and they notice that it seems to be of a longer wavelength than expected. It appears to be **red-shifted**.

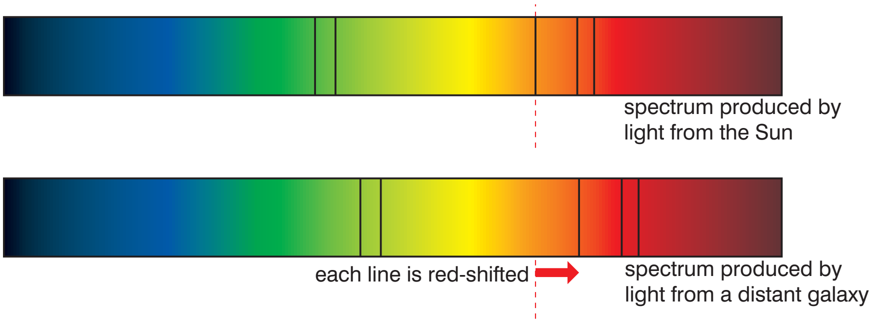
We know from our work on waves (section 3) that when a sound source is moving towards us, the sound waves from it are reduced in wavelength and increased in frequency. This causes the pitch of the sound to increase as the source (such as an ambulance siren) approaches. This is known as the **Doppler effect**.

The Doppler effect also occurs for moving light sources. There will be a change in the observed frequency and wavelength of light from a star that is moving towards or away from the Earth.



Δ Fig. 8.11 The Doppler effect for light waves.

The Sun produces helium by nuclear fusion. Atoms of helium in the atmosphere of the Sun absorb particular wavelengths of light emitted by the core of the Sun. This top spectrum in the diagram is the spectrum of the light from our Sun. The black lines show where helium has absorbed light of particular wavelengths. Less light escapes from the Sun at these wavelengths – that part of the spectrum is dark.



Δ Fig. 8.12 The whole pattern of lines from a distant galaxy has been red-shifted compared with light from the Sun.

If we compare the Sun's spectrum with that of a star from another galaxy we can see that the absorption lines due to helium gas in the star's atmosphere are there but they have moved towards the red coloured part of the spectrum. The red light has a longer wavelength than blue and so we can say that the absorption lines have been **red-shifted**. This is like the increase in frequency of sound waves of an ambulance that moves away from us at speed. This shows that the star is moving away from us.

QUESTION

1. Most galaxies that have been observed show red-shift. A few galaxies show blue-shift.
   a) Use the Doppler effect to explain how some galaxies show blue-shift.
   b) Why is it a relief to know that the great majority of galaxies show red-shift rather than blue-shift?

Using red-shift

It is possible to work out the speed of a moving ambulance by measuring the frequency (or wavelength) of sound waves heard by a stationary observer. It is also possible to calculate the speed at which a star is moving away from Earth by looking at how much the wavelength of the light has shifted towards the red end of the spectrum.

The equation for the relationship between the change in wavelength, wavelength, velocity of a galaxy and the speed of light is:

$$\frac{\text{change in wavelength}}{\text{reference wavelength}} = \frac{\text{velocity of a galaxy}}{\text{speed of light}}$$

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

Where:

λ = wavelength observed

λ_0 = reference wavelength

v = velocity of galaxy

c = velocity of light

WORKED EXAMPLE

A spectral line for hydrogen on Earth has a wavelength of 760 nm. The same spectral line for hydrogen observed from a distant quasar is 645 nm. (Quasars are very distant, extremely bright objects that drown out the light from all the other stars in the same galaxy).

The velocity of light in free space, $c = 3.0 \times 10^8$ m/s.

Calculate the velocity at which the quasar is moving away from the Earth. Give your answer in m/s.

Write down the equation:

$$\frac{\text{change in wavelength}}{\text{reference wavelength}} = \frac{\text{velocity of a galaxy}}{\text{speed of light}}$$

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

change in wavelength: $\underline{\Delta\lambda}$ $= 760 - 645 = 115$ nm

rearranging the equation: $v = \dfrac{\Delta\lambda \times c}{\lambda_0}$

substitute the values: $v = \dfrac{115 \times 3 \times 10^8}{645}$

$v = 53\ 488\ 372$ m/s

Velocity of the quasar is 5.35×10^7 m/s (to 3 significant figures)

QUESTION

1. A spectral line for hydrogen on Earth is 760 nm. The same spectral line for hydrogen for a distant quasar is 680 nm.

The velocity of light in free space, $c = 3.0 \times 10^8$ m/s.

Calculate the velocity of the quasar relative to the Earth. Give your answer in m/s.

How red-shift provides evidence for the Big Bang

Scientists have measured the red-shift from many galaxies and found that:

- most galaxies show red-shift, hence most galaxies are moving away from Earth.
- distant galaxies show greater red-shift, hence distant galaxies are moving away from us more quickly that nearby ones (since $\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$).

Edwin Hubble was the first astronomer to show the relationship between the recession velocity of galaxies and their distance, and to deduce that the Universe is expanding. If the Universe is expanding now, then in the past it must have been smaller. Ultimately, the idea goes back to the Universe starting at a single point in a violent 'explosion' – the Big Bang theory.

SCIENCE IN CONTEXT

THE UNIVERSE

In the 1920s, the astronomer Edwin Hubble (1889–1953) was trying to answer the question of how big the Universe is. Was the Milky Way, our own galaxy, everything there is, or were there other objects outside it? Using the Mount Wilson telescope in California, Hubble studied small 'fuzzy' objects in the sky. Building on the work of Henrietta Leavitt (1868–1921), which described how to measure the distance to a type of star called a Cepheid Variable, Hubble discovered that these 'fuzzy' objects were complete galaxies of their own, clearly outside the Milky Way. This settled the argument and showed that the Universe (everything there is) was much bigger than anybody previously thought.

Hubble also discovered, through observations of red shift (a process where the frequency of light waves changes depending on whether the object is moving), that distant galaxies are all moving away from us – the Universe is expanding.

If the Universe is expanding now, then in the past it must have been smaller. Ultimately, the idea goes back to the Universe starting at a single point in a violent 'explosion'. This is the Big Bang theory. It is also supported by observations of the cosmic microwave background radiation – the 'echoes' of the Big Bang that can still be detected. Ever since then, gravity has been acting to slow down the expansion. It is unclear whether the Universe will expand forever or not.

However, observations in the past 20 years have suggested that the Universe has expanded faster we would expect from our current theories. There appears to be much more to the Universe than we have previously detected. Only when we add in factors called dark matter and dark energy do the observations make sense. At this time, the exact nature of these materials is not known and they have not been detected directly.

From the rate of expansion scientists have calculated that the Universe started from a single point about 13.8 billion years ago. This is the estimated age of the Universe.

Supporting evidence: Cosmic microwave background radiation

In the 1960s scientists detected a low energy, low frequency electromagnetic radiation coming from all parts of the Universe. It is detected by using radio telescopes on Earth and is not associated with any star, galaxy or other object. Radio telescopes are very large and can collect and concentrate the electromagnetic waves that come from space. Unlike optical telescopes, radio telescopes are not affected by clouds in the Earth's atmosphere. Clouds do not block radio waves as they do for visible light. So radio telescopes can be used day and night regardless of the weather conditions on Earth.

This background radiation is in the microwave range of the electromagnetic spectrum and is called the **cosmic microwave background** (CMB) radiation. The CMB radiation is very uniform – it comes from all directions in space. The COBE satellite was launched in 1989 by NASA to measure CMB radiation. The evidence from COBE also supports the uniformity of the CMB detected on Earth.

In 1948 the Big Bang theory predicted that this microwave radiation should exist as a relic of the thermal radiation from the original Big Bang explosion. The theory also predicted that the observed wavelength of the radiation today would be much greater than the wavelength of the light emitted shortly after a hot Big Bang. This is due to the expansion of the Universe, which stretches the wavelength of the light. The Big Bang theory predicted that the present-day radiation should be equivalent to a temperature slightly above absolute zero at 2.7 K. That is about 270 °C.

In the 1960s this background radiation was detected and the temperature was confirmed as 2.7 K. The COBE satellite has also confirmed these predictions. The thermal radiation from shortly after the Big Bang 13.8 billion years ago has been travelling through space ever since that time. Big Bang theorists continue to interpret this evidence.

The future of the Universe

Scientists are unsure how the Universe will progress. It depends on two things:

- how quickly the galaxies are moving apart
- how much mass there is in the Universe.

End of topic checklist

The **cosmic microwave background** (CMB) radiation is microwave radiation left over from the thermal radiation of the Big Bang.

The **Doppler effect** is how the wavelength or frequency of waves changes if the source of the waves is moving relative to the observer.

Red-shift occurs when stars are moving away from us at great speeds. This movement increases the wavelength of the light that is emitted by the star.

Observations of red-shift and CMB radiation provide evidence to support the **Big Bang** theory.

The facts and ideas that you should understand by studying this topic:

- ❍ Know that if a wave source is moving relative to an observer there will be a change in the observed frequency and wavelength.
- ❍ Use an understanding of the Doppler effect to explain red-shift.
- ❍ Know and use the relationship between change in wavelength, wavelength, velocity of a galaxy and the speed of light:

$$\frac{\text{change in wavelength}}{\text{reference wavelength}} = \frac{\text{velocity of a galaxy}}{\text{speed of light}}$$

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

- ❍ Describe the past evolution of the Universe and the main arguments in favour of the Big Bang.
- ❍ Describe evidence that supports the Big Bang theory (red-shift and cosmic microwave background (CMB) radiation).
- ❍ Describe the red-shift in light received from galaxies at different distances away from the Earth.
- ❍ Explain why the red-shift of galaxies provides evidence for the expansion of the Universe.

End of topic questions

1. Explain the difference between red-shift and blue-shift. **(5 marks)**

2. The Big Bang theory predicted the existence of cosmic microwave background radiation today at an equivalent temperature of 2.7 K.

   a) Describe how this radiation can be detected on Earth and in space. **(2 marks)**

   b) Describe how scientists confirmed these predictions. **(5 marks)**

3. 'Distant galaxies show more red-shift than nearby ones'.

   a) What does this say about the speeds and directions of distant and nearby galaxies? **(3 marks)**

   b) How does this evidence support the idea that the Universe started at a point in the past? **(1 mark)**