Topic Review

A Level Year 2 AQA Physics

Topic 9: Astrophysics

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Contents

Teacher's Introduction

This Topic Review covers the optional unit Section 3.9: Astrophysics of the AQA Physics A Level. The aim is to go over the topics in the specification in a focused but comprehensive way, allowing students to consolidate their learning and to prepare for the exams. The resource includes questions after each small topic to allow students to test their understanding and ability to apply what they have learnt. Worked answers are included with the questions so that students can check their answers and see where they've gone wrong.

Remember!

Always check the exam board website for new information, including changes to the specification and sample assessment material.

Each section of the review starts with a checklist of all the topics in the section, and what students should expect to know about the topic before moving on. This can be used as a self-assessment tool at the start of revision, so that students know where to focus their time, or at the end to ensure they have no gaps in their learning.

Worked examples for calculations are provided throughout (including derivations where appropriate), giving students not only knowledge of the appropriate facts and equations, but how they are applied as well.

Exam-style questions are provided, so that students can test their knowledge and practise for their upcoming exams. These exam-style questions have worked mark schemes in the same style as those used by the exam board, so that students can check their own answers and see where they've gone wrong.

🔑 Key equations and definitions are highlighted with a key symbol.

☆ DB Equations on the data booklet are marked with a star so that students know what they have to memorise and what they can refer to the data book for in the exam.

🦉 Exam tips are included regularly throughout to help students avoid misconceptions and common mistakes and to give students a steer on things they should particularly practise in revision.

Students should be able to work through this review in their own time, after they have completed the topic in lessons, or during revision, and it is a great accompaniment for students as they make their revision notes or where they need an easy reference text as they do practice papers.

I hope that this review will be of real benefit.

9.1 Telescopes

Chapter 9.1 checklist

By the end of this chapter you should be able to:

9.1.1

- Understand the difference between converging and diverging lenses ....
- Recognise and sketch ray diagrams showing image formation in a telescope ..
- Calculate magnifications of telescopes consisting of two converging lenses ....
- Understand and calculate the focal lengths of telescopes consisting of two c

9.1.2

- Describe Cassegrain arrangements of reflecting telescopes ....
- Recognise and sketch ray diagrams of light passing through Cassegrain teles
- Explain the advantages and disadvantages of reflecting and refracting telesc
- Explain and understand what is meant by spherical and chromatic aberratio

9.1.3

- Describe similarities and differences between radio and optical telescopes ...
- Understand how telescopes' structures and positions affect their abilities to
- Compare resolving and collecting powers of telescopes ....

9.1.4

- Understand why telescopes have a minimum angular resolution ....
- Calculate the Rayleigh criterion ....
- Understand how the collecting power of a telescope depends on the telesco
- Understand how charge coupled devices (CCDs) are used in telescopes ....
- Compare resolution and efficiency of CCDs and the human eye ....

9.1.1 Astronomical telescope consisting of two converging len

The earliest telescopes were all refracting telescopes. These are telescopes that magnify the light from stars and other celestial objects.

Lenses

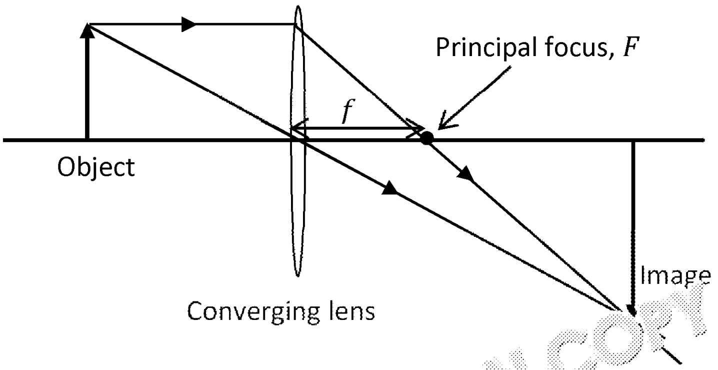
Lenses are either **convergent** or **divergent**.

Key Terms:

Converging lens: A lens which brings parallel beams of light to a
Convex lenses are converging lenses.

Diverging lens: A lens which spreads out parallel beams of ligh
Concave lenses are diverging lenses.

The ray diagram for a **converging lens** can be seen below.



Exam
As you
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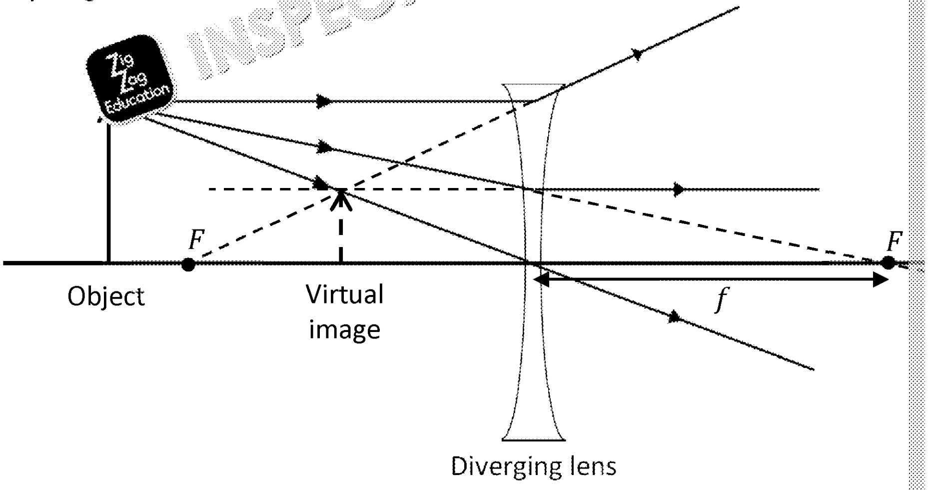
is **inver**

The ray diagram for a **diverging lens** can be seen below.



A diverging lens creates a **virtual image**, as the rays of light never actually meet. The virtual image is one that the divergent rays appear to come from.

Key Terms:

Principal focus: The point at which rays parallel to the principal axis (before t lens) cross the principal axis (after passing through the lens).

$f =$ focal length: the distance between the lens and the principal focus (in m)

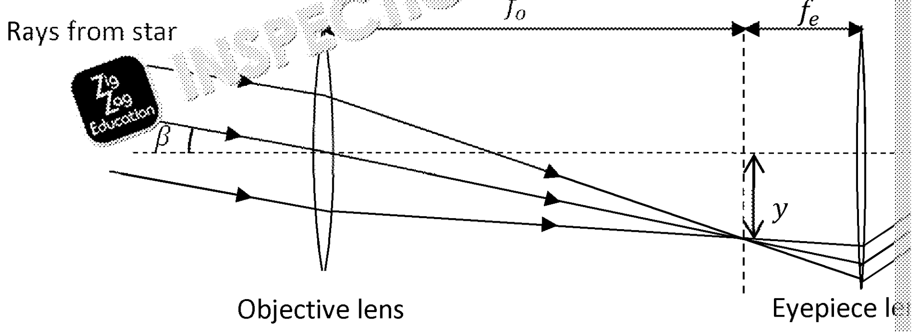
Normal adjustment

Ke
No
co
vie

The ray diagram below shows how an image is formed by a refracting telescope in the **normal adjustment**. Telescopes used for viewing stars are in the normal adjustment as the stars are considered to be **at infinity**.

When discussing lenses, 'at infinity' means that the rays are parallel.

Stars and other objects we see through telescopes are not actually infinitely far aw
the angle between their light rays when they reach the Earth is negligible.



f_o = focal length of the objective le
f_e = focal length of the eyepiece le
α = angle subtended by image at e
β = angle subtended by object at u
$f_o + f_e$ = distance between lenses i

Angular magnification and Focal Lengths

The **angular magnification** of a telescope is the factor by which the angle betwee
normal to the lens is increased at the eyepiece lens.

$$M = \frac{\alpha}{\beta} = \frac{\textit{angle subtended by image at eye}}{\textit{angle subtended by object at unaided eye}}$$

Focal lengths

The magnification of the telescope is dependent on the focal length of the lenses

First define $\tan\alpha = \frac{y}{f_e}$ and $\tan\beta = \frac{y}{f_o}$, which can be found using trigonometry fr

α and β are both small – we can use the small-angle approximation for $\tan\theta$.

Using the small-angle approximation gives
$\alpha = \frac{y}{f_e}$ and $\beta = \frac{y}{f_o}$

Putting this into the equation for magnification gives

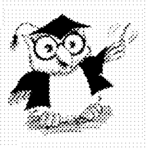
$$M = \frac{\alpha}{\beta} = \frac{y/f_e}{y/f_o}$$

which rearranges to

$$\boxed{M = \frac{f_o}{f_e}}$$

Exam tip

There are seve
For $\theta \approx 0$



Exam tip

For telescopes, the magn
always be positive – a te
an image smaller isn't m

This equation tells us that the focal length of the objective lens must be greater t
eyepiece lens so that the magnification is positive. The distance between the len
refracting telescopes are very long.

Example

A refracting telescope has a magnification of +2.

a) The angle subtended by the image of an object at the eye is 6°.
What is the angle subtended by the object at the unaided eye?

b) The focal length of the eyepiece lens of the telescope is 1.5 m.
What is the minimum total length of the telescope?

a) We first use $M = \frac{angle\ subtended\ by\ image\ at\ eye}{angle\ subtended\ by\ object\ at\ unaided\ eye} = \frac{\alpha}{\beta}$

We rearrange this to find the angle subtended by the objected at an unaid

$\beta =$ [illegible]

$\boldsymbol{\beta} = \mathbf{3}$

b) The magnification of the telescope is given by $M = \frac{f_0}{f_e}$

We have the focal length of the eyepiece lens, but not the objective lens.

Rearranging to find the focal length of the objective lens, f_o

$f_0 = f_e M = 1.5 \times 2$

$f_0 = 3$ m

But we don't want just the focal length of the objective lens! We want the
telescope.

The minimum total length of the telescope is the sum of the focal lengths

$L_{\text{min}} = f_0 + f_e = 1.5 + 3$

$\boldsymbol{L_{\text{min}}} = \mathbf{4.5\ m}$

Questions

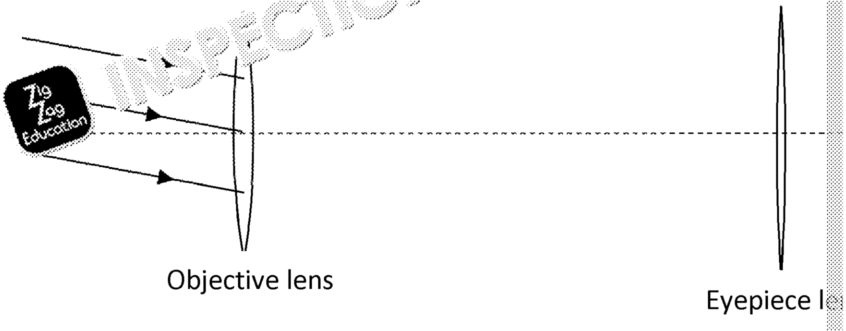
1. Do refracting telescopes use converging or diverging lenses?

   Give a reason for your answer.

2. The focal length of the objective lens of the telescope is 15.0 m.
   a) Should the focal length of the eyepiece lens be longer or shorter than t
   objective lens?
   Give a reason for your answer.
   b) Calculate the focal length of the eyepiece lens that should be used for
   c) A star is viewed at an unaided angle of 8.00°.
   Calculate the angle at which the light from the star reaches the eye wh

3. Complete the diagram below to show light passing through a telescope in no

   Label the focal length of the objective lens (f_o) and the focal length of the ey



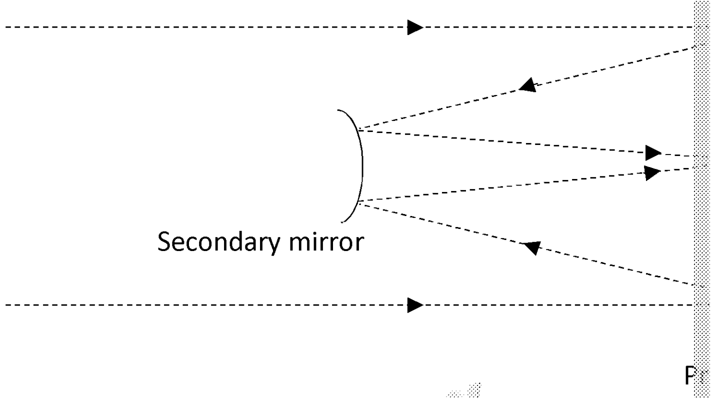
9.1.2 Reflecting telescopes

Key Terms:
A **reflecting telescope** is one that uses **mirrors** instead of lenses t

Cassegrain arrangement

The Cassegrain arrangement is a system of mirrors used in reflecting telescopes. arrangements consist of two mirrors: a parabolic concave primary mirror and a c secondary mirror.

A ray diagram showing the path of light through a telescope in the Cassegrain arr be seen below.



The parabolic shape of the primary mirror is used to reflect parallel beams of ligh a secondary mirror, which then reflects the light back through an aperture in the the eyepiece.

On reflect

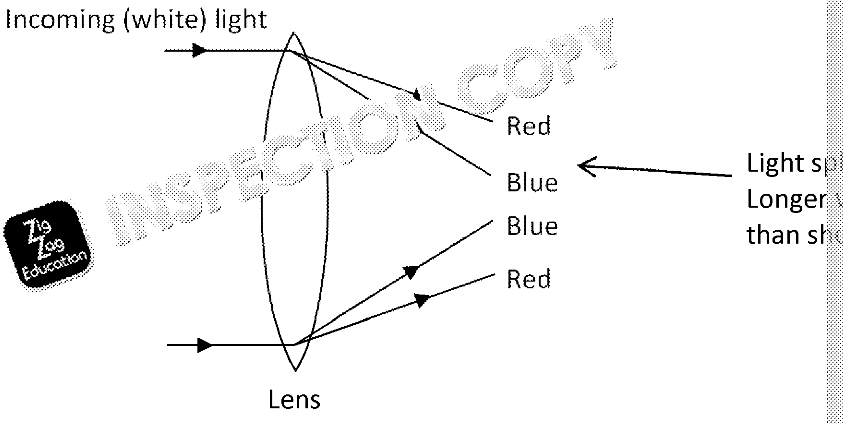
While refracting telescopes are the oldest type of telescope, reflecting telescope advantages over refracting telescopes.

Size matters:	Refracting telescopes need to be incredibly long, as the total l at least the length of the eyepiece plus objective lens focal len Meanwhile, the focal length of reflecting telescopes can be ex telescope larger – additional mirrors can be added to 'fold' th extending the focal length without making the telescope long
Crystal clear:	For the best-quality image, high quality glass is needed for ref and expensive to make such large lenses with no defects or im In comparison, there's no real difficulty in creating a large sm for a high-quality reflecting telescope.
Heavyweights:	The long lengths and large lenses required for refracting teles astronomical events can develop quickly, and it's difficult to m in time to catch these events. Reflecting telescopes are relatively light in comparison to refra lot easier to move reflecting telescopes to the portion of the sk
Brace yourself:	Large, heavy lenses can distort under their own weights, disto correct for this because lenses can only be supported at the ed Because only the front surface of the mirrors is used in reflect support them from behind without obscuring the image.
Aberrations:	Reflecting telescopes don't suffer from **chromatic aberration**, telescopes. **Spherical aberration** is also easier to correct in re

Chromatic and spherical aberrations

Chromatic aberrations occur due to the refraction of coloured light.

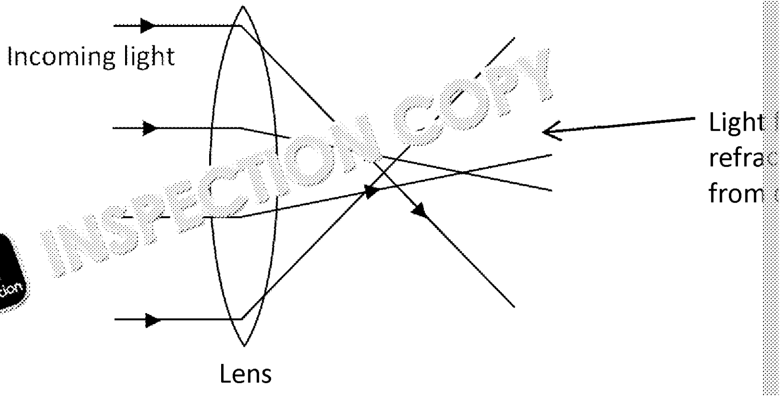
When light passes through a lens, it is split into its component colours; shorter w
refract more than longer wavelengths of light (red light).



Chromatic aberration in refracting telescopes can be corrected by using two lens
indexes, which can correct for the effect.

Chromatic aberration doesn't occur at all for reflecting telescopes.

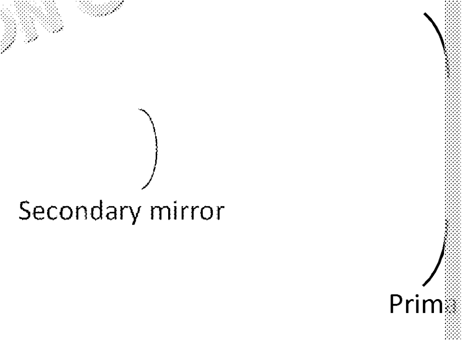
Spherical aberration occurs when beams of light passing through the edges of th
point to rays passing through the centre of the lens.



Spherical aberration can be minimised by changing the shape of the lens to focu
Reflecting mirrors can still suffer from spherical aberration, but it's much easier t
perfectly parabolic mirror.

Questions

1. Make a list of the advantages of reflecting telescopes over refracting telesco
   Remember: It's important to consider not just the quality of the image, but
2. Describe chromatic and spherical aberration, including the sources of these
3. Complete the diagram opposite to show the path of parallel beams of light through [illegible]es [illegible] the Cassegrain arrangement.



9.1.3 Single-dish radio telescopes and IR, UV and X-ray teles

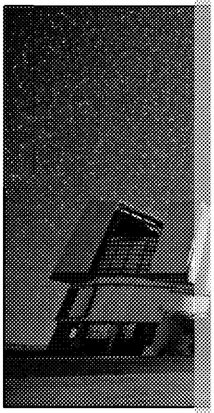
Telescopes aren't just used for the light we can see! Visible light makes up just a sm and other astronomical objects give off – looking at lower energy light (radio and in (ultraviolet and X-rays) can give us a lot more information about the universe.

For any type of telescope it's important to consider some key factors: what the tele **structure** of the telescope and where it's best to **position** it, and the telescope's **res**

Optical telescopes

Uses

- Optical telescopes study the visible part of the EM spectrum, roughly **400 to 700 nm.** Optical telescopes can show us things that we can already see in far greater detail, and can see much dimmer objects than the eye can see.



Optical telesc
altitudes. Th

Positioning Although visible light can pass through the atmosphere, it is refracted. This means that, although optical telescopes can be positioned **on the ground**, it's important to try to reduce atmospheric effects.

Many optical telescopes used for scientific research are placed at very **high altitudes** – this reduces the effect of refraction by the atmosphere, including additional refraction from turbulence in the where the refractive index of air changes.

Radio telescopes

Radio signals have much larger wavelengths than visible light – **typically centimetres to metres.**

Uses

- Many radio sources can't be seen in the visible range; these include **active galaxies**, **pulsars** and **quasars**. Radio astronomy has been used to study **the Sun** and the **cosmic microwave background**.
- Radio frequencies can penetrate the **gas and dust clouds** that run through the Milky Way, and so radio astronomy can be used to study the **centre of our galaxy**.
- Radio telescopes are particularly useful for studying energy emitted by **neutral hydrogen** – the most abundant element in the universe. The difference between energy states of hydrogen corresponds to 21 cm, a radio wavelength.
- Unlike other ground-based telescopes, radio telescopes can be used both **day and night**.

Structure Radio waves have longer wavelengths than visible light, and so radio dishes can be made using **wire frames**. Radio telescopes tend to be in the **Cassegrain arrangement**.

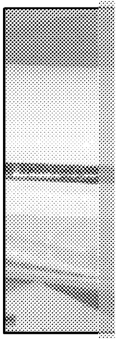
Positioning While some very long wavelength radio waves are absorbed by the there's a window of wavelengths (around 1 cm to 10 m) that pass thro For this reason, radio telescopes can be positioned **on the ground**.

Man-made radio signals can interfere with radio astronomy – radi far away from urban centres. There's even a radio silent zone in A 34,000 km^2 just to do radio astronomy away from radio sources!

Infrared (IR) telescopes

Infrared light corresponds to wavelengths of light from **0.7 to 1 mm**.

Uses
- Infrared astronomy is used to investigate cool regions and objects, such as **interstellar gas**, **nebulae where stars form** and **cool stars**.



Infrare
altitu
NASA's

Structure Infrared telescopes are comprised of lenses and mirrors, like an optical telescope.

Modern infrared telescopes use solid-state detectors, but early infrared telescopes detected **changes in temperature** caused by the absorption of infrared light.

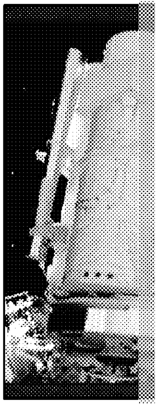
Infrared telescopes have to be **cooled to very low temperatures** using liquid helium or nitrogen, and have a lot of **thermal insulation** to shield them from external infrared radiation.

Positioning Most infrared wavelengths are very strongly absorbed by gases in our atmosphere, particularly water vapour and carbon wavelengths pass through. For this reason, most infrared telescop **atmosphere satellites**, but there are some infrared telescopes pla high-altitude aircraft.

There are two narrow windows (3 to 5 µm and 7 to 14 µm) where atmosphere – ground-based telescopes can be used to study thes

Ultraviolet (UV) telescopes

Uses
- Ultraviolet light has wavelengths of **400 to 10 nm**.
- Ultraviolet telescopes can be used to investigate the **chemical composition** and **temperatures** of stars and interstellar gases.
- Ultraviolet astronomy has been used to investigate the **halo of gas around our galaxy** and the **corona around the Sun**.



NASA's A
position
absorbed b

Structure Ultraviolet telescopes are in Cassegrain arrangements.

The detector of an ultraviolet telescope consists of solid-state devices – when ultraviolet photons hit this detector, a current is produced.

Positioning Ultraviolet wavelengths are absorbed by the ozone layer, so UV telescopes have to be positioned **in space**.

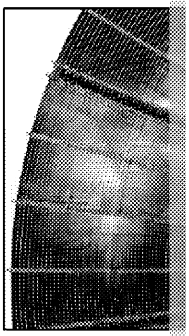
X-ray and gamma ray telescopes

X-rays have wavelengths of **0.01 to 10 nm**. Wavelengths shorter than ~10^{-12} m are gamma rays.

Uses
- X-ray and gamma rays have extremely high energies, so come from high-energy events and objects – **binary systems**, **active galaxies**, **supernovae remnants** and **black holes**.

Structure X-rays will penetrate mirrors used for other types of astronomy, so mirrors in X-ray and gamma rays telescopes have to be very smooth.
A combination of hyperbolic and parabolic mirrors – X-rays **'skim' the surface** of the mirrors at a low angle, so that they're guided to the detector.
X-rays are detected by **CCDs**, solid-state devices that use high-ener
creating a current.

Positioning X-rays and gamma rays are absorbed by the atmosphere, so both X-
have to be positioned **in space**.



NASA's Nu
using 133
ic

Power

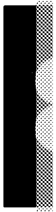
The image a telescope produces doesn't just depend on the wavelength of light, b
telescope. A larger telescope will be able to produce clearer images of an object

Resolving power

> The **resolving power** of a telescope is how easily **two close together objects can be distinguished** by the telescope.

Resolving power is **inversely proportional to wavelength** – longer wavelengths are diffracted more by the aperture of the telescope, so the distinctions between objects blur.

So radio telescopes have the worst resolving power and X-ray telescopes have the best.



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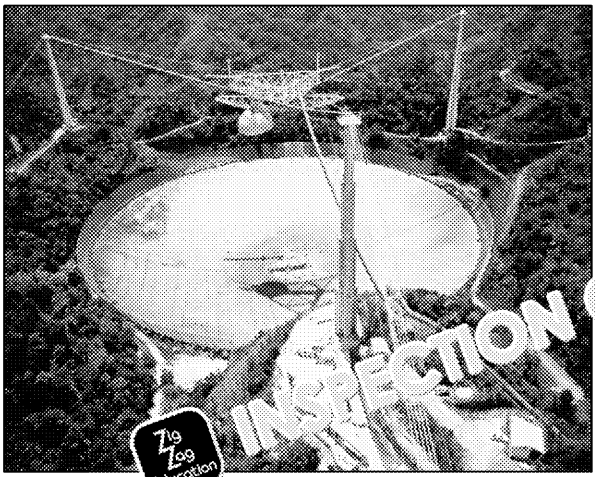


The Arecibo radio telescope has a diameter of over 300 m, increasing its collecting power massively.

Collecting power

> The **collecting power** of teles
> **area** of the telescope (or dia

The collecting power of teles
dish can be created and supp
be easily supported but is dif

This doesn't mean that large t
space; for instance, the Hubb
of 4.5 m^2.

The effective size of radio tel
using multiple dishes acting a

Questions

1. The highest altitude ground-based telescope in the world is at the Universit Observatory (TAO), at 5,640 m above sea level.

   What is the advantage of positioning a telescope at such a high altitude?

2. How do UV telescopes detect photons?

3. The Lovell telescope at Jodre [illegible] telescope with a collecting area of 4, village of Goostrey in [illegible]

   What [illegible] electromagnetic radiation is the Lovell telescope likely to stud

4. The James Webb space telescope (due to launch spring 2019) will be an infr 1,500,000 km away from Earth with a collecting area of 25 m^2. The intende study the formation of galaxies.

   Comment on the choices made in the planning of this telescope, including t radiation studied and the position of the telescope.

9.1.4 Advantages of large-diameter telescopes

Angular resolution

Key Terms:
The **angular resolution** of a telescope is the ability of the telescope to distinguish between two objects. An angular resolution of, for example, x radians, means that the telescope can distinguish between two objects subtended by a minumum x radians. Any two objects closer than this will appear as a single object.

Due to diffraction, light in a telescope is focused into a pattern called an Airy disc. As light passes through the aperture (opening) of the telescope, it diffracts, causing objec
to blur.

The size of the Airy disc produced by a telescope gives the telescope's angular re
subtended by two objects that the telescope can make out without the images b
smaller angular resolution means that smaller or closer together objects can be s

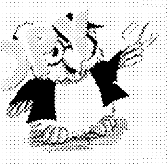
The resolution of a telescope is given by the **Rayleigh criterion**

DB

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

θ = angul
(in r
λ = wavel
D = diam

As you can see, larger-diameter telescopes have a better (smaller) angular resolution, and resolution depends on the wavelength of light captured – shorter wavelengths correspond to a better resolution (as long as you're using the same type of telescope!).



Exam tip
θ is the sm
distinguish
resolution

Example

a) The Arecibo radio telescope is 305 m across and mainly studies the 21.0 cm
What is the minimum angle the Arecibo radio telescope can resolve?

b) Estimate the size of an X-ray telescope with the same resolution as the Are

a) The minimum resolvable angle of a telescope is given by

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

Plugging in numbers

$$\theta \approx \frac{21.0\times10^{-2}}{350}$$

$$\boldsymbol{\theta \approx 6.89 \times 10^{-4}}\ \textbf{rad}$$

b) A typical X-ray has a wavelength of around 1 nm.

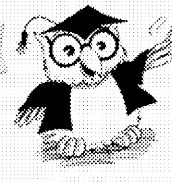
$$\theta \approx \frac{\lambda}{D}$$

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

$$D \approx \frac{[illegible]}{6.89\times10^{-4}}$$

$$\boldsymbol{D \approx 1.45}\ \boldsymbol{\mu m}$$

As you can see, the biggest radio telescopes won't have as good a resoluti
telescopes!



E
Y
ra
a
a
g

degrees = radian

radians = degree

Collecting power

Collecting power is the amount of light a telescope can gather. A telescope with

able to detect dimmer objects.

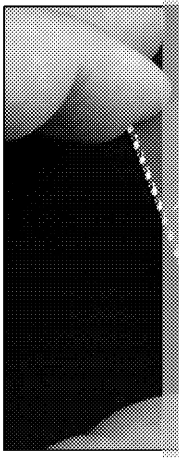
$$\text{Collecting power} \propto \text{diameter}^2$$

Or

$$\text{Collecting power} \propto \text{area}$$

Charge-coupled devices (CCDs)

Most modern telescopes will use CCDs as detectors. CCDs are sensors covered in tiny semiconductors that are sensitive to light – the photosensitive portion of the CCD is backed onto a charge carrying medium. When a photon strikes a pixel a charge is released and a current is generated – this signal is used to build up a picture.



A CCD pa

produces a cu

Key Terms:

The **quantum efficiency** of a detector is a measure of how much incident light is captured and converted into a signal by a detector.

The quantum efficiency of a CCD can be almost 95 %, but is more typically around 80 %. For comparison, the quantum efficiency of the human retina is around 4–5 %.

Example

The Kepler telescope has a collecting area of 0.708 m^2 and uses CCDs with a qua

The human eye has a collecting area of 1,200 mm^2 and has a quantum efficie

a) *How many times more powerful would a CCD in the Kepler telescope be th had the same area?*

b) *By what factor is the Kepler telescope more powerful than the human retin*

a) Quantum efficiency is a direct measurement of the power of a detector.

$\frac{80}{5} = 16$

So CCDs are **16 × more powerful** over the same area.

b) Collecting power ∝ area

The area of the human eye is $1200 \text{ mm}^2 = 1200 \times (10^{-3})^2 \text{ m} = 0.0012$

$\frac{0.708}{0.0012} = 590$

So by area alone, the Kepler telescope would be 590 × more powerful tha

However, the Kepler telescope not only has a larger collecting area than th have a higher quantum efficiency.

From (a), CCDs are 16 × more powerful than the human retina

$16 \times 590 = 9440$

So the Kepler telescope is **9440 × more powerful** than the human eye! This means that the Kepler telescope can view objects that are 9440 × dim eye alone.

Questions

1. A series of radio telescopes over a large distance can gather data from a sin
   a single much larger radio telescope dish.

   The Arcminute Microkelvin Imager (AMI) is one such telescope, comprising
   diameters of 12.8 m and a combined diameter of 110 m.

   The AMI studies radio waves with frequencies of 1[illegible] GHz.

   a) Calculate the minimum angular resolution of the AMI.

   b) Calculate how many times more powerful the eight telescopes of the A
   combined than if they worked individually.

2. A CCD array has an area of 0.04 m^2 and a quantum efficiency of 75 %.
   The human retina has an area of 0.001 m^2 and a quantum efficiency of 5 %.

   Estimate how much more powerful the CCD array is compared to the huma

9.2 Classification of stars

Chapter 9.2 checklist

By the end of this chapter you should be able to:

9.2.1

- Understand and use concepts of apparent magnitude
- Understand and explain the Hipparcos scale, including how it was compiled
- Know the magnitude of the dimmest objects in the sky
- Use the relation between brightness and apparent magnitude
- Understand that brightness is a subjective scale of measurement

9.2.2

- Understand and use light years
- Understand how a parsec is defined and use parsec as a unit
- Understand absolute magnitude
- Understand the relation between absolute and apparent magnitude and the

9.2.3

- Understand and use Stefan's law to compare power output, temperatures a
- Understand and use Wein's displacement law to estimate black-body tempe
- Recognise and sketch the general shape of black-body curves
- Know that stars are black bodies
- Use the inverse square law as it applies to black bodies
- Know the assumptions made when applying the inverse square law

9.2.4

- Describe the main stellar spectral classes
- Understand how the temperature of stars is related to absorption spectra
- Understand the hydrogen Balmer absorption lines

9.2.5

- Describe, sketch and interpret the shape of the Hertzsprung–Russell diagra
- Place stars of different classes on the Hertzsprung–Russell diagram
- Identify the position of the Sun on the Hertzsprung–Russell diagram
- Know the scales and ranges of the axes of the Hertzsprung–Russell diagram
- Describe and explain the path of main sequence stars on the Hertzsprung–R

9.2.6

- Understand that supernovae are defined by a rapid increase in absolute ma
- Explain how type 1a supernovae are used as standard candles to determine
- Describe the controversy concerning the acceleration of the universe and da
- Understand the composition of neutron stars, including their high densities
- Define a black hole as an object in which the escape velocity is greater than
- Describe the formation of neutron stars and black holes from supergiant sta
- Understand the origin of gamma ray bursts
- Describe supermassive black holes at the centre of galaxies
- Understand what is meant by the event horizon of a black hole
- Calculate the Schwarzschild radius of a black hole

9.2.1 Classification by luminosity

The most obvious way to categorise stars and other astronomical bodies is by how b the Sun is obviously the brightest star at any time, and the Moon, when full, is the br However, **brightness is subjective** (it varies depnding on how far away an object in the sky because the Earth is much closer to the Sun than any other star.

Apparent magnitude

Key Terms:

Luminosity is th[illegible]wer output of a star.

Int[illegible]ity [illegible]jective measure of brightness – the power per unit a

[illegible]ess is expressed using the **Hipparcos scale**. This is a logarithmi b[illegible]pparcos, an astronomer in the second century BCE from Nicea, in The Hipparcos scale catalogues stars according to their **apparent mag**

Observed brightness follows an inverse square law – as the light from a source sp

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

$b =$ observed brightn
$L =$ luminosity (in W)
$r =$ distance from so

The unit of brightness is W m^{-2}.

The observed brightness and apparent magnitude of a star are related by

$$m = -2.51 \log_{10} b$$

$m =$

The observed brightness and apparent magnitude of two stars are related by

$$m_2 - m_1 = - \text{[illegible]} \log_{10} \frac{b_2}{b_1}$$

A change in magnitude of 1 corresponds [illegible]ang[illegible] in brightness by a factor of magnitude of 1 appears 2.51 × b[illegible] [illegible]n a star with an apparent magnitude correspond to brighter st[illegible] [illegible]un has an apparent magnitude of around -26 eye can see [illegible] an [illegible]ent magnitude of 6**.

Example

a) *The luminosity of the Sun is 3.85 × 10^{26} W. Calculate the apparent magnitude of the Sun from Pluto, which has an average orbital radius of 5.91 × 10^9 km.*

a) First find the brightness:

$b = \frac{L}{4\pi r^2} = \frac{3.85\times10^{26}}{4\pi\times(5.91\times10^{12})^2}$

$b = 0.877$ W m^{-2}

We then use the brightness to find the apparent magnitude.

$m = -2.51 \log_{10} b$

$\boldsymbol{m} = 0.143$

b) *The apparent magn seen from Pluto. Ca more bright the Sun seen from Pluto.*

b) A change in apparen to a factor of bright

$m_{Sun} - m_{Sirius} = ($

$m_{Sun} - m_{Sirius} = 1$

$\frac{b_{Sun}}{b_{Sirius}} = 1.60 \times 2.5$

[illegible]e Sun is 4.02 × as from Pluto.

Questions

1. Explai[illegible]he [illegible]osity, brightness and apparent magnitude of a star dif
2. The Su[illegible] luminosity of 3.85 × 10^{26} W.
   Calculate the apparent magnitude of the Sun as seen from the Earth, 1.50 ×
3. Star A has an apparent magnitude of 5.7, as seen from Earth.
   Star B has an apparent magnitude of -2.3.
   Compare the brightness of the two stars.

9.2.2 Absolute magnitude, *M*

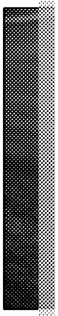
Apparent magnitude only gives us how bright a star appears from Earth. Two objects of the same luminosity will have different apparent magnitudes depending on how far away they are.

So, how do scientists tell how far away an object is?

Parallax

Think about an analogue scale, such as an ammeter. The needle lies in front of the scale, so the angle at which you view it changes where it appears to be on the scale. If you look at the reading directly straight on from the scale you will get one reading, whereas if you move to the left or right you will read something different.

This effect is called **parallax**. Parallax is a source of error you should be aware of in experiments, but it's actually very important for astronomy! The same is true for stars, but with much greater distances involved!



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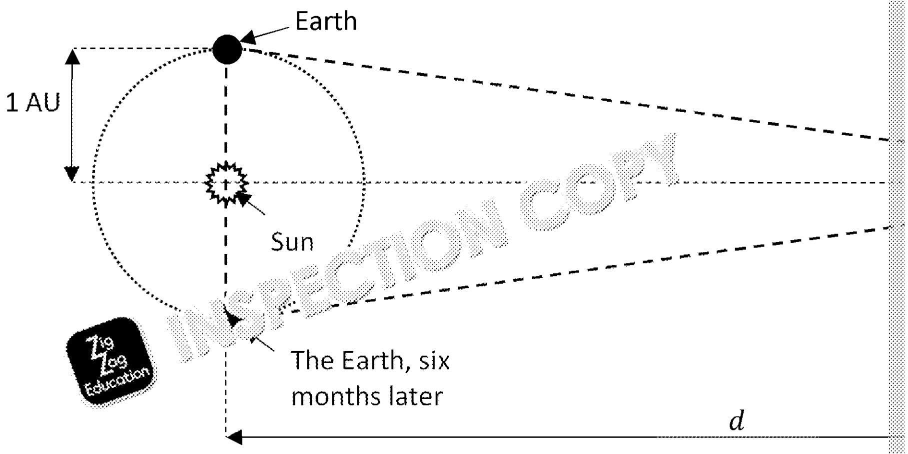
Key Terms:

Parallax is the phenomenon of an object's apparent position changing dependi

1 AU or **astronomical unit** is the average distance between the Sun and Earth. 1



d is very big compared to 1 A

The diagram above shows the Earth orbiting the Sun. As the Earth changes posit star is seen at with respect to more distant stars changes.

We can use trigonometry to determine the distance to the star based on the ang course of six months.

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

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

The angles used are very small, so we can use the small-angle approximation for tan

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

If we use d in parsecs and θ in arcseconds we can write

$$d = \frac{1}{\theta}$$

There are other methods of determining the distances to stars, but using parallax is the earliest method used by astronomers.

1 arcmi

1 arcsec
or $\frac{1}{3600}$ c
1 arcsec
4.9 × 10

A **parse**
to a star

A **light y**
astrophy
light tra

Absolute magnitude

Absolute magnitude is the magnitude a star would appear if viewed from 10 pc away.

We know that brightness scales with distance, and we know that it's possible to find the distance to a star. We can use this information to find the **absolute magnitude** of a star.

Absolute magnitude can be expressed in terms of apparent magnitude:

Exam tip

Remember t
light year are
distance, not
Science fictio
get this wron
these units ju
in a galaxy fa

DB

$$m - M = 5\log_{10}\frac{d}{10}$$

m
M
d

Example

The apparent magnitude of Melnick 34 is 13.10. The distance to Melnick 34 is 16

Calculate the absolute magnitude of Melnick 34.

Use $m - M = 5\log_{10}\frac{d}{10}$

Rearrange for M

$M = 5\log_{10}\frac{d}{10} - m$

$d = 160$ kly $= 160 \times 10^3 \div 3.26 = 49.08$ kpc

$M = 5\log_{10}\frac{49.08\times10^3}{10} - 13.10$

$M = 5.35$

Questions

1. Describe the origin of these units:
   a) Light year
   b) Parsec

2. A star subtends 0.0037 arcminutes in the sky over the course of six months. Calculate the distance to the star.

3. A star has an apparent magnitude of -1.8 and an absolute magnitude of -14.5 Calculate the distance to the star.

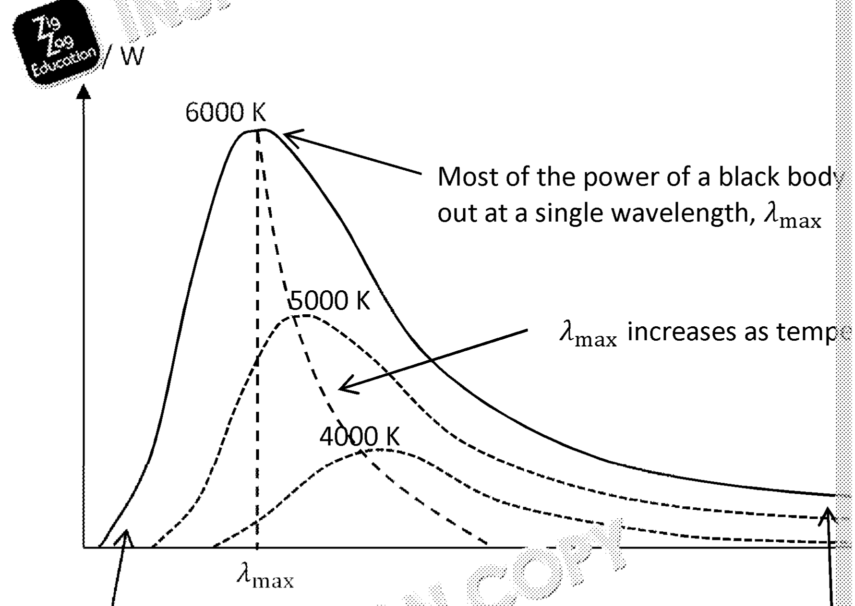
9.2.3 Classification by temperature, black-body radiation

Black-body curves and Wien's displacement law

Key Terms:
A black body is an object that perfectly absorbs and emits radiation of

The graph of the radiation emitted by a black body has a characteristic shape.
The wavelength at which the most power is radiated depends on the temperatur

You can see the graph of the radiation emitted by a black body below.



Most of the power of a black body out at a single wavelength, $\lambda_{\max}$

$\lambda_{\max}$ increases as temp

Photons with short wavelengths have a lot of energy but not many are given out, so the total power of light emitted as short wavelengths is low

There are mor wavelengths gi but each indivi energy, so the t long waveleng

Wien's law lets astrophysicists estimate the black-body temperature of a source

DB

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

Star power

Stefan's law gives the power output of a star based on the star's temperature an

DB

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

P = power (ir
σ = Stefan co
A = surface a
T = temperat

All stars are assumed to be black bodies.

The intensity emitted from a star decreases over distance via the inverse square l

$$I = \frac{P}{4\pi r^2} \propto \frac{1}{r^2}$$

This is why more distant stars can appear dimmer, despite emitting more power

The inverse square law works on the assumption that the power **only** dissipates w something absorbing or reflecting the light, the amount of power will decrease.

Example

The radius of the Sun is 6.96 × 10⁸ m, and its luminosity is 3.85 × 10²⁶ W. Calculate the peak wavelength emitted by the Sun.

First use Stefan's law to find the temperature of the Sun.

$P = \sigma A T^4$

Rearrange this to find T

$T = \left(\frac{P}{\sigma A}\right)^{\frac{1}{4}}$

To find A, [illegible] face area of the Sun, we use $A = 4\pi r^2$.

$T = \left(\frac{P}{\sigma 4\pi r^2}\right)^{\frac{1}{4}}$

$T = \left(\frac{3.85\times10^{26}}{5.67\times10^{-8}\times4\pi\times(6.96\times10^{8})^2}\right)^{\frac{1}{4}}$

$T = 5779$ K

We then use this in Wien's law to find the peak wavelength.

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

$\lambda_{\max} = \frac{2.9\times10^{-3}}{T} = \frac{2.9\times10^{-3}}{5779}$

$\lambda_{\max} = 5.02 \times 10^{-7}$ m $= 502$ nm

Questions

1. The sur[illegible]emperature of the Sun is 5,800 K.

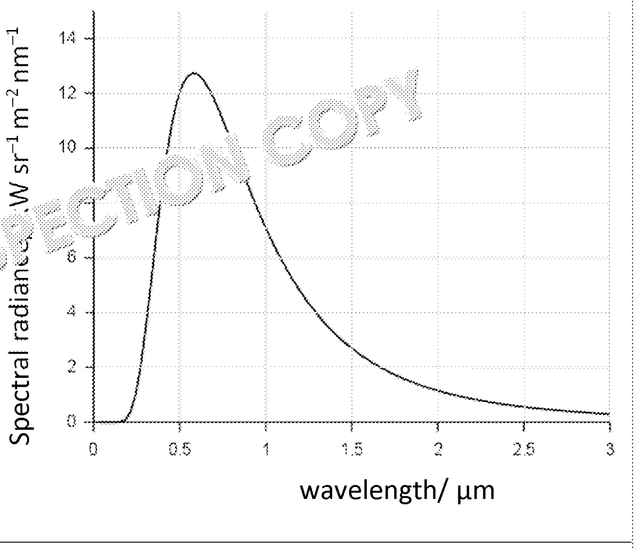
   Estimate the peak wavelength of the Sun.

2. A star has a surface temperature of 7,800 K and a total power output of 6.8

   Calculate the surface area of the star.

3. The star that produces the black-body curve seen below has a radius of 645,

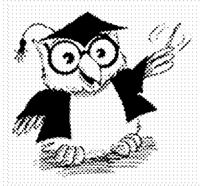
   Estimate the total power output of the star.



9.2.4 Principles of the use of stellar spectral classes

Stars are split into different spectral classes depending on their temperature, pe
colour the star appears to be) and the prominent absorption lines.

Spectral class	Intrinsic colour	Temperature/ K	Pron
O	Blue	25,000–50,000	
B	Blue	11,000–25, 000	
A	Blue – white	7,500–11,000	Io
F	White	6,000–7,500	Io
G	Yellow – white	5,000–6,000	Ionised
K	Orange	3,500–5,000	N
M	Red	< 3,500	Ne

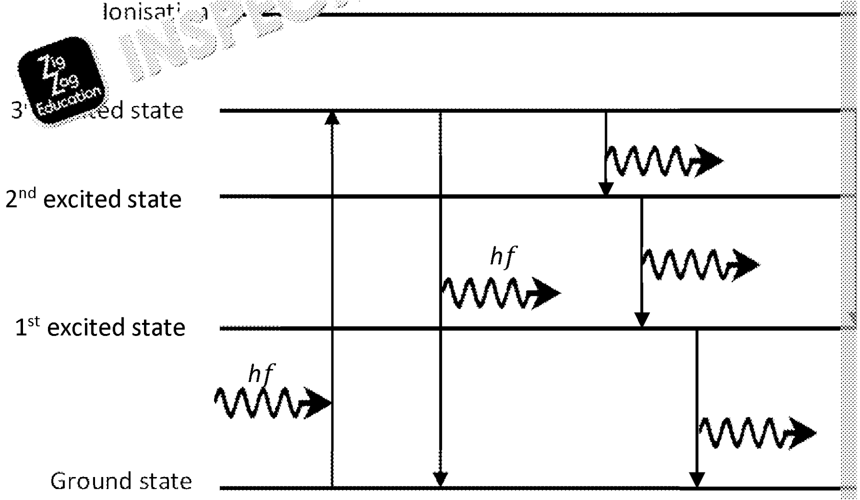


Exam tip

Learn this table!
A good starting point is to learn the general tren
temperature decreases down it and the colours
wavelengths.
A mnemonic for learning the spectral classes is:
Only **B**ad **A**stronomers **F**orget **G**enerally **K**nown

Absorption lines

Light is generated in the heart of stars by nuclear fusion. As the photons pass th
they are continually absorbed and re-emitted by the atoms and ions in the outer

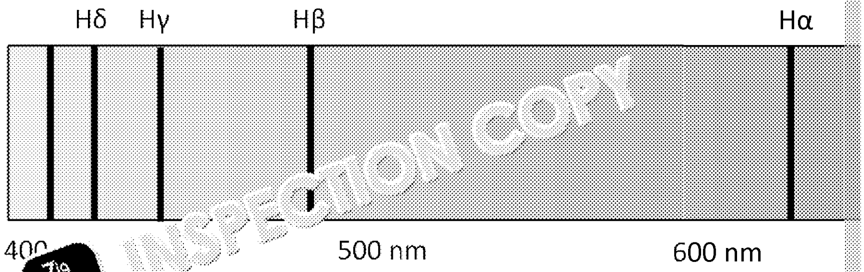


The wavelengths of light corresponding to the energy levels of these absorptions
spectra of these stars.

In stars with low temperatures, most atoms are in the lowest energy state. These
temperatures increase, and distinct absorption spectra are produced.

The **hydrogen Balmer series** corresponds to the wavelengths absorbed by excite
$n = 2$ state.

The hydrogen Balmer absorption lines can be seen below.



Absorption spectra are unique to each element. The absorption spectra of a star
up the star, giving clues to the age of a star and its origins.

Many H atoms in A and B class stars already have electrons in the $n = 2$ excitatio
absorption and re-emission absorbs and re-emits visible photons. These are calle

Questions

1. Complete the table below with information about the main stellar spectral c

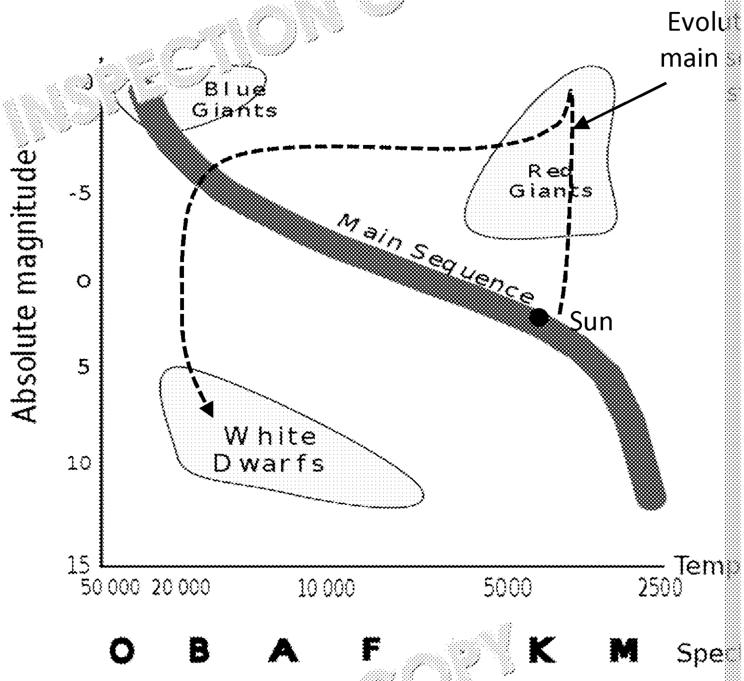
Spectral class	Intrinsic colour	Temperature/ K	Pr
O	Blue	25,000–50,000	
B			
	White	6,000–7,500	
[illegible]			Ionis
	Orange		
M		< 3,500	

2. Describe the origin of the hydrogen Balmer absorption lines and what absor
about stars.

9.2.5 The Hertzsprung–Russell (HR) diagram

Key Terms:

The Hertzsprung–Russell (HR) diagram shows different types of star magnitude and temperature (or spectral class).



Stellar classes

The Hertzsprung–Russell diagram is split into four distinct areas.

Main sequence stars run diagonally across the HR diagram.

All stars have a main sequence stage of their life cycle – this is when stars fuse hy Most stars are in the main sequence, including the Sun – its position is marked o

As main sequence stars use up their hydrogen, they move onto other areas of th based on their mass.

Giants are large bright stars.

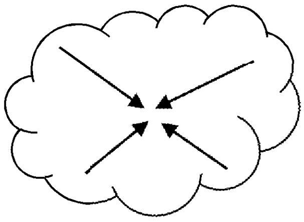
- **Red giants** are relatively cool giants. Helium fuses in the core of red giants.
- **Blue giants** are incredibly large and incredibly hot. The cores of blue giants heavier elements (up to iron) from nuclear fusion.
- **White dwarfs** are the cores of stars which have stopped undergoing fusion. fuel, it ejects its outer layers, leaving behind an incredibly hot core. White d their heat and become **black dwarfs**.

The axes

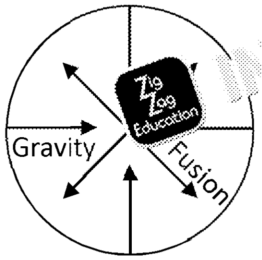
- The x-axis of the diagram is **temperature**. This is a **logarithmic** scale and inc **to left.**
  The temperature axis ranges from 50,000 K to 2,500 K (or O to M if using sp
  - The x-axis of the Hertzsprung–Russell diagram can also be spectral class
- The y-axis of the Hertzsprung–Russell diagram is **absolute magnitude**. The **increases in brightness**.
  The absolute magnitude axis ranges from +15 to -10.

Stellar evolution

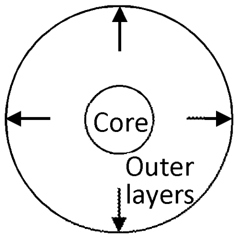
The path of a star such as the Sun can be seen on the diagram above.



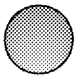
Stars form when interstellar gas and dust clouds coll
incredibly high gravitational pressures – eventually th
enough to **begin nuclear fusi**



During the star's **main sequence**, hydrogen fuses into h
The increased radiation pressure caused by the energy
gravitational forces, so the star is stable.
For most stars this stage lasts for billions of years.



Eventually the hydrogen in the star's core is used up. T
helium in its core, called a **helium flash**, and it gets m
point it will leave the main sequence and become a **gi**
surface will cool.



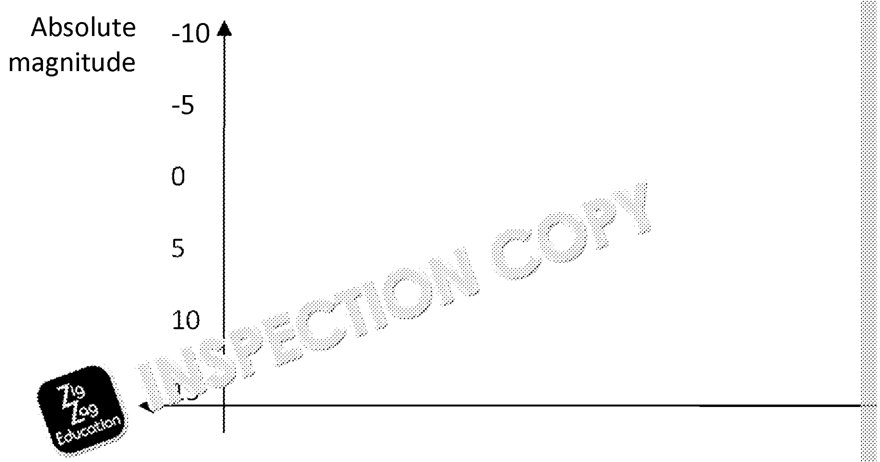
Eventually, all the fuel in the star is used up by fusion
During this stage no fusion occurs. The white dwarf lo
the incredibly hot core exposed.

When the outer layers of the star are lost, they are blo

Eventually even the heat of the core dissipates and th

Questions

1. Sketch the Hertzsprung–Russell diagram below, including filling in values for spectral class.



2. On your Hertzsprung–Russell diagram above, mark the position of the Sun.

3. Describe the life cycle of a star such as our Sun, including its formation and e

9.2.6 Supernovae, neutron stars and black holes

While stars that are the mass of our Sun become red giants and then white dwar
fusion runs out, higher-mass stars may end their lives in more dramatic fashion.

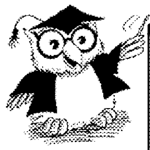
Supernovae

Supernovae are categorised by a rapid and enormous increase in the absolute m
Supernovae can have absolute magnitudes tens of millions of times that of the Sun!

When a star with a mass eight or more times that of the Sun runs out of fuel, ene
sufficient to balance out the gravity of the star.

The star collapses and the increased gravitational forces become high enough to
creating a dense core.

The falling outer layers bounce off the core and explode outwards at incredibly h
The shock wave from supernovae can be strong enough to begin fusion in nearby
of stars.



Exam tip

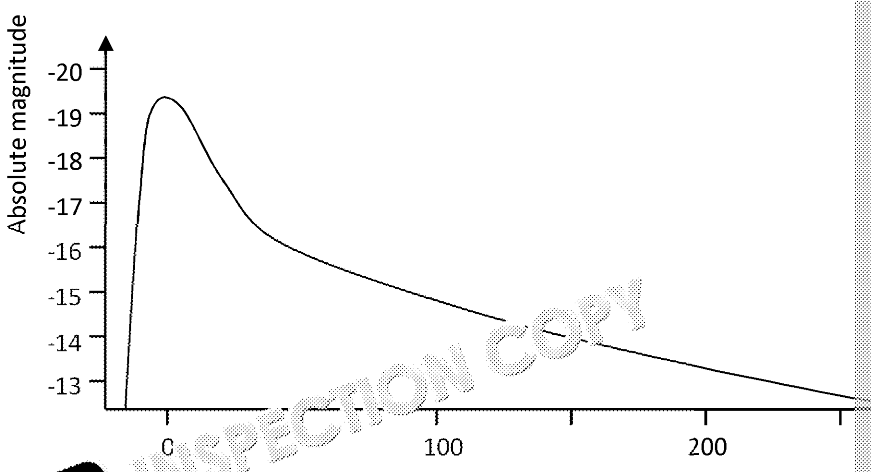
All elements heavier than iron were formed in supernovae.
A nearby supernova would have either injected high-mass elem
Sun formed in, or even led directly to the formation of our sola

In binary systems, type Ia (type one-a) supernovae form by stealing or **accreting**
When the star gathers enough mass (1.4 times the mass of the Sun), it collapses
other supernovae.

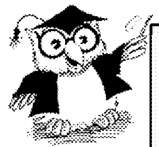
Key Terms

Accretion is the process of a star attracting the mass from a near
[illegible]ce of its gravity.

Type Ia supernovae always form at the same critical mass. Because of this, all ty
similar light curves, as seen below.



The absolute magnitude of a type Ia supernova increases rapidly to around -19.3 and then decreases slowly over several hundred days.



Exam
$t = 0$ o
type Ia s
its lumi

Standard candles

Key Terms:
A standard candle is a star which has a known luminosity and which
use to determine the distance to other stars.

Because all type Ia supernovae have the same absolute magnitude and light curv
their apparent magnitude, and hence how far away they are.

Astrophysicists then use these known distances to calibrate for other techniques

Cepheid variables are another type of standard candle. These stars cycle in brig
cycle is directly related to the maximum luminosity of the Cepheid variable.
Knowing the luminosity of a star and its apparent magnitude lets astronomers de

Example

A type 1a supernova is observed with a peak apparent magnitude of +16. Calculate the distance to the supernova.

We use $m - M = 5\log_{10}\frac{d}{10}$

We know that the peak absolute magnitude, M, of a type Ia supernova is -19.3.

Rearrange for d

$$\log_{10}\frac{d}{10} = \frac{m-M}{5}$$

$$\frac{d}{10} = 10^{\frac{m-M}{5}}$$

$$d = 10 \times 10^{\frac{m-M}{5}}$$

We have $m = 16$ and $M = -19.3$

$$d = 10 \times 10^{\frac{16+19.3}{5}}$$

$d = 10^{7.06}$ pc $= 115$ Mpc

After standard candles were discovered in 1908 by Henrietta Swan Leavitt, catalo
distances to stars were compiled. Similar star catalogues are maintained to this d
shocking results.

While the Big Bang theory suggests that the universe is expanding, it was presum
constant or slowing. The study of type 1a supernovae as standard candles actua
the universe may in fact be accelerating.

There must be some driving force behind any such acceleration, which astrophys

Key Terms:
Dark energy is the term given to the unknown driving force behind t
the expansion of the universe. The nature and origin of dark ener
mystery, and is an ongoing subject of research.

Neutron stars

While a supernova ejects a star's outer layers into space, the star's core will be le
1.4 times or more that of the Sun, the incredibly dense core left over is called a n

Key Terms:
A neutron star is an object where the gravitational pressure has become s
and protons fuse, becoming neutrons. A neutron star is composed almost

A neutron star has a core of neutrons surrounded by an outer crust of high neutr

Neutron stars are incredibly dense. Their diameter is on the order of magnitude
between 1.[illegible] solar masses.

Example

Estimate the density of a neutron star.

A neutron star has a diameter of $\sim$ 10 km, or a volume of

$$V = \frac{4}{3}\pi r^3 \approx \frac{4}{3}\pi(5 \times 10^3)^3 = 5.24 \times 10^{11}\ \text{m}^3$$

The lower mass of a neutron star is 1.4 solar masses.

$$m_n \approx 1.4 \times m_s = 2.79 \times 10^{30}\ \text{kg}$$

So the density of a neutron star is

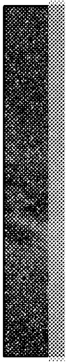
$$\rho = \frac{m_n}{V} \approx \frac{2.79\times10^{30}}{5.24\times10^{11}} = \mathbf{5.3 \times 10^{18}\ kg\ m^{-3}}$$

This is about the density of an atomic nucleus!

Black holes

When a supernova is so large that the remaining core is over approximately three solar masses, a black hole is formed.

Key Terms:
A **black hole** is an object that has such a high gravity that nothing can escape it – not even light.



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The escape velocity for a black hole is $v_{esc} > c$. This means that an object would have to be travelling faster than the speed of light – something which is impossible! This means that nothing can ever escape a black hole. The distance from the centre of a black hole from which nothing can escape a black hole is the **event horizon** (where $v_{esc} = c$).

Key Terms:
The **Schwarzschild radius, R_S,** of a black hole is the radius of its event horizon.

Escape velocity is given by $v_{esc} = \sqrt{\frac{2GM}{R}}$

At the event horizon, $v_{esc} = c$ and $R = R_S$ so

$c^2 = \frac{2GM}{R_S}$ and

G = gravitational co
M = mass of black h
c = speed of light in

DB

Schwarzschild radius, $R_S \approx \frac{2GM}{c^2}$

Supermassive black holes

At the centre of our galaxy, stars have been observed orbiting incredibly quickly – presence of a highly massive object at the centre of the galaxy. Astrophysicists b a **supermassive black hole**.

> **Key Terms:**
> **Supermassive black holes** at the centre of galaxies have masses millions of

There are three proposed methods by which supermassive black holes could form

- Enormous clouds of gas coalesce when the galaxy first forms
- A black hole formed by [illegible] means accretes mass from surrounding stars
- Numerous black holes form in a cluster and eventually merge into a single,

Gamma ray bursts

Astrophysicists will occasionally detect enormous amounts of energy for milliseconds up to several minutes or even hours at a time. These flashes of high-energy light are known as **gamma ray bursts**.

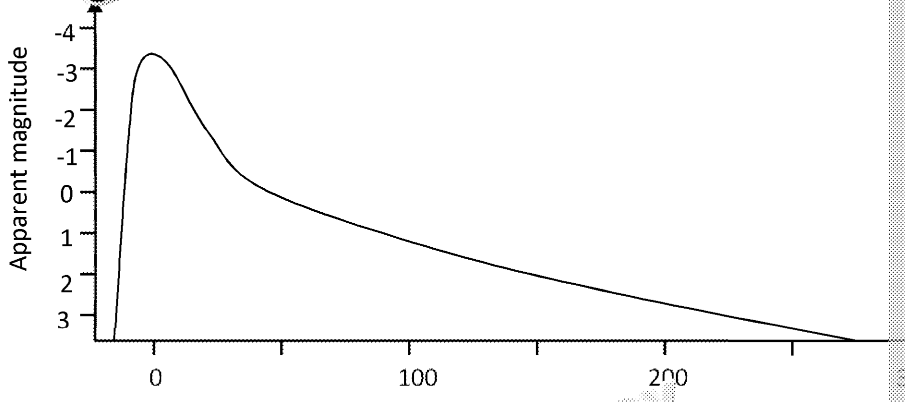
Gamma ray bursts are thought to originate from collapsing supergiant stars forming neutron stars and black holes. As matter falls inwards, it heats up and ejects gamma rays in high-energy beams.

Gamma ray bursts can have energies of around 10^{44} J, making them some of the most energetic electromagnetic events ever recorded. A single gamma ray burst lasting seconds could have the equivalent energy of the total amount of energy the Sun will ever release over billions of years.

If a gamma ray burst was directed at Earth from a nearby star, the majority of life This may have been the cause of historical extinction events.

Questions

1. Describe the appearance and formation of a supernova.
2. A type 1a supernova is observed to produce the light curve seen below.



   a) Why can type 1a supernovae be used to determine distances?
   b) Calculate the distance to the supernova in k
   c) Cosmological distances calculated using type 1a supernovae have result size of the universe.
      Explain this [illegible].

3. a) Describe a neutron star, including its formation.
   b) A neutron star has a mass of 1.5 solar masses. If the density of a neutr density of an atomic nucleus ($\sim 2.3 \times 10^{17}$ kg m^{-3}), estimate the radius

4. a) How is the event horizon of a black hole defined?
   b) Estimate the Schwarzschild radius of the Sun in metres, if its mass was c black hole.

9.3 Cosmology

Chapter 9.3 checklist

By the end of this chapter you should be able to:

9.3.1

- Understand the origin of the Doppler effect ....
- Calculate shifts in wavelength and frequency due to Doppler shift for optical
- Apply the Doppler effect to the movement of binary stars, galaxies and quas

9.3.2

- Understand red shift...
- Calculate the distance to stars from their red shifts ....
- Interpret red shift as resulting from the expansion of the universe ....
- Use the red shift of distant stars to estimate the age of the universe ....
- Describe the Big Bang theory, including evidence ....

9.3.1

- Describe quasars...
- Describe the discovery of quasars ....
- Estimate distances to quasars from red shifts and power outputs ....
- Understand how quasars are formed ....

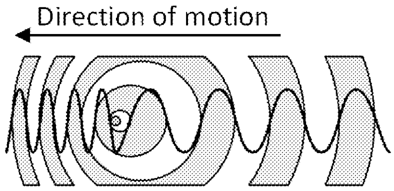
9.3.2

- Describe the difficulties of detecting exoplanets directly.................................
- Understand how the radial velocity method and the transit method are used
- Recognise and sketch the typical light curves associated with the detection o

9.3.1 Doppler effect

When a police or ambulance siren is approaching you, the frequency of the siren the frequency decreases again. This is the **Doppler effect**.

Key Terms:
The **Doppler effect** is the phenomenon of wavelengths increasing o depending on the velocity of the source compared to the observer.



For a moving wavesource, wavefronts are pushed together in the direction of motion, and spread out behind.

Starlight also undergoes the Doppler effect – light from stars moving away from u longer wavelengths. The light is said to be **red shifted**.

Light from sources approaching us – such as stars in our own galaxy – has compre wavelengths. The light is said to be **blue-shifted**.

For light sources moving with a velocity much lower than the speed of light, $v \ll$ $v < 0.1\,c$)

DB

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

The red shift of light is given by

DB

Red shift, $z = -\frac{v}{c}$

f =
Δf
λ =
$\Delta\lambda$
v =
c =
z =

Δf = **observed frequency – original frequency**

$\Delta\lambda$ = **observed wavelength – original waveleng**

Red shift is measured from known spectroscopic lines. The hydrogen Balmer seri absorption; if this pattern is seen at a longer wavelength to the one expected, it h

Exam tip
A recessional velocity (an object moving away from us) is taken to be negative. Thi means that an object moving away from u will have a positive red shift.

Binary stars

The radius of binary stars that orbit each other in the plane of observation (i.e. they eclipse each other as seen from Earth) can be determined from the changing red shift of the stars.

Key Terms:
A **binary star** system
other around a com

When a star is moving towards Earth, its observed spectral pattern becomes blue
moving away from Earth, its observed spectral pattern is red shifted.

The difference in time between peaks of red shift give the period of the orbiting
shift and blue shift we can find the velocity of the stars with respect to each othe
can find the distance between the stars.

Example

A binary system is observed.
The spectroscopic data shows that the orbital period of the system is 50 days.
The H_α absorption line (6256.8 nm) is observed to be a double line with periodic
is at a minimum of 6256.6 nm while the other is at a maximum of 6257.1 nm.
Calculate the distance between the stars.

First we find the period of the system in seconds:

Period, $T = 50 \times 24 \times 60 \times 60 = 4.32 \times 10^6$ s

Then the velocity of the star at the maximum absorption line (Star 1) is given by

$$\frac{v_1}{c} = -\frac{\Delta\lambda}{\lambda}$$

$$v_1 = -c\frac{\Delta\lambda_1}{\lambda} = -3.00 \times 10^8 \times \frac{6256.6-6256.8}{6526.8}$$

$$v_1 = 9.193 \times 10^3 \text{ m s}^{-1}$$

The orbital radius of Star 1 is then given by

$$R_1 = \frac{\text{circumference of orbit}}{2\pi} = \frac{v_1 T}{2\pi}$$

$$R_1 = \frac{9.193\times10^3\times4.32\times10^6}{2\pi} = 6.238 \times 10^{10} \text{ m}$$

We can do the same for the second star as well:

$$\frac{v_2}{c} = -\frac{\Delta\lambda_2}{\lambda}$$

$$v_2 = -c\frac{\Delta\lambda_2}{\lambda} = -3.00 \times 10^8 \times \frac{6527.1-6526.8}{6526.8}$$

$v_1 = -13.789 \times 10^3$ m s^{-1} *We don't actually need the sign of the velocity her*
[illegible] the star is moving away from Earth – it's been red

And the orbital radius:

$$R_2 = \frac{v_2 T}{2\pi} = \frac{13.789\times10^3\times4.32\times10^6}{2\pi} = 9.481 \times 10^9 \text{ m}$$

Adding these for the total distance gives us

$6.238 \times 10^{10} + 9.481 \times 10^9 = \mathbf{7.186 \times 10^{10}}$ **m** $=$ **0.479 AU**

Quasars

For most galaxies, individual stars can't be made out. Instead, the light of whole galaxies is used.

Quasars form when matter falls into the supermassive black holes at the centre of galaxies. The matter heats up as it falls and emits huge amounts of energy in two beams – these beams make up the light of a quasar.

Quasars are some of the furthest observable objects in the universe, due to their high brightness, and so show very high red shift.

Because quasars are so far away from Earth, their velocity compared to Earth is too high for $z = -\frac{v}{c}$ to give an accurate estimate of their speed. Quasars can travel at speeds up to 0.2c and so **relativistic effects** must be accounted for.

Questions

1. The wavelength of light emitted by excited atomic hydrogen is 21 cm.

   Light from a star shows this line at 19 cm.

   a) Has the light from the star been red shifted or blue-shifted? What does
   of the star?
   b) Calculate the velocity of the star relative to Earth.
   c) Calculate the red shift of the star.

2. An absorption line for mercury is 1[illegible]499 nm.

   A binary system is observed to have two mercury absorption lines, one at 18
   184.95[illegible]

   The period of the system is 84 days.

   Calculate the distance between the two stars in the binary system.

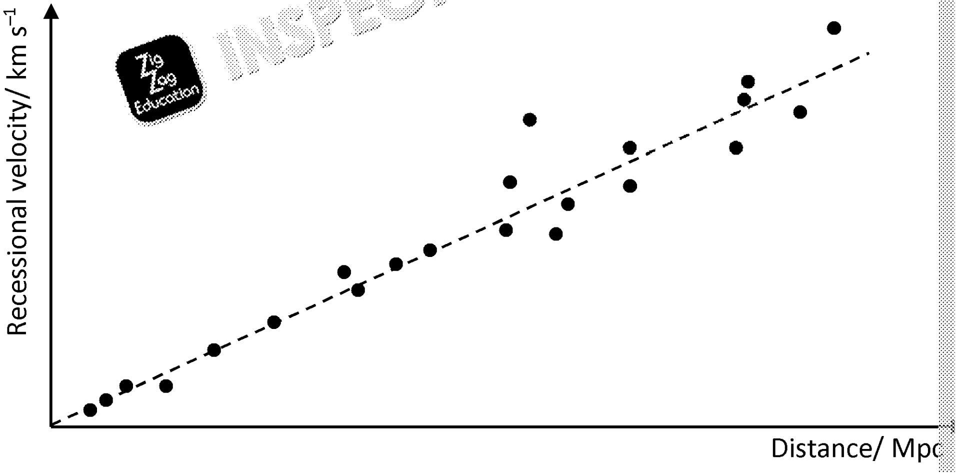
9.3.2 Hubble's law

Key Terms:

The **Big Bang theory** describes the beginning of the universe as the expansio
single infinitely dense and hot point.

This expansion is still occurring today and accounts for the larger red shift of

Plotting the recessional velocities against distance of galaxies, a trend emerges.



The rate at which galaxies recess from Earth is proportional to their distance fro
This is called Hubble's law, named after the scientist who discovered it, Edwin Hu

$$v = Hd$$

v =

d =

H =

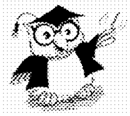
The Hubble constant is the gradient of the graph of recessional velocity against distance.

Hubble's law implies that the space in between galaxies itself is expanding – the
the faster they move away from each other.

A consequence of this is that in the past the galaxies were once much closer toge
may have even been in a single infinitely hot and dense point of space containin

This single infinitely dense point expanded outwards in a single enormous expan

Exam tip



For Hubble's law, we take recessional velocities (objects moving away from us) to be positive and the opposite as for [illegible]. This is because Hubble's law only applies to recessional galaxies.

Example

A galaxy is observed to have a red shift
Calculate the distance to this galaxy.

First we find the velocity of the galaxy f

$z = -\frac{v}{c} \rightarrow v = -zc = -0.100 \times 3.00$

$= -3.00 \times 10^4$ km s^{-1}

Remember to always put the velocities
with Hubble's constant!

Then use Hubble's law:

$v = Hd \rightarrow d = \frac{v}{H} = \frac{3.00 \times 10^4}{65} = \mathbf{462\ M}$

The age and size of the universe

Hubble's law allows us to estimate the size and age of the observable universe.

A galaxy moving at speed v can move a distance d in a time t, so that

$t = d/v$

From Hubble's law,

$v = Hd$ or $\qquad H = \frac{v}{d} = \frac{1}{t}$

so that

$\boldsymbol{t}$ (age of th[illegible]rse) $= \frac{\mathbf{1}}{\boldsymbol{H}}$

Using the value for H above

$H = 65$ km s^{-1} Mpc^{-1} which we'll need to convert into seconds^{-1}

(by converting Mpc^{-1} to m^{-1}):

$H = \frac{65 \times 1000}{3.08 \times 10^{22}} = 2.110 \times 10^{-18}$ s^{-1}

Exa
Thes
estin
that
of th
thro
If the
slow
obse
reach
less

So $t(\text{age of universe}) = \frac{1}{H} = \frac{1}{2.110 \times 10^{-18}} = 4.738 \times 10^{17}\text{s} =$ **15.0 billion years**

With the limit of $v = c$, light can only have travelled a limited distance – the radi
$d(\text{radius of observable universe}) = ct = 3.00 \times 10^{8} \times 4.738 \times 10^{17}$
$d(\text{radius of observable universe}) = 1.422 \times 10^{26}$ m = [illegible]20 Mpc

But this is only half the size of the observable universe, so we have to double this
diameter of the observable universe = **9230 Mpc**.

Evidence [illegible] Big Bang

As well as Hu[illegible]'s law, there is plenty of other evidence for the Big Bang theory

1. **The cosmic microwave background** (CMB) radiation is a type of radiation th
   CMB is very low energy, corresponding to a temperature of only a few kelvi
   from the Big Bang. While the Big Bang would have been enormously energe
   the course of the age of the universe across vast distances.

   The static on an old television set is the TV picking up the CMB – a visual rep
   universe!

2. The abundance of elements in the universe is also evidence for the Big Bang
   and 2 % other elements. This abundance agrees very closely with models of
   incredibly high temperatures shortly after the Big Bang.

   Hydrogen and helium were produced when the temperature of the universe
   form, about three minutes after the Big Bang, in a ratio of roughly 3:1, while
   produced later in stars.

Questions

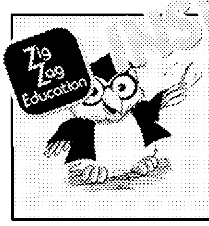
1. Outline [illegible]ain pieces of evidence for the Big Bang.
2. A galaxy has a red shift of 0.081.
   Calculate the distance to this galaxy from Earth.
3. Use Hubble's constant to estimate an age for the universe.

9.3.3 Quasars

Quasars are incredibly bright and incredibly distant radio sources.

As matter falls into the supermassive black holes at the centre of a galaxy, it reach temperatures and emits super-fast jets of particles. These particles emit electrom decelerate, which we can detect on Earth. A quasar is the centre of a galaxy that p

Quasars are some of the most distant objects observable from Earth, and as a res to around $z = 7$.



Exam tip

Some quasars have red shifts that correspond to sp speed of light! They're not actually moving faster th which is impossible, but moving faster than c with r after taking into account the expansion of the spac

Example

One of the first quasars ever observed, 3C 48, has a red shift of 0.367.

a) Estimate the distance to 3C 48.

b) The apparent magnitude of 3C 48 is 16.2. Estimate the power output of 3C

a) To find distance from red shift we can use

$z = -\frac{v}{c}$ and then $v = Hd$

$v = -zc = 0.367 \times 3.00 \times 10^8 = 1.101 \times 10^8$ m s^{-1}

$d = \frac{v}{H} = \frac{1.101\times10^8}{2.110\times10^{-18}} = \mathbf{5.218 \times 10^{25}\ m = 1.69\ Gpc}$

b) We can find the absolute magnitude of 3C 48 from

$m - M = 5\log\frac{d}{10}$

$M = m - 5\log\frac{d}{10} = 16.2 - 5\log\frac{1.69\times10^9}{10} = -24.9$

We can then find brightness from

$M = \text{-}2.5\log b \rightarrow b = 10^{-M/2.5} = 10^{24.9/2.5} = 10^{9.96}$ W m^{-2}

Absolute magnitude is measured at 10 Pc (3.08×10^{17}), so

$L = b \times 4\pi r^2 = 10^{9.96} \times 4 \times \pi \times (3.08 \times 10^{17})^2 \approx 1.09 \times 10^{46}$ W, ~10

Questions

1. Describe the formation and importance of quasars.
2. 3C 295 is a quasar with a red shift of 0.464.
   a) Estimate the distance from Earth to 3C 295.
   b) The apparent magnitude of 3C 295 is 19.8.
   Calculate the absolute magnitude of 3C 295.

9.3.4 Detection of exoplanets

Key Terms:
Exoplanets are planets outside of our solar system, orbiting ot

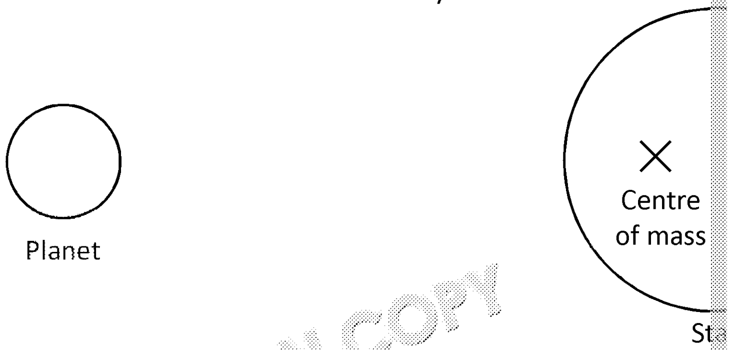
One of the most exciting recent developments in astrophysics is the detection of

It's only recently that measurements of stars have become detailed enough to de are so much brighter than their planet, most exoplanets can't be directly detected determined via different methods.

Variation in Doppler shift

As planets orbit a star, the star is in fact also orbiting the planet; they have a com

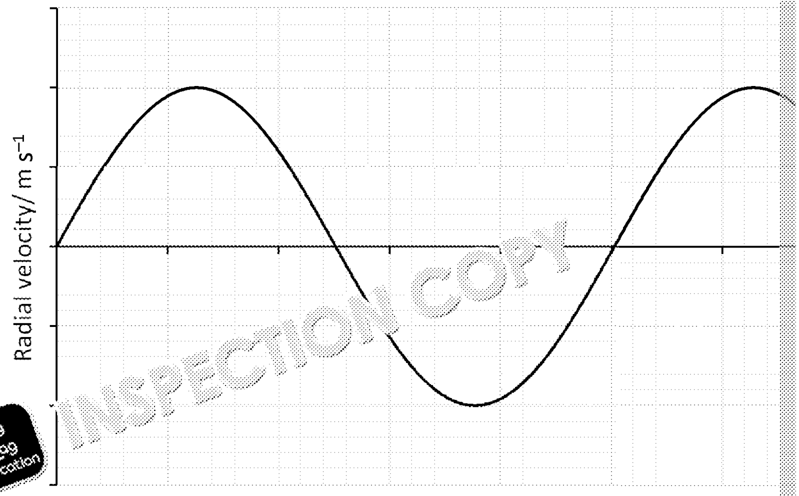
This centre of mass lies within the star as a star will have much higher mass than for instance, contains 99.9 % of all the mass in our solar system.



While a star will not orbit with as large a radius as the planet, it will still appear to star as it moves around [illegible]

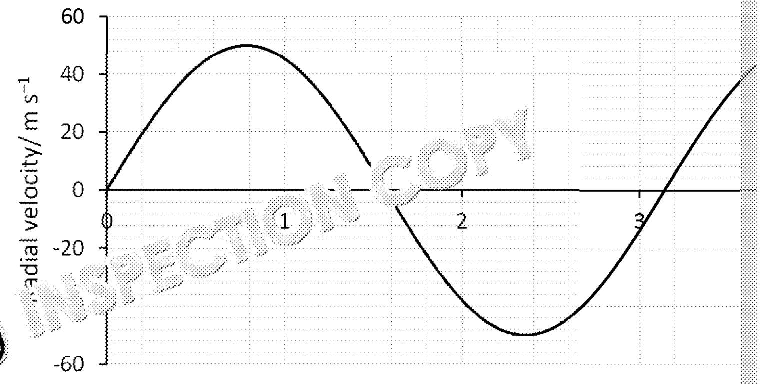
While we cannot observe this wobble directly, it corresponds to a change in velo and forwards – this change in velocity is apparent in the red shift of the star as d binary systems.

This produces a curve like the one seen below.



Example

The graph below shows the radial velocity of a star over time.



a) What is the period of the star's 'wobble'?
b) Calculate the radius of the star's 'wobble'.

a) The period of the star's 'wobble' is the time taken for a single oscillation. The period of the star's 'wobble' is, therefore, around 3.1 years = **9.78** ×

b) Angular velocity can be given in terms of both radial velocity and radius, a

$\omega = \frac{2\pi}{T}$ and $\omega = \frac{v}{R}$

The radial velocity is the peak of the curve, 50 m s^{-1}

Both of these are equations are equivalent

$\omega = \frac{2\pi}{T} = \frac{v}{R}$

Rearranging for R

$R = \frac{vT}{2\pi} = \frac{50\times9.78\times10^7}{2\pi}$ [illegible] **78** [illegible] **10**$^{[illegible]}$ **m**

Transit method

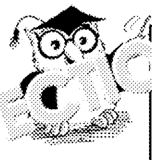
Planets do not give off light of their own, only reflect light from their stars. This in front of a star, some of the light is reflected back.

This decrease is very small – for a planet the size of Jupiter the decrease in brigh

The decrease in brightness as a planet passes in front of a star can be found from

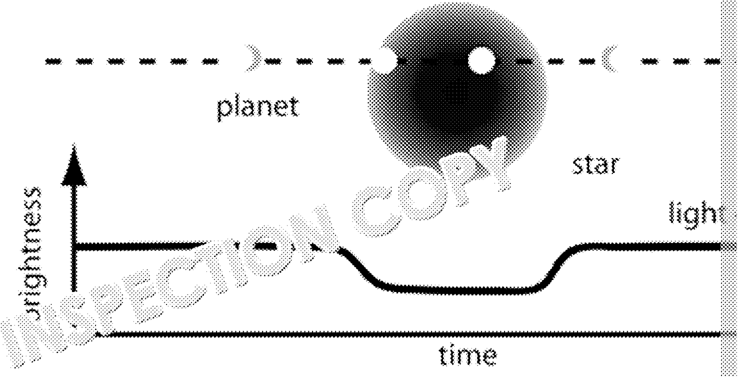
$$\text{Decrease in brightness} = \left(\frac{r_{planet}}{r_{star}}\right)^2$$

r_{p}
r_{st}



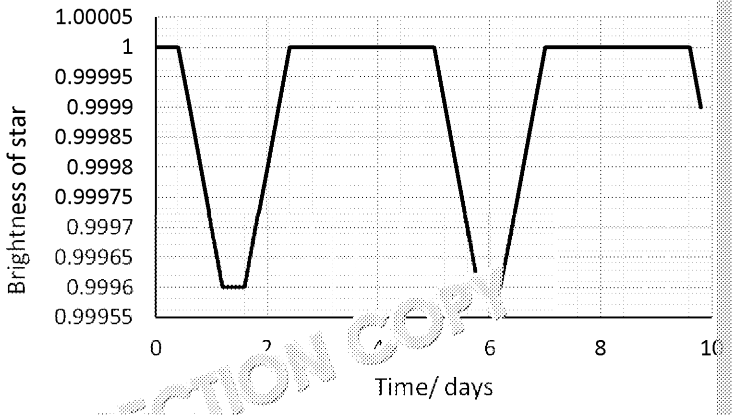
Exam tip
The radius of a star can be found using Stefan's law!

As a planet passes in front of a star, the light curve below is seen.



Example

The brightness curve for a star can be seen below.



a) W[illegible] th[illegible] period of the exoplanet?

b) C[illegible] the radius of the exoplanet as a fraction of the radius of the s

a) The orbital period of the exoplanet is the time taken for the star to reach t between the start of each dip in brightness:
$T = 5 - 0.4 =$ **4.6 days**
The star would have to have a very high mass for this to be possible – typic would only be seen once in this time period.

b) $\text{Decrease in brightness} = \left(\frac{r_{planet}}{r_{star}}\right)^2$

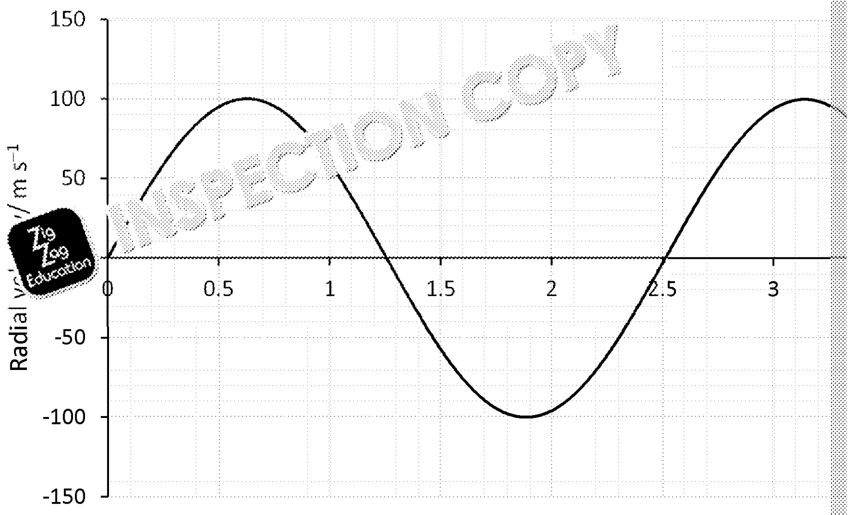
$$\sqrt{\text{Decrease in brightness}} = \frac{r_{planet}}{r_{star}}$$

$$\text{Decrease in brightness} = 1 - 0.9996 = 0.0004$$

$$\frac{r_{planet}}{r_{star}} = \sqrt{0.0004} = \mathbf{0.02}$$

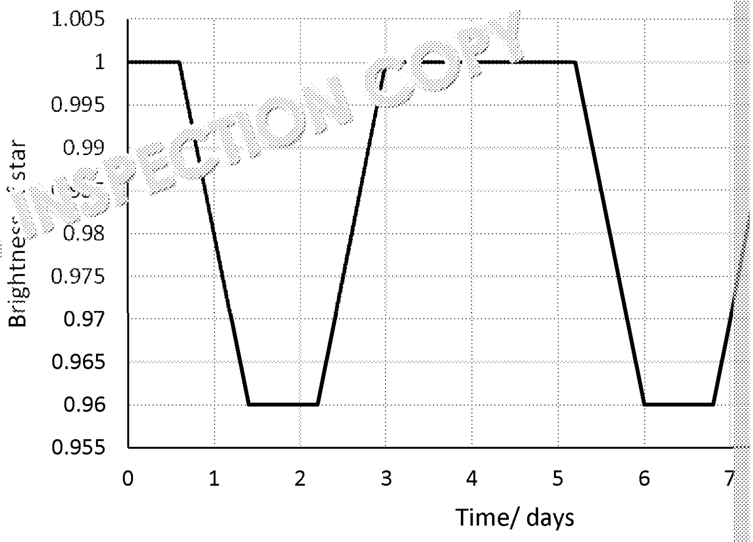
Questions

1. Why is it so difficult to detect exoplanets directly?
2. A star is observed to 'wobble' slightly, producing the curve seen below.



   a) Describe why this curve implies the presence of an exoplanet around th
   b) Estimate the radius of the star's 'wobble'.

3. The *light* curve of a star is seen below.



   a) How does the presence of an exoplanet around the star cause the shap
   b) What is the radius of the exoplanet as a fraction of the radius of the sta

Exam-style questions

1. The Hubble space telescope is positioned in low Earth orbit and has a

   The Hubble space telescope can be used to study infrared, optical and

   1.1 Explain the advantages of positioning the Hubble space telescope

   ....

   ....

   ....

   1.2 Describe the mechanism by which telescopes collect images of ult

   ....

   ....

   ....

   1.3 Show that the minimum angular resolution of the Hubble space t wavelengths of 535 nm is 2.23×10^{-7} rad.

   1.4 The proposed replacement for the Hubble space telescope is the J which has a mirror of diameter 6.5 m.

   Compare the collecting powers of the Hubble space telescope to t space telescope.

   State any assumptions you have made.

   Assumption..

   1.5 The minimum angular resolution of the human eye is 2.91×10^{-4}

   If a refracting telescope has an eyepiece with a focal length of 15 telescope would be required to view an object the same size as th of the Hubble space telescope?

2. Kepler's Supernova was a supernova observed in 1604.

Kepler's Supernova had an apparent magnitude of -2.25 and was 20,0

2.1 Describe how a supernova is formed.

....

....

....

....

2.2 Show that the absolute magnitude of Kepler's Supernova was -16.

2.3 Calculate the luminosity of Kepler's Supernova.

2.4 Kepler's Supernova may have been a type 1a supernova.

Describe how type 1a supernovae can be used as standard candle

....

....

....

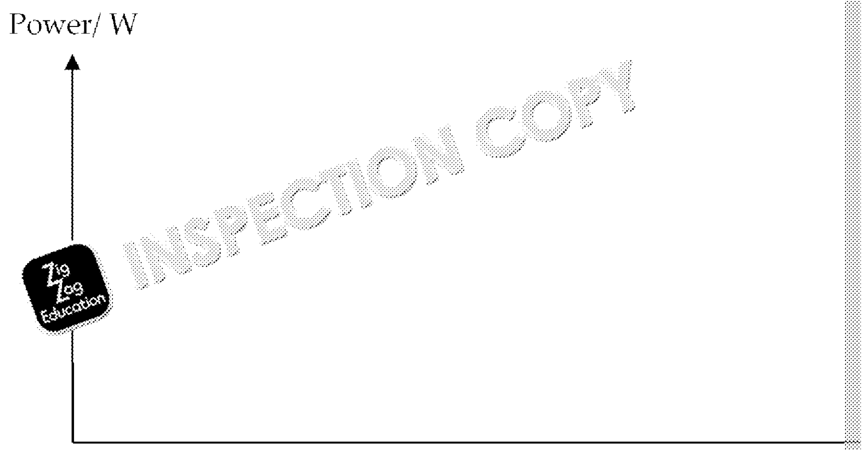
3. Sirius A is a main sequence star in a binary system with another star,
The luminosity of Sirius A is 9.72×10^{27} W.

3.1 Describe how binary stars can be identified from their absorption

3.2 The radius of Sirius A is 1.71 times the radius of the Sun.

Show that the peak wavelength emitted by Sirius A is 2.93×10^{-7}

3.3 Sketch the black body spectrum of Sirius A.



3.4 Sirius A's binary twin, Sirius B, is a white dwarf.

Explain how a main sequence star, such as Sirius A, becomes a w

4. A quasar, 3C 48, shows the 21.0 cm Hydrogen line at 28.7cm.

4.1 Describe how a quasar is formed.

....

....

....

....

4.2 Ignoring relativistic effects, calculate the distance to quasar 3C 48

4.3 The red shift of some quasars is greater than 1

Explain why this goes against conventionally agreed physics and

....

....

....

....

4.4 Describe how quasars provide evidence for the Big Bang theory.

....

....

....

....

Answers

9.1.1 Astronomical telescopes consisting of two converging le

1. Refracting telescopes use **converging lenses** so that parallel beams of light can an image.

2. a) The focal length of the eyepiece should be [illegible] than the focal length of in an **increased magnification** [illegible] image will be enlarged).

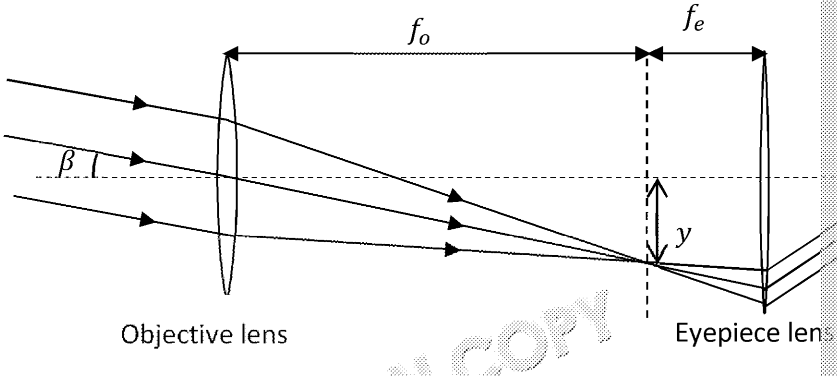
   b) $M = \frac{f_o}{f_e}$

   f_e [illegible] **3.33 m**

   c) $M =$ [illegible] $\frac{}{\beta}$

   $\alpha = M\beta = 1.80 \times 8.00 = 14.4\,°$

3.

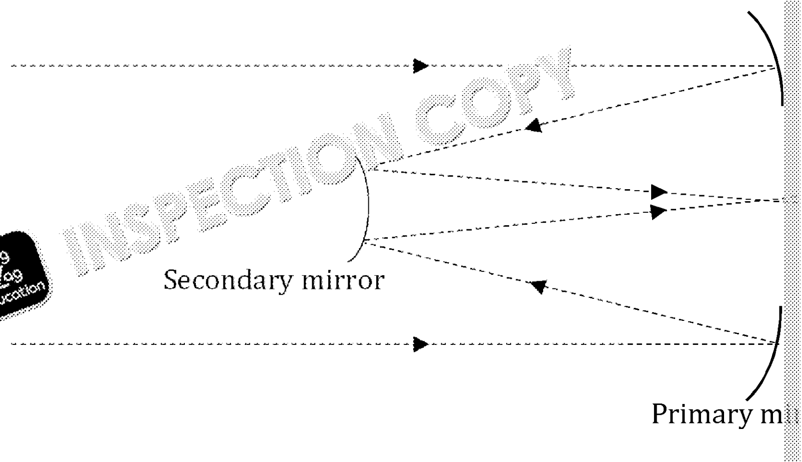


9.1.2 Reflecting telescopes

1. Refracting telescopes must be made incredibly long for desired magnification, r compact.
   It is much more difficult to create high-quality lenses than it is to make high-qua
   Refracting telescopes are much heavier and much more difficult to move than r
   Mirrors are much easier to support than lenses, reducing distortion.
   Reflecting telescopes do not suffer from chromatic aberration, and spherical abe

2. Chromatic aberrations are caused by different wavelengths of light being diffrac resulting in a blurred image.
   Spherical aberrations occur when light rays passing through the edges of the le to the rays passing through the centre. The shape of the lens must be changed t

3.



9.1.3 Single-dish radio telescopes and IR, UV and X-ray teles

1. Building telescopes at high altitudes **reduces the effects of light refracting** in
refractive effects due to **turbulence**.

2. UV telescopes detect light via solid-state devices – a photon of sufficiently high f
and the energy is used to emit an electron, creating a current.

3. The Lovell telescope is **a radio telescope**.
It is **ground-based** as only radio and visible light can penetrate the atmosphere
It is **outside urban areas** to reduce radio interference.
It has a **large dish** to increase the low resolving power of radio telescopes.

4. Infrared telescopes are useful for studying **cool regions of space**, such as regio
In space as infrared light is **absorbed by Earth's atmosphere**.
Far from Earth to **shield against temperature changes**.
Large diameters **increase resolving and collecting power**.

9.1.4 Advantages of large-diameter telescopes

1. a) $\theta \approx \frac{\lambda}{D}$

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{12\times10^9} = 0.025\text{ m}$$

$$\theta \approx \frac{0.025}{110} = \mathbf{2.27\times10^{-4}\ rad}$$

b) collecting power ∝ diameter^2

$$\frac{\text{collecting power (total)}}{\text{collecting power (individual)}} \propto \frac{110^2}{12.8^2} = 73.9\times\textbf{ more powerful}$$

2. By area:

$$\frac{\text{Area (CCD)}}{\text{Area (retina)}} = \frac{0.04}{0.001} = 40\times\text{ more powerful}$$

By efficiency:

$$\frac{\text{Efficiency (CCD)}}{\text{Efficiency (retina)}} = \frac{75}{5} = 15\times\text{ more powerful}$$

In total, the CCD array is **600 × more powerful** than the human retina

9.2.1 Classification by luminosity

1. Luminosity is the power given off by a star.
Brightness is the observed light from a star at a certain distance from the star.
Intensity is an objective measure of brightness – the power per unit area at a ce
Apparent magnitude is a logarithmic scale of brightness.
An increase in apparent magnitude of 1 relates to a dimming of 2.51 times in br

2. $b = \frac{L}{4\pi r^2} = \frac{3.85\times10^{26}}{4\pi(1.50\times10^{11})^2} = 1362\text{ W m}^{-2}$.

$m = -2.5\log_{10} b = -2.5\log_{10} 1362$ [illegible]

3. $m_B - m_A = -2.51\log_{10}\frac{b_B}{b_A}$

$$\frac{m_A - m_B}{2.51} = \log_{10}\frac{b_B}{b_A}$$

$$\frac{b_B}{b_A} = 10^{\frac{m_A - m_B}{2.51}} = 10^{\frac{5.7+2.3}{2.51}} = 1540$$

Star B is **1,540 times brighter** than star A.

9.2.2 Absolute magnitude, *M*

1. As the Earth orbits the Sun, stars appear to shift position due to the **parallax ef** distance to a star which subtends **1 arcsecond over the course of a year**.
   A light year is the distance **light in a vacuum** covers in **one year**.

2. $d = \frac{1}{\theta}$ where d is in parsecs and θ is in arcseconds.

   1 arcminute = 60 arcseconds

   0.0037 arcminutes = 0.222 arcseconds

   $d = \frac{1}{0.222} = \mathbf{4.5\ pc}$ (= 1.39 × 10^{17} m)

3. $m - M$ [illegible] $\frac{}{10}$

   $d = 10 \times 10^{\frac{m-M}{5}} = 10 \times 10^{\frac{-1.8+14.5}{5}} = \mathbf{3470\ pc}$ (= 1.07 × 10^{30} m)

9.2.3 Classification by temperature, black-body radiation

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

   $\lambda_{\max} = \frac{2.9 \times 10^{-3}}{T} = \frac{2.9 \times 10^{-3}}{5800} = \mathbf{500\ nm}$

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

   $A = \frac{P}{\sigma T^4} = \frac{6{,}81 \times 10^{27}}{5.67 \times 10^{-8} \times 7800^4} = \mathbf{3.24 \times 10^{19}\ m^2}$

3. The peak wavelength of the star is around 0.6 μm

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

   $T = \frac{2.9 \times 10^{-3}}{0.6 \times 10^{-6}} = 4833$ K

   $A = 4\pi$ [illegible] $\times \pi \times (645000 \times 10^3)^2 = 5.23 \times 10^{18}$ m²

   $P = \sigma A T^4 = 5.67 \times 10^{-8} \times 5.23 \times 10^{18} \times 4833^4 = \mathbf{1.62 \times 10^{26}\ W}$

9.2.4 Principles of the use of stellar spectral classes

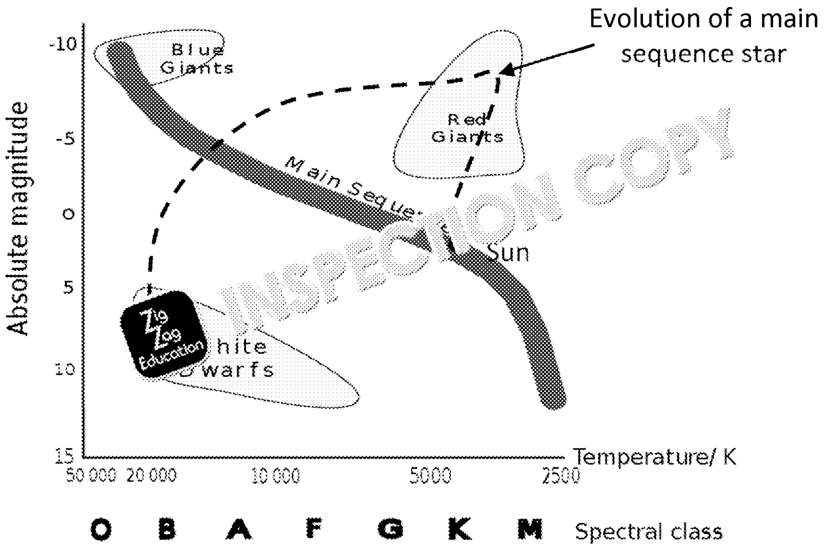
1.

Spectral class	Intrinsic colour	Temperature/ K	Prominent lin
O	Blue	25,000–50,000	He^+,
B	**Blue**	**11,000–25, 000**	**He**
A	**Blue – white**	**7,500–11,00**	H (stro Ionised
F	White	6,000–7,500	**Ionised**
G	**Yellow – white**	**5,000–6,000**	Ionised an me
K	Orange	**3,500–5,000**	Neutral
[illegible]	**Red**	< 3,500	**Neutral m**

2. Hydrogen Balmer lines come from the wavelengths absorbed by electrons in hy
   Absorption lines give information on the composition of stars.

9.2.5 The Hertzsprung–Russell (HR) diagram

1.



2. Marked S above.

3. Formation – interstellar gas and dust coalesce until gravitational pressure is en
those required for fusion.
Main sequence – hydrogen fuses into helium. Fusion energy balanced by gravit
Red giant – hydrogen used up in core, hydrogen in outer layers fuses. Outer lay
and higher luminosity.
White dwarf – fuel runs out, fusion stops and only residual heat left. Loses oute

9.2.6 Supernovae, neutron stars and black holes

1. A supernova is the **incredibly bright death of a massive star**.
When large stars run out of **fuel**, gravity overcomes energy from fusion and the
increase pressure and there is a sudden burst of fusion, resulting in a **huge**

2. a) All type 1a supernovae reach the **same maximum absolute magnitude** (-
From the **relation between absolute and apparent magnitude** the dista

b) Maximum **apparent magnitude** is around -3.4 (from graph)
Maximum **absolute magnitude** for type 1a supernovae is -19.3

$$m - M = 5\log_{10}\frac{d}{10}$$

$$d = 10 \times 10^{\frac{m-M}{5}} = 10 \times 10^{\frac{-3.4+19.3}{5}} = 15.1\text{ kpc}$$

c) Furthest type 1a supernovae seem to have accelerating recessions. This im
universe is accelerating. This requires a driving force – 'dark energy'.

3. a) After large supernovae eject most of their mass, they leave behind a dense
between 1.4 and 3 solar masses, electrons and protons are forced together
largely comprised of neutrons.

b) $m_N = 1.5 \times m_S = 1.5 \times 1.99 \times 10^{30} = 2.985 \times 10^{30}\text{ kg}$

$$\rho_N = \frac{m_N}{V_N} = \frac{m_N}{\frac{4}{3}\pi r^3}$$

$$r = \sqrt[3]{\frac{m_N}{\frac{4}{3}\pi\rho}} = \sqrt[3]{\frac{2.985\times10^{30}}{\frac{4}{3}\pi\times2.3\times10^{17}}} = 14.6 \times 10^3\text{ m}$$

4. a) The event horizon of a black hole is the point from which nothing can esca

b) $R_s \approx \frac{2GM}{c^2} = \frac{2\times6.67\times10^{-11}\times1.99\times10^{30}}{(3\times10^8)^2} = 2.95 \times 10^3\text{ m}$

9.3.1 Doppler effect

1. a) The light has been blue-shifted (the wavelength is shorter). This means that the star is moving towards Earth.

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

   $v = -\frac{\Delta\lambda c}{\lambda} = -\frac{-2\times10^{-2}\times3.00\times10^{8}}{21\times10^{-2}} = 2.86\times10^{7}\ \text{m s}^{-1}$

   c) $z = -\frac{v}{c} = -\frac{2.86\times10^{7}}{3.00\times10^{8}} = -0.0$[illegible]

2. Period [illegible] × 2[illegible] × 60 $= 7.26\times10^{6}$ s

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

   $v_1 = -c\frac{\Delta\lambda_1}{\lambda} = -3\times10^{8}\times\frac{184.9496-184.9499}{184.9499} = 487\ \text{m s}^{-1}$

   $v_2 = -c\frac{\Delta\lambda}{\lambda} = -3\times10^{8}\times\frac{184.9500-184.9499}{184.9499} = -162\ \text{m s}^{-1}$

   $R_1 = \frac{v_1 T}{2\pi} = \frac{487\times7.26\times10^{6}}{2\pi} = 5.63\times10^{8}\ \text{m}$

   $R_2 = \frac{v_2 T}{2\pi} = \frac{162\times7.26\times10^{6}}{2\pi} = 1.87\times10^{8}\ \text{m}$

   $R_{Total} = R_1 + R_2 = (5.63+1.87)\times10^{8} = 7.50\times10^{8}\ \text{m}$

9.3.2 Hubble's law

1. **Increasing red shift of stars at further distances** implies an **expansion of sp** be assumed to be from a single point in space in the early universe which all ma

   The **cosmic microwave background** is a low-level radiation that permeates **remaining energy** from the enormous expansion in the Big Bang.

   The **abundance of el**[illegible] the universe (73 % hydrogen, 25 % helium, 2 % closely to the **al**[illegible] **expected from a short, high-energy period** of matt

2. $v = Hd$

   $z = \frac{v}{c}$

   $v = zc$

   $d = \frac{v}{H} = \frac{zc}{H} = \frac{0.081\times3.00\times10^{5}}{65} = \mathbf{374\ Mpc}$

3. $H = \frac{v}{d}$ and $v = \frac{d}{t}$ so $H = \frac{1}{t}$

   $t_{Universe} = \frac{1}{H} = \frac{1}{65\times10^{3}\div(3.08\times10^{22})} = 4.74\times10^{17}\ \text{s} = \mathbf{1.50\times10^{10}\ years}$

9.3.3 Quasars

1. Quasars are **extremely bright radio sources** and the most **distant observabl** Quasars are formed as matter falls into black holes, heating up and emitting gam

2. a) $z = -\frac{v}{c}$

   $v = -z$[illegible]

   v [illegible]

   $d = \frac{v}{H} = \frac{0.464\times3.00\times10^{5}}{65} = \mathbf{2140\ MPc}$

   b) $m - M = 5\log\frac{d}{10}$

   $M = m - 5\log\frac{d}{10} = 19.8 - 5\log\frac{2140\times10^{6}}{10} = \mathbf{-21.85}$

9.3.4 Detection of exoplanets

1. Stars are significantly brighter than any planet, and so any light given off / refle by the light from the parent star.

2. a) As an exoplanet orbits its parent star, both the star and planet **orbit a com** star. This causes the star to move backwards and forwards, resulting in a used to measure the velocity of the star.

   b) Period, $T = 2.5 \text{ years} = 7.88 \times 10^7$ s

   Linear velocity, $v = 100\ \mathrm{m\,s^{-1}}$

   $\omega = \frac{v}{r} = \frac{2\pi}{T}$

   $R = \frac{100 \times 7.88\times10^7}{2\pi} = 1.25 \times \mathbf{10^9}\ \mathbf{m}$

3. a) As the exoplanet **passes in front of the star**, light from the star is **blocked** reducing the light observed from the star.

   b) Decrease in brightness $= \left(\frac{r_{planet}}{r_{star}}\right)^2$

   $\sqrt{\text{Decrease in brightness}} = \frac{r_{planet}}{r_{star}}$

   Decrease in brightness $= 0.04\ (4\ \%)$

   $\frac{r_{planet}}{r_{star}} = \sqrt{0.04} = \mathbf{0.2}$

   i.e. the planet is one-fifth the radius of the star, twice as large as Jupiter, assu

   Sun.

Exam-style questions

Q1.1	(Positioning a telescope in space) removes refractive effects OR turbulence from atmosphere (for optical wavelengths) ✓ Allows ultraviolet and infrared wavelengths to be seen as these are absorbed by Earth's atmosphere ✓
Q1.2	Detector absorbs a photon ✓ Electron uses energy of photon to overcome binding energy and creates a curr
Q1.3	$\theta \approx \frac{\lambda}{D}$ ✓ $\theta \approx \frac{535\times10^{-9}}{2.4}$ ✓ (θ [illegible] $\times 10^{[illegible]}$ rad)
Q1.4	collecting power $\propto$ (diameter)^2 $\frac{\text{collecting power (Hubble)}}{\text{collecting power (James Webb)}} = \frac{(\text{diameter(Hubble)})^2}{(\text{diameter(James Webb)})^2}$ $\frac{\text{collecting power (Hubble)}}{\text{collecting power (James Webb)}} = \frac{2.4^2}{6.5^2}$ ✓ $\frac{\text{collecting power (Hubble)}}{\text{collecting power (James Webb)}} = 0.136$ ✓ **Assumption:** quantum efficiencies of (CCDs in) James Webb and Hubble telescopes are the same ✓
Q1.5	Magnification required, $M = \frac{2.91\times10^{-4}}{2.23\times10^{-7}}$ $M = 1305$ ✓ $M = \frac{f_o}{f_e}$ $f_o = Mf_e$ $f_o = 1305 \times 15 \times$ [illegible] f_o [illegible].7 [illegible] Total length $= f_e + f_o$ Total length $= 15 \times 10^{-2} + 195.7$ Total length $= 196$ m ✓

Q2.1	Star runs out of (hydrogen) fuel for fusion ✓ Inward gravitational forces overcome outward forces from fusion ✓ Inward rushing matter 'bounces' back from core ✓
Q2.2	$m - M = 5\log_{10}\frac{d}{10}$ $M = m - 5\log_{10}\frac{d}{10}$ ✓ $M = -2.25 - 5\log_{10}\frac{20000\div3.26}{10}$ ✓ $(M = -16.2)$

Q2.3 $m = \text{-}2.51 \log_{10} b$

$b = 10^{-\frac{m}{2.51}}$

$b = 10^{\frac{16.2}{2.51}}$ ✓

$b = 10^{6.45}$ W m^{-2}(= 2.85×10^{6} W m^{-2}) ✓

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

$L = b \times 4\pi r^2$

(Absolute magnitude measure at 10 pc)

$L = 10^{6.45} \times 4\pi \times (10 \times 3.08 \times 10^{16})$ ✓

$L =$ [illegible] $\times 10^{42}$ W ✓

Q2.4 All type 1a supernovae reach a specific absolute magnitude (-19.3) ✓ so that their distances can be easily determined and compared to other stars ✓

Q3.1 (As binary stars orbit each other) they move at different velocities ✓ so absorption lines appear with two different red shifts ✓

Q3.2 $P = \sigma A T^4$

$T = \left(\frac{P}{\sigma 4\pi r^2}\right)^{\frac{1}{4}}$ ✓

$T = \left(\frac{9.72\times10^{27}}{5.67\times10^{-8}\times4\pi\times(1.71\times6.96\times10^{8})^2}\right)^{\frac{1}{4}}$

$T = 9906$ K ✓

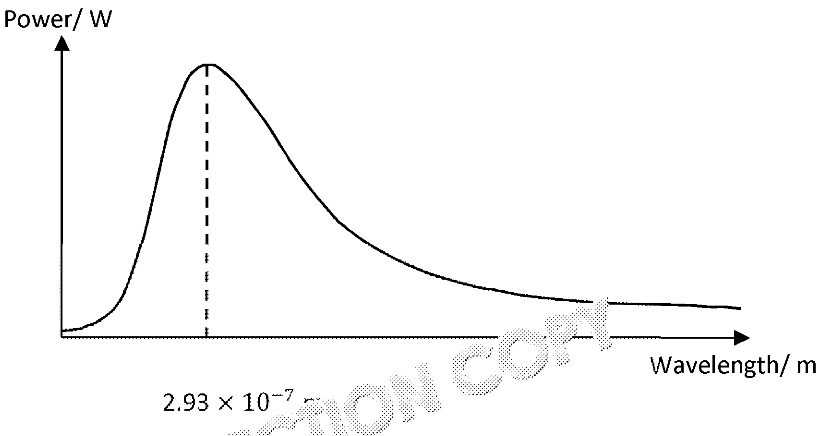
$\lambda_{\max} T = 2.9 \times 10^{-3}$ m K

$\lambda_{\max} = \frac{2.9\times10^{-3}}{T}$ ✓

$\lambda = \frac{2.9\times10^{-3}}{9906}$ ✓

($\lambda = 2.93 \times 10^{-7}$ m)

Q3.3 Correct shape ✓
Peak wavelength at 2.93×10^{-7} m ✓



Q3.4 (Main sequence star) runs out of hydrogen in core and collapses ✓
Increased pressure causes helium to fuse and the star expands (into red giant)
Eventually fuel for fusion runs out in outer layers and only hot core (white dw

Q4.1	Matter falls into black hole ✓ Matter interacts as it falls and emits radiation ✓	
Q4.2	$-\frac{\Delta\lambda}{\lambda}=\frac{v}{c}$ $v=-\frac{\Delta\lambda c}{\lambda}$ $v=-\frac{(13.3-21)\times10^{-2}\times3.00\times10^{8}}{21\times10^{-2}}$ ✓ $v=-1.10\times10^{8}$ m s^{-1} ✓ $v=Hd$ $d=\frac{v}{H}$ d [illegible] 10 [illegible] $d =$ [illegible]90 Mpc ✓	
Q4.3	A red shift of $z>1$ corresponds to a velocity $v>c$ (which is impossible) ✓ This is possible as it is the expansion of space that makes it appear as if $v>c$ ✓	
Q4.4	Quasars are some of the furthest observable objects with the highest red shift ✓ Implying the expansion of space from the Big Bang ✓	D q fu **o** re co th th