AQA Physics A-level

Topic 9: Astrophysics

Key Points

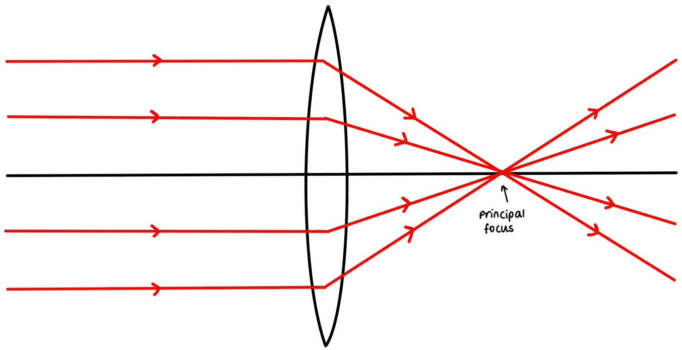
The Converging Lens

Lenses are used to change the path of light rays as they pass through, in order to **focus** or **magnify** an image. They achieve this through the process of **refraction**:

- As light passes into a **optically denser** medium, it will **slow down**
- This change in speed causes the ray to bend towards the **normal**
- When passing out of a denser medium, the light will **speed up**, causing it to bend back away from the normal

The diagram to the right, shows how rays of light are brought together at a point by a **convex lens**:

- The central black line is known as the **principal axis**
- The rays entering the lens are known as **axial rays** since they are **parallel** to the principal axis
- The point where the rays meet is known as the **principal focus**
- The distance from the centre of the lens to that point is known as the **focal length**
- The lens is assumed to be **very thin**, and the ray is only assumed to bend once in the centre of the lens

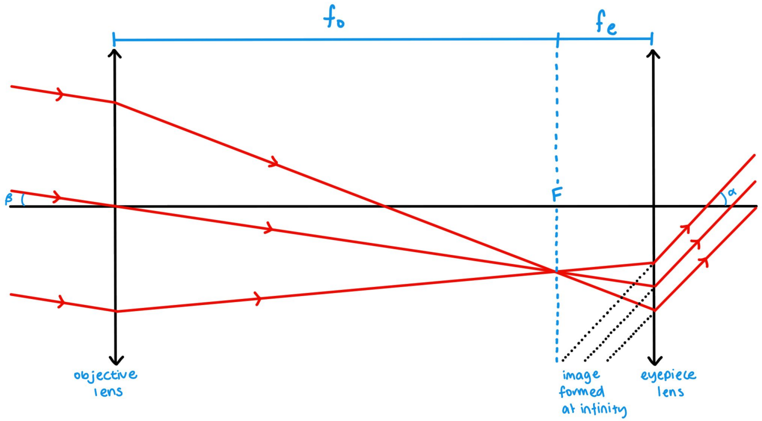


Astronomical Refracting Telescope

A **refracting telescope** is made up of **two** lenses. The **objective lens** brings light from a distant object together, and focuses it to a point on the focal plane. The **eyepiece lens** is then positioned so its **focal plane** lies on the focal plane of the objective lens. It produces a magnified image that is produced at **infinity**, and because of this, it is in **normal adjustment**.

In an exam you may be required to draw a ray diagram:

1. Draw and label the **principal axis** and the two lenses
2. Mark on the common **principal foci**
3. Add an **off-axis ray** to the eyepiece, starting from the centre of the objective lens and then draw an **intermediate image** from this ray to the common principal foci
4. Draw a **construction line** from the centre of the eyepiece to the intermediate image
5. Add two more **parallel rays** entering the objective lens and follow them through to the eyepiece so that they cross at the edge of the intermediate image
6. Continue all three rays from the eyepiece, so that they are **parallel** to the construction line



Angular Magnification

Due to the image from a telescope being formed at **infinity**, the **magnification** of the image cannot be calculated using lengths. Instead, the **angles subtended** by the object and image are used. To calculate the angle subtended by an object at a distance *d* away, and with a height *h*, you need to use the following formula:

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

Where θ is measured in radians.

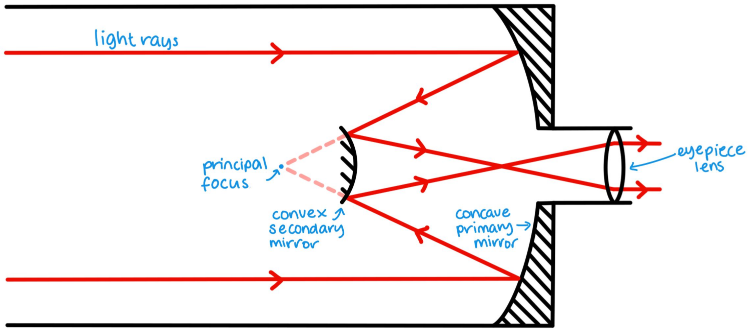
When making calculations with the above equation, you will realise that the angle subtended by the image will be **greater** than the angle subtended by the object, and hence the image is **magnified**. To calculate the **angular magnification** of an image, use the following the formula:

$$\textit{angular magnification, } M = \frac{\textit{angle subtended by image at eye}}{\textit{angle subtended by object at unaided eye}}$$

Cassegrain Telescopes

A second type of telescope you should know about, is the **reflecting telescope**. These are based on the idea that for reflection, the angle of incidence will always equal to the angle of reflection. A **Cassegrain telescope** is the type of reflecting telescope that you should be familiar with:

- **Parallel light** from a distant objects enters the telescope
- A **large parabolic reflector** focuses the light together at the principal focus
- A **convex reflector** then directs the light through the eyepiece lens which sits in a hole in the large reflector



When drawing **ray diagrams**, you should be aware of the following:

- Only two rays are required, and these are drawn parallel to the **principal axis**
- The curve of the primary mirror should look like a **continuous parabola** rather than two separate mirrors
- The rays shouldn't cross until after they hit the secondary mirror

Reflectors and Refractors

Reflecting telescopes are widely considered to be better than **refracting telescopes** for several reasons:

- Reflectors can be much **larger** than refractors since **mirrors** can be held from **behind,** whereas **lenses** can only be supported at their **edge**, as well as being likely to fracture under its own weight
- Lenses, unlike mirrors, suffer from **chromatic aberrations** - different wavelengths of light are focused onto slightly different positions, causing **different focal points** for different colours and resulting in **multi-coloured blurry edges**
- Lenses, also unlike mirrors, suffer from **spherical aberrations** too

However, it is also important to note that **reflectors** also suffer from **problems**:

- Both the **secondary mirror** and the **framework** holding it in place cause **diffraction** as light passes through, resulting in a **lower quality** image
- **Refraction** still occurs in the **eyepiece** meaning **chromatic aberration** can still occur, albeit on a lesser scale

Radio Telescopes

When making observations of the universe, the **atmosphere** can heavily affect electromagnetic waves. However, waves in the **radio wave** regions are **less** affected, and so **radio telescopes** are often used:

- A **parabolic metal surface**, known as the **reflecting dish**, reflects incoming radio waves onto an aerial
- The aerial is placed at the focal point so that no secondary reflector is needed
- Since radio waves have relatively **large wavelengths**, a **mesh** can be used for the reflecting dish, rather than a solid piece of metal
- The condition for the above to apply, is that the gaps in the mesh are less that **1/20** of the wavelength, so that they are reflected and not diffracted
- Radio telescopes generally have fairly **low resolving powers**
- **Man-made interference**, such as that from mobiles and satellites can interfere with the operation of radio telescopes, making it harder for object's to be detected
- **Linked** telescopes can help reduce issues caused by interference

Infrared and UV Telescopes

Telescopes using different regions of the electromagnetic spectrum are also used. The first type you should be familiar with are **infrared telescopes**:

- Large **concave mirrors** are used to focus radiation onto a **detector**
- Since all objects emit **infrared radiation**, infrared telescopes must be cooled to almost **absolute zero**
- The cooling process is achieved by using a **cryogenic fluid** such as **liquid nitrogen** or **hydrogen**
- They are used to observe **cooler regions** in space but since the atmosphere absorbs most infrared radiation, they must be **launched into space** and accessed **remotely**

Ultraviolet telescopes are also used for some purposes:

- The atmosphere blocks UV radiation with wavelengths less than **300nm** and so UV telescopes must also be positioned **in space**
- They use the **Cassegrain configuration** in order to focus the radiation
- The rays are detected by **solid state devices** that make use of the **photoelectric effect** to convert **UV photons** into electrons that pass around a circuit
- UV telescopes are used to observe **interstellar medium** and **star formation regions**

Large Diameter Telescopes

In general, **large diameter telescopes** are regarded as being **superior** to smaller diameter telescopes. There are **two** main advantages that you should be aware of:

1. They have a **greater collecting power**, resulting in brighter images
2. They have a **better resolving power,** resulting in clearer images

The **collecting power** of a telescope is the **rate** at which **useful energy** is taken in by a telescope. It is dependant on the area of the **collecting surface**, which is normally taken to be the area of the primary mirror or objective lens. In general, it is known as the telescope's **aperture.** You should understand the significance of a telescope's collecting power:

- The area of a circle = $\pi(d/2)^2$ and the so collecting power is **proportional** to the square of the diameter
- A greater collecting power allows **fainter objects** to be seen more easily
- **Doubling** the diameter of a telescope's aperture, means a given object can be seen from **twice** the distance it previously could been seen from

The Rayleigh Criterion

The **resolution** of a telescope is a measure of how much a **detail** a telescope can produce. When light enters a telescope, **diffraction** occurs and the resolution of the image produced is **reduced**.

The **resolving power** of a telescope is a measure of its ability to produce **separate** images of **close-together** objects. Whether the two objects will be resolved is determined by the **Rayleigh criterion**:

- The **diffraction** of light as it enters forms a **target-like** diffraction pattern consisting of a **central maximum** surrounded by circular fringes made up of dark rings known as the **minimum diffraction rings**
- **Rayleigh's criterion** states that two objects **won't** be resolved if any part of either of their central maximums falls within the **first** minimum diffraction ring of the other object

Using the equation for a circular diffraction pattern, allows the **minimum angular separation** to be calculated:

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

The **smaller** the angle, the greater the **detail** of the image that is produced, and so the better the **resolution**.

Problems with Resolving Power

If a question asks you to calculate the **resolving power** for a given situation, you need to calculate θ. This angle is therefore often known as the **minimum angular resolution of the telescope**. There are several common problems that you should be aware of that are related to resolving power:

- Power is usually measured in Watts, however in this case it is an angle that is being calculated and so the unit of **radians** must be used instead
- The aperture diameter and the wavelength must have **consistent units** before being used in calculations
- The angle calculated is only a **theoretical** and **minimum** value - in practice, especially at **shorter** wavelengths, this value is less useful due to effects such as **refraction** and **diffraction**

Charged-Coupled Devices

Telescopes often project the images they produce onto a **charged-coupled device**, to convert it into an easily viewed and processed image. You should be able to compare a **CCD** to the **human eye**:

- Photons of light are incident on a **silicon layer** in the CCD, which causes **electrons** to be liberated
- These electrons are then trapped by the **pixels' potential wells**, and then values of **charge** are measured to form an image
- Whereas for CCDs, most photons will cause an electron to liberated (**high quantum efficiency**), the human eye has a much **lower quantum efficiency** for **low-light** regions, as well as losing colour, meaning CCDs are much more **effective** in low-light scenarios
- A simple comparison between the number of pixels/light sensitive cells per unit area suggests that CCDs and the human eye have **similar resolutions**
- CCDs also allow for **remote viewing**, **long exposure times**, detection of waves outside the visible region and **computer analysis**

The Apparent Magnitude Scale

The **apparent magnitude scale**, in its most basic form, is a measure of the **brightness** of a star as viewed from Earth:

- This basic definition avoids the problems relating to **non-visible** parts of the spectrum, that terms like luminosity and intensity have
- **Luminosity** is the total power that the star radiates and **intensity** is the power per unit area reaching the observer - neither of these depend on just visible light and so can't be used as a pure measure of brightness
- Stars may appear **brighter** because they are **closer** to Earth
- Stars may have a higher apparent brightness since they are emitting more of their radiation in the **visible light region**

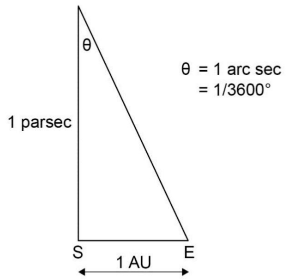
Further developments on the brightness of stars and the apparent magnitude scale later led to the following conclusions:

- There is a **negative relationship** between intensity and apparent magnitude
- There is a **2.51 ratio** for an apparent magnitude difference of 1
- The **sun** is the brightest visible star on Earth and has an apparent magnitude of **-26**

Units of Distance

Due to the vast scale of the distances between bodies in space, standard distance units such as those used on Earth aren't practical. This led to the rise of several types of **Astronomical distances**:

- A **light year** is the distance that a photon of light will travel through a **vacuum** in the period of a year - in metres, 1ly = 9.46×10^{15} m.
- The **Astronomical Unit** (AU) is the **average** distance between the Sun and Earth - in metres, 1AU = 1.5×10^{11}m
- The **parsec** is the distance at which 1AU subtends an angle of 1 arc second
- 1pc ≈ 3.26 ly



Absolute Magnitude

A star's **apparent magnitude** is unable to tell you much about the properties of the star, unless you know how far away it is. This leads to the definition of a star's **absolute magnitude**:

- A star's absolute magnitude is the apparent magnitude that the star would have, at a distance of **10 pc**
- It is a measure of **inherent brightness** and both the apparent and absolute magnitudes lie on the same **logarithmic scale**
- Apparent magnitude is represented by 'm' and absolute magnitude is represented by 'M'

Absolute and apparent magnitudes can be related using the following equation:

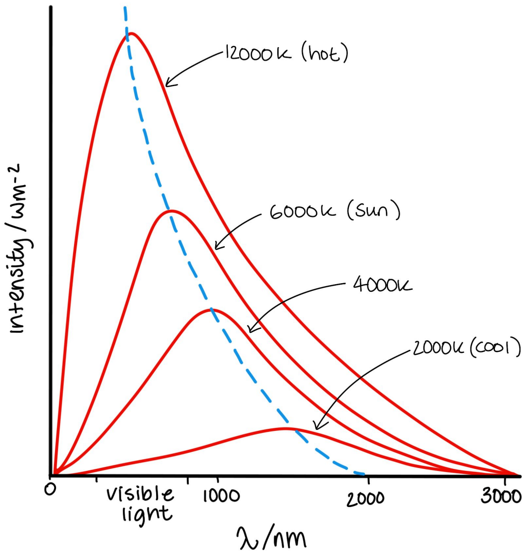
$$m - M = 5 \log (d/10)$$

This equation leads to a few useful conclusions:

- Stars **closer** than 10pc have a **brighter** apparent than absolute magnitude
- Stars **further** than 10pc have a **dimmer** apparent than absolute magnitude
- If the apparent and absolute magnitudes are **equal**, the star is 10pc away

Black Bodies

A black body is one that absorbs **all** wavelengths of EM radiation that is incident upon it. The radiation emitted by a black body depends on temperature:



- The **hotter** the object, the **shorter** the wavelength at which it has its **intensity peak**
- **Stars** are assumed to act like black bodies
- **Hotter** stars will emit more light at the **blue/violet** end of the spectrum
- **Cooler** stars will emit more light at the **red** end of the spectrum

The **peak wavelength** and **temperature** of a body is governed by **Wien's displacement law**:

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

Stefan's Law

Another law that you should be familiar with is **Stefan's Law**. This relates a star's **total power output** to its **surface area** and **temperature** as follows:

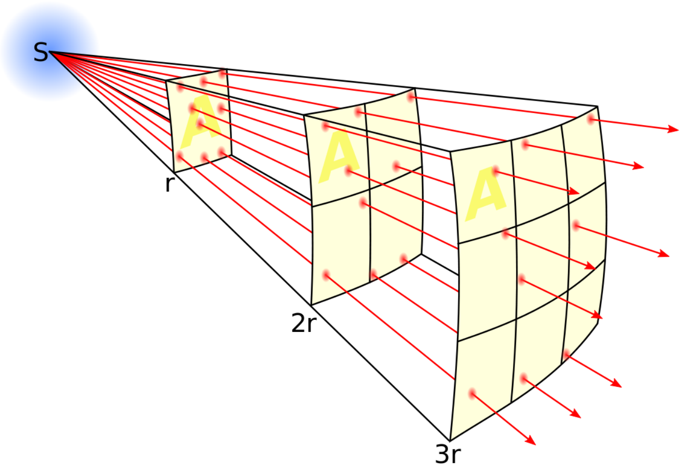
$$P = \sigma A T^4$$

- P is the star's total power output measured in W
- A is the star's surface area measured in m^2
- T is the the star's temperature measured in K
- σ is Stefan's constant

$$\sigma = 5.67 \times 10^{-8}\ Wm^{-2}K^{-4}$$

The Inverse Square Law

Any quantity that quarters when the distance doubles follows an inverse square law



Absorption Spectra

When light passes through a **gas**, certain wavelengths of light are absorbed. This same process occurs when the light from a star passes through the **atmosphere**, and results in **gaps** in the spectrum of light that a star emits. This is known as an **absorption spectrum**:

- Different wavelengths of light have different frequencies determined by **$c=f\lambda$**
- Different frequencies means that different photons have different energies determined by **$E=hf$**
- **Electrons** in the gases in the atmosphere absorb the photons that have the correct amount of energy to excite them to a higher **discrete energy level**, but can't absorb photons that don't have the correct energy
- This results in certain wavelengths being absorbed, and the rest passing straight through, forming a spectrum with **absorption lines**

The absorption spectra from **stars** can be analysed to determine their **properties**.

Stellar Spectral Classes

Star types can be grouped into spectral classes based on their temperature. Each class is labelled with a letter and they are as follows:

A useful mnemonic for the order is: 'Oh Be A Fine Girl, Kiss Me!'

- O: 25,000K -50,000K
- B: 11,000K - 25,000K
- A: 7500K - 11,000K
- F: 6000K - 7500K
- G: 5000K- 6000K
- K: 3500K - 5000K
- M: <3500K

The **temperature** of a star determines the **prominent absorption lines** present in its **absorption spectra** since temperature affects the energy of the star:

- At **low temperatures** there may be insufficient energy to **break molecular bonds** or **excite atoms**
- At **high temperatures** there is an excess of energy and so there is too much energy to form molecules, but enough for **ionisation** to take place

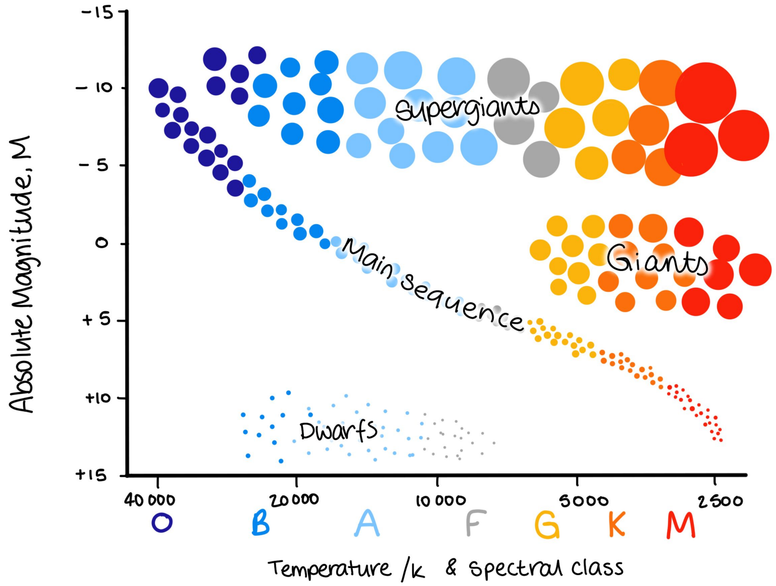
The Hydrogen Balmer Series

The **hottest** stars have an abundance of hydrogen and helium in their atmospheres and so the spectral lines from these elements tend to dominate. This gives rise to the **Hydrogen Balmer series**:

- **Hydrogen Balmer lines** are absorption lines that are produced as a result of the **excitation** of electrons from the **n=2** state of **hydrogen** atoms
- The lines are **most prominent** in **class A** stars since at these temperatures there is a large amount of hydrogen in n=2 state
- Classes **O** and **B** have **weaker** lines since most of the hydrogen in these classes is **ionised** due to the very high temperatures
- Class **F** is quite cool so it is unlikely that hydrogen is excited, meaning the lines are weak
- For classes **G**, **K** and **M**, the temperatures are **too low** for excitation to occur and so there are **no**, or extremely weak, Balmer lines

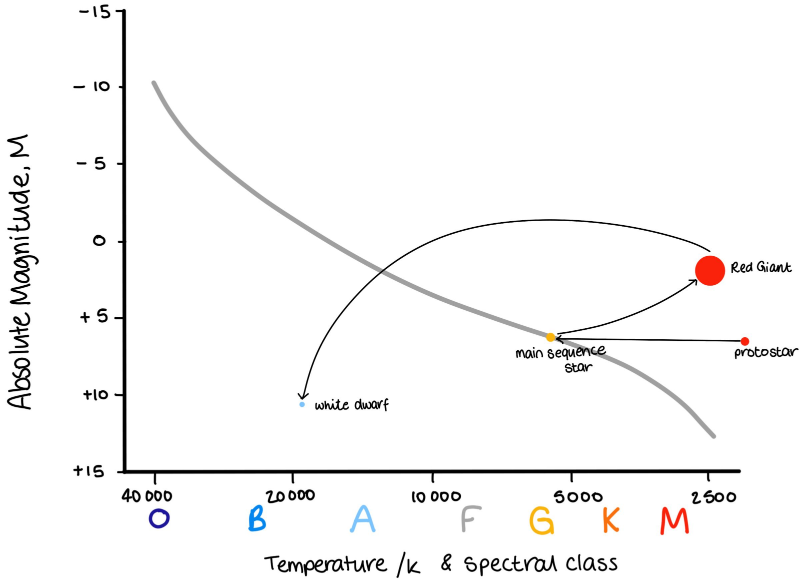
The Hertzsprung-Russell Diagram

The Hertzsprung-Russell diagram is a plot of the absolute magnitude of a star to its temperature or spectral class:



The Sun

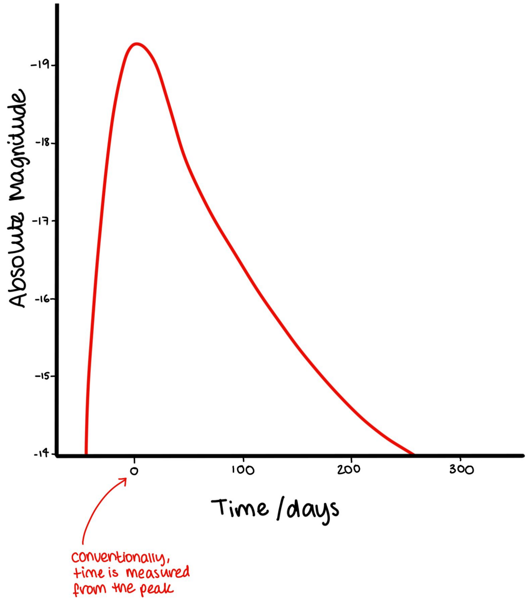
You can plot the evolution of a star using a **H-R diagram**. You should be able to do this for the **sun**, and understand the processes that it undergoes in its **evolution**:



- The sun currently has an **absolute magnitude of 5**, and is in spectral **class G** - this means it is a **main sequence star**
- As it uses up hydrogen, the hydrogen in its outer regions will fuse, causing the star to **expand** and become a **red giant**
- As it continues to use up fuel, it will **collapse**, causing an increase in **temperature** and **pressure** which will induce **helium fusion**
- Following this, **helium shell fusion** will begin to occur, once again causing the sun to expand
- Over time the outer material will be expelled and only the extremely hot but small core will be left - this is known as **white dwarf**
- Once all fusion processes have stopped, the white dwarf will cool to become a **black dwarf**

Supernovae

A **supernovae** is an object that undergoes a very quick and very large **increase** in its absolute magnitude. You should be familiar with the nature of type 1a supernovae:



- They result from the explosion of a **white dwarf** star
- The variation of **absolute magnitude** against **time** for a type 1a supernovae is shown to the left - this type of diagram is known as a **light curve**
- The **maximum peak value** of absolute magnitude is the **same** for **all** type 1a supernovae
- The peak value occurs at around **20 days** and is **-19.3**
- Since the peak value is always this value, type 1a are **standard candles**
- The consequence of this is that the **distance** of a type 1a supernovae can be calculated since the absolute magnitude is known and the apparent magnitude can be measured

Neutron Stars

When the sun expels its outer layer, it becomes a **white dwarf,** however for massive stars the core that is left is **too large** for this to occur. Instead, a **neutron star** is formed:

- They are believed to mainly consist of **neutrons**, although some theories suggest that they also have an outer layer of atomic nuclei and electron fluid
- Their density is estimated to be the same as **nuclear matter**
- They have a **diameter** of around **12 km**
- They spin very rapidly so that **angular momentum** is **conserved** as the **core collapses**
- Over time they **lose energy**, and so their speed of rotation will decrease
- They can act as **very strong radio sources** due to their **strong magnetic fields**

Black Holes

The biggest cores can continue to collapse and will eventually form **black holes**:

- The **escape velocity** of a black hole is **greater** than the **speed of light**
- The **Event Horizon** of a black hole is the boundary at which the escape velocity is exactly equal to the speed of light
- Anything that passes the Event Horizon cannot escape the black hole
- The **Schwarzschild radius** (R_s) is the name given to the radius of a black hole's Event Horizon
- The **density** of a black hole is proportional to the **inverse** of the **square of its mass** - this means that the larger a black hole is, the lower its density

Schwarzschild Radius

The equation for the **Schwarzschild radius** can be derived using **Newton's Law of Gravitation**:

$$\tfrac{1}{2} mv^2 = \frac{GMm}{R}$$

Kinetic Energy Lost = Gravitational Potential Energy Gained

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

Rearranging and dividing both sides by 'm'.

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

For a black hole with an escape velocity equal to the speed of light.

Doppler Effect

The **doppler effect** is the apparent change in **wavelength** of a wave, when the source moves relative to the observer:

- When the source moves **away** from the observer the wavelength will appear to **increase**
- When the source moves **towards** the observer the wavelength will appear to **decrease**

These apparent changes to wavelength consequently also result in a corresponding **change in frequency**. In the case of light, these changes mean that the **colour** of the light will visibly appear to change:

- When a light source moves **away** from the observer, the light will be shifted towards the **red** end of the colour spectrum
- When a light source moves **towards** an observer, the light will be shifted towards the **blue** end of the colour spectrum

The Doppler Equation

The **magnitude** of the wavelength shift that occurs due to the doppler effect, depends on the **relative speed** at which the source and observer are moving away or towards each other. The shift can be calculated using the below equation:

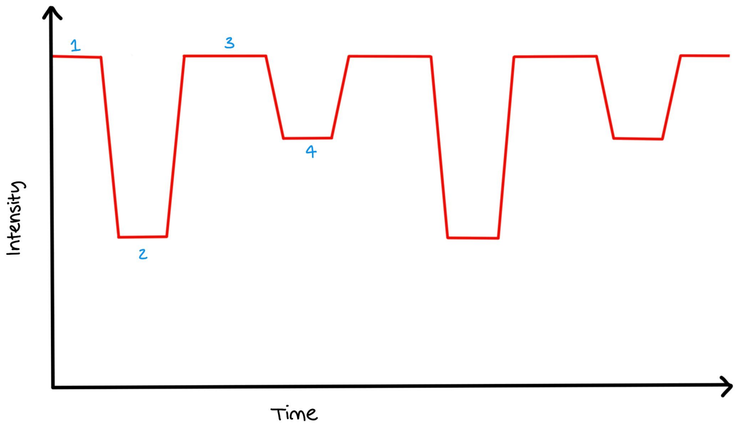
$$z = \frac{\Delta\lambda}{\lambda} = \frac{\Delta f}{f} = \frac{v}{c}$$

Where z = Doppler Shift, $\Delta\lambda$ = the change in wavelength, Δf = the change in frequency and v = the relative speed of the source and observer

You should be aware the when the source and observer are approaching each other, the relative speed should be a **negative** quantity, whereas when they are moving away from each other, the relative speed quantity should be **positive**. This means that positive z values indicate red-shift whereas negative z values indicate blue-shift.

Binary Star Systems

A **binary star system** consists of **two stars** rotating around the **same centre of mass**. You should understand the different sections of the **simplified light curve** for such a system below:



- At position **1**, the two stars are side by side and so no eclipse occurs, and the absolute magnitude is at its greatest
- At position **2**, the larger of the two stars is in front of the smaller one, resulting in all of the smaller star's light being blocked out
- At position **3**, the two stars are once again side by side and so no eclipse occurs, and the absolute magnitude is again at its greatest
- At position **4**, the smaller star is in front of the larger one and so part of the larger star's light is blocked and the intensity is at a secondary minimum

Redshift

The observation of **redshift** in the light emitted by **distant galaxies** has led to **two** key conclusions about the universe:

1. All visible galaxies show redshift, suggesting that all galaxies are **moving away** from each other
2. The more **distant** galaxies demonstrate a **greater** amount of redshift, suggesting they are moving away at a **faster rate**

These redshifts are observed by analysing the **absorption** or **emission spectra** from the light emitted by these galaxies. The positions of the absorption or emission lines are seen to be shifted towards the red end of the spectrum when redshift occurs.

Hubble's Law

Due to the observed **redshift** of distant galaxies, it is known that the further away a galaxy is, the faster it is receding. The **doppler equation** can be used to calculate the velocity that it is moving away at. **Hubble's Law** forms a relationship between the **recessive velocity** and the **distance** of a galaxy:

$$v = Hd$$

- The speed at which it is moving away, is **directly proportional** to the distance it is at
- The **constant of proportionality** in this relationship is known as '**Hubble's Constant**' and is denoted by 'H'
- $H = 65\ kms^{-1}Mpc^{-1}$

Hubble's Law suggests that the universe is **expanding**, and also supports the idea that it started from a **single point**. By dividing the distance to a galaxy by its recessional velocity, the time since it started receding can be approximated. This leads to the currently accepted **age of the universe** being around **15 billion years**.

Dark Energy

Astronomers have taken several measurements of the distance to distant **Type 1a Supernovae** and measured the **redshift** of their galaxies. They **expected** to observe that:

- The rate of expansion of the universe is **slowing down**
- The supernovae would appear **brighter** than predicted by Hubble's Law
- They weren't receding as fast as predicted

However, in **reality** they observed very different results:

- The supernovae were **dimmer** than predicted by Hubble's Law
- They were receding faster than predicted
- The rate of expansion of the universe appears to be **accelerating**

Currently there is no confirmed explanation of how the universe is expanding at an accelerating rate, but one prediction is the existence of **dark energy**. Since dark energy hasn't been observed, it is a controversial idea that is still being investigated.

The Big Bang Theory

The **Big Bang theory** is the **currently accepted** model for the origin of the universe. It states that the universe began from a single, very small, hot and dense point, from which it has **expanded**. You should be familiar with the evidence that supports this theory:

- The **redshift** observed from distant galaxies suggests that they are receding, which demonstrates that the universe is expanding as predicted
- **Cosmic Microwave Background Radiation** (CMBR) is radiation that can be observed throughout the universe - the Big Bang can explain its existence as being the result of high energy radiation produced in the big bang that has been stretched as the universe has expanded
- The Big Bang theory predicts that early fusion reactions produced helium by fusing hydrogen, before the universe cooled and expanded to leave a relative abundance of those two elements - this agrees with **observations** of nuclear matter in the universe

It is due to the magnitude of evidence supporting the Big Bang theory that it is currently accepted over other models.

Quasars

The most distant and yet most powerful observable objects in the universe are **quasars**:

- Believed to originate from **supermassive black holes** at the centre of early active galaxies
- Appear at the centre of **young galaxies** and consequently often obscure the host galaxy due to their **brightness**
- Calculations using the **inverse square law** suggest that their **power output** is the same as that of **several galaxies** combined
- From the variation in their output, they are estimated to be roughly the size of a **solar system**
- They were first observed as being **very strong radio sources**
- Later observations confirm that they emit **electromagnetic radiation** across the **whole range** of the spectrum

Exoplanets

An exoplanet is a planet that is found **outside** of our own **solar system**. The ability to observe them is a fairly new development in astrology due to a number of **issues**:

- Direct observations of exoplanets are difficult because the light they emit is usually **obscured** by the brighter **star** that they **orbit**
- **Resolving** exoplanets that are too close to their star is often beyond current **optical abilities**
- If the exoplanet and star can be resolved, they don't **reflect** much light and so will only appear very **dimly**

However, more recently methods of observing exoplanets have been developed:

- Large exoplanets with **large orbits** are easiest to observe
- **Hot** exoplanets can be viewed from the **infrared radiation** that they emit, rather than relying on the limited amount of light that they reflect
- Exoplanets that orbit **brown dwarfs** or other dimmer stars allow for easier observations
- **Masking techniques** have been developed to prevent the bright light from stars obscuring the exoplanets when being imaged

Radial Velocity Method

One method of observing exoplanets that you should know about, is the **radial velocity method**:

- The **gravitational pull** causes the star the **exoplanet** is orbiting to wobble
- This **wobble** results in a **Doppler shift** in the light it emits
- The **magnitude** of the Doppler shift, and the **direction** in which the shift occurs, is linked to the component of the star's velocity **away from** and **towards** the Earth
- The data can be analysed to calculate an approximate **distance** of how close an exoplanet is to the star
- The analysis used is similar to that of a **binary star system**

The Transit Method

Another method used to discover exoplanets it the **transit method**:

- There is a small dip in the **apparent magnitude** of a star when a planet passes in front of it
- A light curve can be plotted to show the dip in intensity as well the **period of time** that is is over
- Dips like this can also be caused by processes such as variations in the **star's output** itself as well as **sun spots**, however the observation of **repeated transits** like this, indicate the existence of an **exoplanet**