AQA Physics A-level

Section 9: Astrophysics

Notes

3.9.1 Telescopes

- **Convex/converging lens - focuses** incident light.
- **Concave/diverging lens - spreads out** incident light.
- **Principal axis -** the line passing through the centre of the lens at **90º to its surface**
- **Principal focus (F) -**
  - In a **converging** lens: the point where incident beams passing **parallel to the principal axis** will **converge**.
  - In a **diverging** lens: the point from which the light rays **appear to come from**. This is the **same distance** either side of the lens.
- **Focal length (f) -** the distance between the centre of a lens and the principal focus
  - The **shorter the focal length**, the **stronger the lens.**
- **Real image -** formed when light rays **cross** after refraction
  - Real images can be formed on a screen.
- **Virtual image -** formed on the same side of the lens. The light rays **do not cross**, so a virtual image cannot be formed on a screen.
- **Lens formula -** $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$
  - Where **u** is the **distance of the object from the centre of the lens, v** is the **distance of the image from the centre of the lens,** and **f** is the **focal length** of the lens.
- **Power of a lens -** a measure of **how closely a lens can focus a beam** that is parallel to the principal axis (in other words, how short the focal length is).
  - The shorter the focal length, the more powerful the lens.
  - In **converging** lenses this value is **positive** and in **diverging** lenses this value is **negative.**
  - Power is measured in **Dioptres (D).**
  - $P = \frac{1}{u} + \frac{1}{v} = \frac{1}{f}$

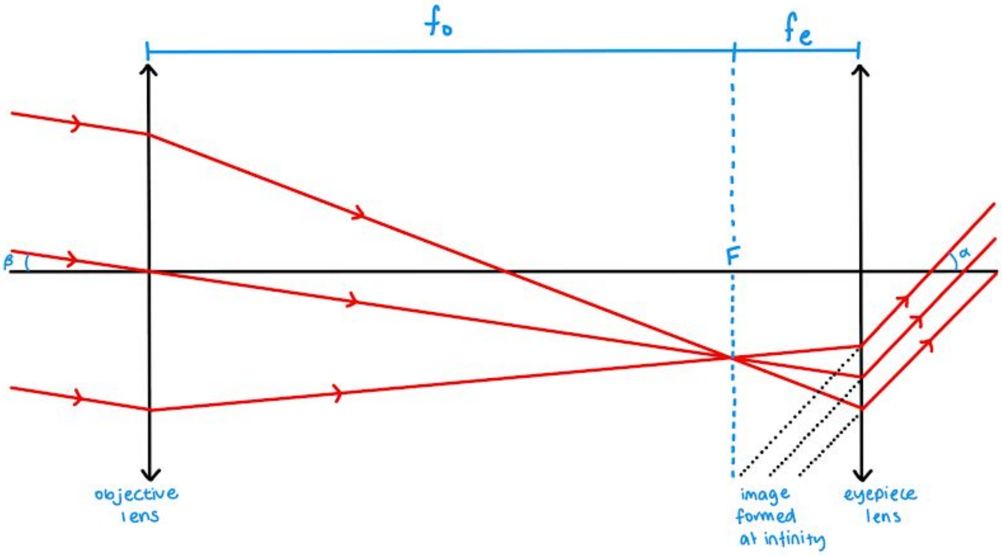
3.9.1.1 - Astronomical telescope consisting of two converging lenses

Refracting telescopes are comprised of **two converging lenses**:

- ➔ The **objective lens -** The role of this lens is to **collect light** and create a **real image** of a very distant object. This lens should have a **long focal length** and be **large** so as to **collect as much light as possible**. The **collecting power** of a telescope is directly proportional to the square of the radius of the objective lens (more on this later).
- ➔ The **eyepiece lens -** This **magnifies the image** produced by the objective lens so that the observer can see it. This lens produces a **virtual image at infinity** since the light rays are parallel. This **reduces eye strain** for the observer as they do not have to refocus every time they look between the telescope image and the object in the sky.

Normal adjustment for a refracting telescope is when the distance between the objective lens and the eyepiece lens is the **sum of their focal lengths ($f_o + f_e$)**. This means the **principal focus (F) for these two lenses is in the same place.**

Ray diagram for a refracting telescope in normal adjustment:



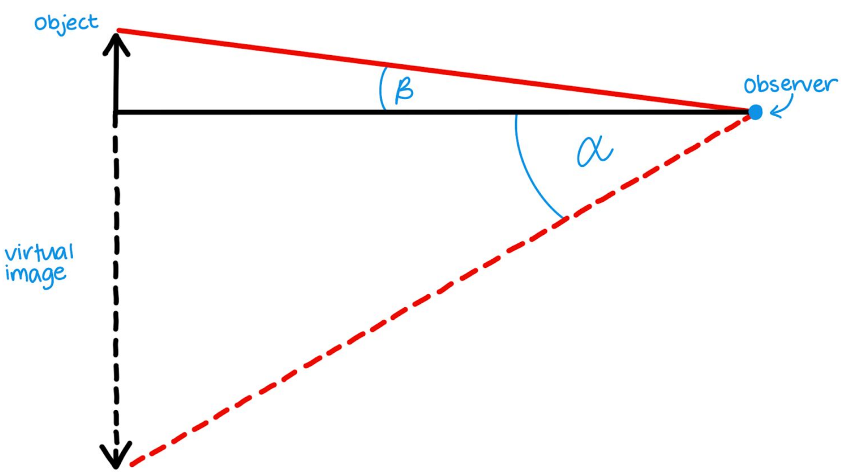
The **magnifying power** or **angular magnification, M**, of a telescope can be calculated by this formula:

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

which can also be written as $\frac{\alpha}{\beta}$.

It does not matter how you label the angles just as long as it is the **larger angle over the smaller angle**. α and β are also shown in the above ray diagram.

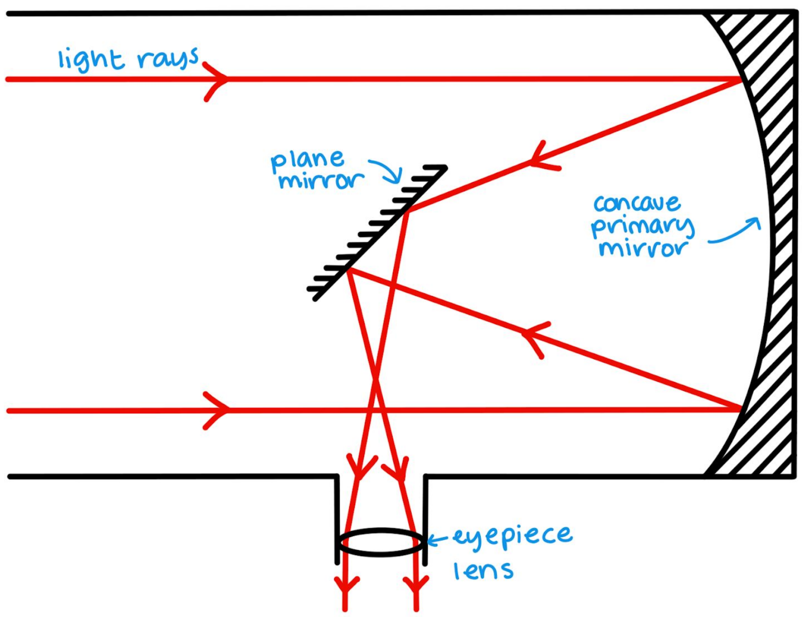
When α and β are both less than 10º, you can say $M = \frac{\alpha}{\beta} = \frac{f_o}{f_e}$



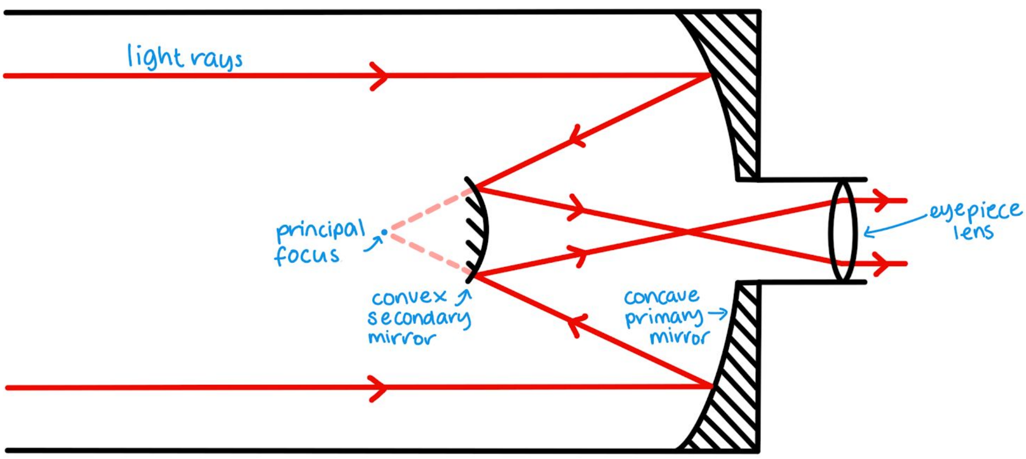
3.9.1.2 - Reflecting Telescopes

Refracting telescopes come in several configurations, but the most common of these is the **Cassegrain reflecting telescope**. This involves a **concave primary mirror** with a **long focal length** and a **small convex secondary mirror** in the centre. The convex mirror **allows the Cassegrain to be shorter** than other configurations, such as the Newtonian reflecting telescope which utilises a plane mirror instead. The light is collected and focused onto an eyepiece lens.

Newtonian Reflecting Telescope:



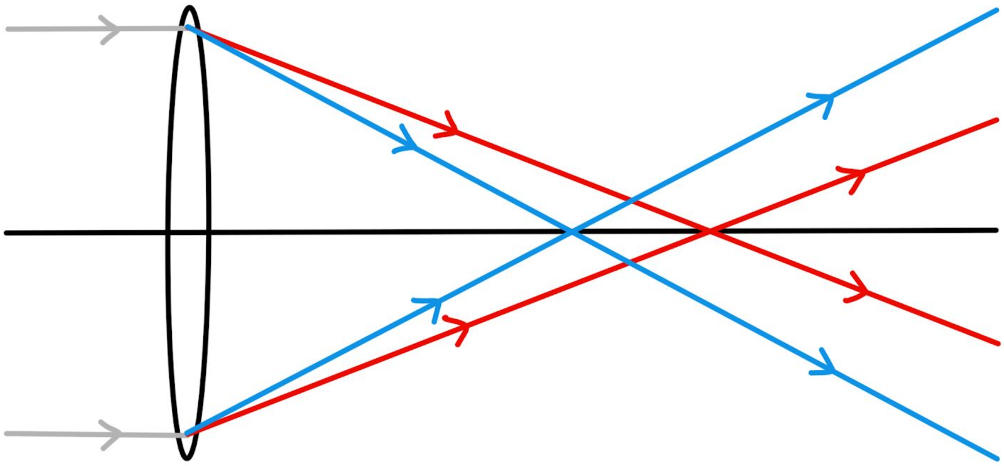
Cassegrain Reflecting Telescope:



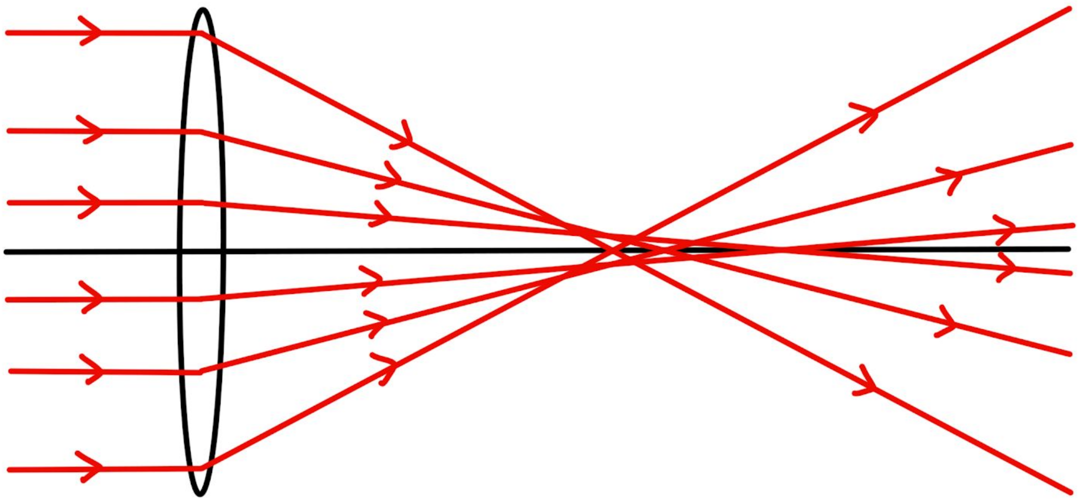
The mirrors in a reflecting telescope are actually a very thin (often **less than 25nm thick**) coating of **aluminium or silver atoms** that are deposited onto a backing material. This allows the mirrors to be **as smooth as possible** and **minimises distortions** in the image.

Chromatic aberration - for a given lens, the focal length of red light is greater than that of blue light, which means they are focused at different points (since **blue is refracted more than red**). This can cause a white object to produce an **image with coloured fringing** (coloured edges), with the effect being most noticeable for light passing through the edges of the lens.

Since chromatic aberration is caused by **refraction**, it has **very little effect on reflecting telescopes** as it only occurs in the eyepiece lens.

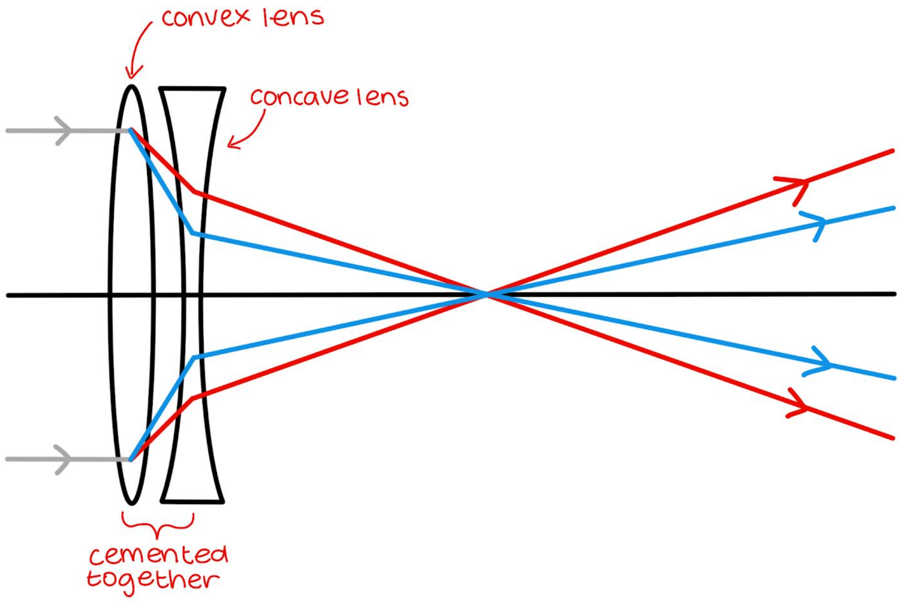


Spherical aberration - the **curvature** of a lens or mirror can cause rays of light at the edge to be **focused in a different position** to those near the centre, leading to **image blurring and distortion**. This effect is most pronounced in lenses with a **large diameter**, and can be avoided completely by using **parabolic objective mirrors** in reflecting telescopes.



Achromatic doublet - one way of minimising spherical and chromatic aberration in lenses is by using an achromatic doublet. This consists of a **convex lens** made of crown glass and a **concave**

lens made of flint glass **cemented together** in order to bring all rays of light into focus in the **same position**.



Comparing Refracting and Reflecting Telescopes -

Disadvantages of **refracting** telescopes	**Advantages** of **reflecting** telescopes
Glass **must** be pure and free from defects. Achieving this for a large diameter lens is very difficult.	Mirrors that are just a few nanometres thick can be made and these give **excellent image quality**.
Large lenses can **bend and distort under their own weight** due to how heavy they are.	Mirrors are **unaffected by chromatic aberration**, and **spherical aberration can be solved** by using parabolic mirrors.
Chromatic and **spherical aberration** both affect lenses.	Mirrors are not as heavy as lenses, so they are **easier to handle** and manoeuvre to follow astronomical objects/events.
Refracting telescopes are **incredibly heavy** and therefore can be difficult to manoeuvre.	Though **chromatic aberration** can affect the eyepiece lens, this **can be solved** by using an **achromatic doublet**.
Large magnifications **require very large diameter** objective lenses with very long focal lengths.	**Large composite primary mirrors can be made** from lots of smaller mirror segments (much like the James Webb Space Telescope - not in the specification but can give you an idea of composite mirrors).
Lenses can **only be supported from the edges**, which can be an issue when they are	Large primary mirrors are **easy to support from behind** since you do not need to be able

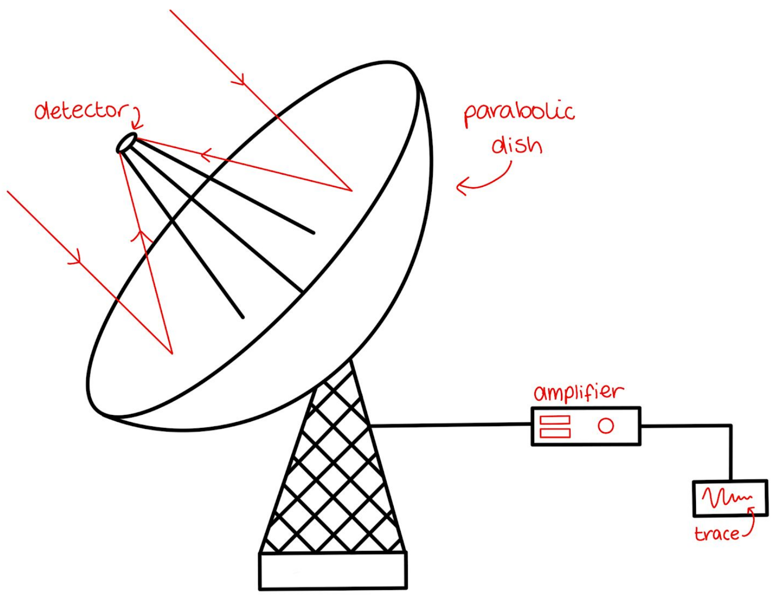
large and heavy.	to see through them.

The reasons above are why reflectors are preferred in modern telescopes.

3.9.1.3 - Single dish radio telescopes, I-R, U-V and X-ray telescopes

Telescopes can be set up to detect varying wavelengths in the electromagnetic spectrum. This can reveal images of objects that we are unable to see using only visible light and optical telescopes.

Radio telescopes use **radio waves** to create images of astronomical objects. Fortunately, the atmosphere is **transparent** to a large range of radio wavelengths (it **does not absorb them**) so it is possible to build radio telescopes that are **ground-based**. However, they should be in isolated locations so as to **avoid interference** from nearby radio sources. The simplest radio telescope uses a **parabolic dish** to focus radio waves onto a receiver.



Simple Radio Telescope

Below is a table with the similarities and differences of radio telescopes and optical telescopes:

Similarities	Differences
Both types of telescopes **function in the same way**: they **intercept and focus incoming radiation to detect its intensity**.	Since radio wavelengths are **much larger than visible wavelengths**, radio telescopes have to be **much larger in diameter** than optical telescopes in order to achieve the same quality image/have the same resolving power. As radio waves have a larger objective diameter, they also have a **larger collecting power** (explained in section 3.9.1.4).
Both radio telescopes and optical telescopes **can be moved to focus on different sources of radiation, or to track a moving source**.	Construction of radio telescopes is **cheaper and simpler** because a **wire mesh is used instead of a mirror.** As long as the mesh size is less than $\lambda/20$, radio waves will be reflected and not refracted.
The **parabolic dish** of a radio telescope (as seen above) is extremely similar to the **objective mirror of a reflecting optical** telescope.	A radio telescope must **move across an area** to **build up an image**, unlike optical telescopes.
Both optical and radio telescopes can be built on the ground (**ground-based**) since both **radio waves and optical light can pass easily through the atmosphere**.	Unlike optical telescopes, radio telescopes experience a large amount of **man-made interference** from **radio transmissions, phones, microwave ovens** etc. Optical telescopes experience interference from the **weather conditions, light pollution, stray radiation** etc.

Infrared telescopes use **infrared radiation** to create images of astronomical objects. These telescopes consist of **large concave mirrors** which focus radiation onto a detector. However, since all objects emit infrared radiation as heat, infrared telescopes must be **cooled using cryogenic fluids** (such as liquid nitrogen or hydrogen) to **almost absolute zero**. They also must be **well shielded to avoid thermal contamination** from nearby objects as well as its own infrared emissions.

Infrared telescopes are used to observe **cooler regions in space**. However, the **atmosphere absorbs most infrared radiation** so these telescopes must be launched into space and **accessed remotely** from the ground.

Ultraviolet telescopes use **ultraviolet radiation** to create images of astronomical objects. The **ozone layer blocks all ultraviolet rays that have a wavelength of less than 300nm**, meaning **UV telescopes also need to be positioned in space**. These telescopes utilise the **Cassegrain configuration** to bring ultraviolet rays to a focus. The rays are detected by **solid state devices**

which use the photoelectric effect to convert UV photons into electrons, which then pass around a circuit.

UV telescopes can be used to observe the **interstellar medium and star formation regions**.

X-ray telescopes use **X-rays** to create images of astronomical objects. Since **all X-rays are absorbed by the atmosphere**, these telescopes **need to be in space** to collect data. These rays have such high energy that using mirrors like an ordinary optical telescope would not work as they would just pass straight through. This means that X-ray telescopes must be made from a **combination of parabolic and hyperbolic mirrors**, all of which must be extremely smooth. The rays enter the telescope, skim off the mirrors, and are brought into focus on CCDs which **convert light into electrical pulses**.

Since X-rays are high-energy, they can be used to observe high-energy events and areas of space such as **active galaxies, black holes and neutron stars**.

Gamma telescopes use **gamma radiation** to create images of astronomical objects. These telescopes do not use mirrors at all as gamma rays have so much energy they would just pass straight through. Instead, they use a **detector made of layers of pixels**. As the gamma photons pass through, they **cause a signal in each pixel they come into contact with**.
These telescopes are used to observe things such as **gamma ray bursts (GRBs), quasars, black holes and solar flares**.

There are two types of GRBs:
- ➔ **Short-lived -** these last anywhere **between 0.01 and 1 second**, and are thought to be associated with merging neutron stars (forming a black hole), or a neutron star falling into a black hole.
- ➔ **Long-lived -** these can last **between 10 and 1000 seconds**, and they are associated with a **Type II supernova** (the death of a massive star - see topic 3.9.2.6).

3.9.1.4 - Advantages of large diameter telescopes

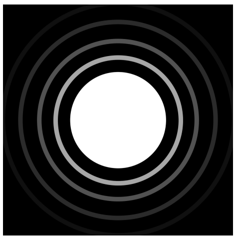
Collecting power - a measure of the ability of a lens or mirror to collect incident EM radiation. The collecting power increases with the size of the objective lens/mirror. It is **directly proportional to the area of the objective lens**.
Since area is given by $\frac{\pi d^2}{4}$, it is generally said that $collecting\ power \propto (objective\ diameter)^2$.
The **greater the collecting power**, the **brighter** the images produced by the telescope.

Resolving power - the **ability of a telescope to produce separate images of close-together objects**. For an image to be resolved, the angle between the straight lines from Earth to each object must be at least the **minimum angular resolution (θ)**, where θ is in **radians**:

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

Where λ is the wavelength of radiation and D is the diameter of the objective lens or objective mirror.

This is also known as the **Rayleigh Criterion**, which states that two objects will **not be resolved** if any part of the central maximum of either of the images falls within the first minimum diffraction ring of the other. This is related to the fact that, as light enters a telescope, it is diffracted in a target-like shape called an 'airy disc', shown in the image. The central maximum is the bright white circle in the centre, and each of the dark rings around it are the minimum rings.



Charge-coupled devices (CCDs) - an array of light-sensitive pixels, which **become charged when they are exposed to light by the photoelectric effect.**

The following features of a CCD can be compared with the human eye:

- **Quantum efficiency -** the percentage of incident photons which cause an electron to be released.
- **Spectral range -** the detectable range of wavelengths of light.
- **Pixel resolution -** the total number of pixels used to form the image on a screen. A lot of small pixels will be able to resolve an image more clearly than a small amount of large pixels.
- **Spatial resolution -** the minimum distance two objects must be apart in order to be distinguishable. This is used to observe small details.
- **Convenience** - how easy images are to form and use.

	CCD	Human eye
Quantum efficiency	~80%	4-5%
Spectral range	Infrared, UV, visible	**Only** visible light
Pixel resolution	Varies, but is ~50 megapixels	~500 megapixels
Spatial resolution	10 μm	100 μm
Convenience	Needs to be set up, but images produced are **digital**	Simpler to use as there is no need for extra equipment.

From the data above, you can see that CCDs are more useful for detecting **finer details** and producing images which can be **shared** and **stored**.

3.9.2 Classification of Stars

3.9.2.1 - Classification by luminosity

Luminosity - rate of light energy released/power output of a star

Intensity - this is the **power received from a star (its luminosity) per unit area** and has the unit, W m^{-2}. The intensity of a star follows the **inverse square law**, meaning it is inversely proportional to the square of the distance from the star. The intensity is the effective brightness of an object, though brightness is a **subjective scale** of measurement, meaning it varies depending on the observer.

The **apparent magnitude (m)** of an object is **how bright the object appears** in the sky, therefore this will depend on a star's luminosity and distance from the Earth.
The **Hipparcos scale** classifies astronomical objects by their apparent magnitudes, with the **brightest** stars given an apparent magnitude of **1**, and the **faintest visible** stars being given an apparent magnitude of **6**. The **intensity of a magnitude 1 star is 100 greater than a magnitude 6 star**.

The Hipparcos scale is **logarithmic**, as the magnitude changes by 1, the intensity changes with a ratio of **2.51**. For example, a magnitude 5 star is 2.51 times brighter than a magnitude 6 star.

3.9.2.2 - Absolute magnitude

The apparent magnitude of an object depends on its distance from the Earth, whereas the **absolute magnitude (M)** doesn't.
The **absolute magnitude (M)** of an object is what its **apparent magnitude would be if it were placed 10 parsecs away from the Earth.**

The relationship between apparent magnitude (m) and absolute magnitude (M) can be expressed by the following equation:

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

Where d is the distance in parsecs (explained below).

Parallax is the **apparent change of position of a nearer star in comparison to distant stars** in the background, **as a result of the orbit of the Earth around the Sun.** The property is measured by the **angle of parallax (θ)** (also known as parallax angle as in the diagram to the right). The greater the angle of parallax, the closer the star is to the Earth.

There are several units of distance used in astrophysics that you need to be aware of:

➔ **Astronomical Unit (AU) -** The average distance between the centre of the Earth and the centre of the Sun.

1 AU = 1.50×10^{11} **m**

➔ **Parsec (pc) -** The distance at which the **angle of parallax is 1 arcsecond (1/3600th of a degree)**. This distance can also be described as **the distance at which 1 AU subtends an angle of 1 arcsecond**.

1 pc = 2.06×10^{5} **AU =** 3.08×10^{16} **m =** 3.26 **ly**

➔ **Light year (ly) -** The distance that an EM waves travels in a year in a vacuum.

1 ly = 9.46×10^{15} **m**

To find the distance, **d** (as shown in the diagram), you can use trigonometry.

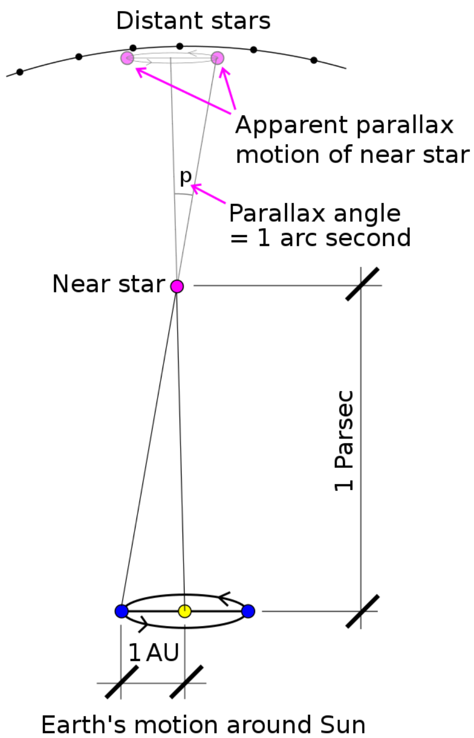
$$\tan\theta = \frac{opp}{adj} \rightarrow \tan\theta = \frac{r}{d} \rightarrow \quad d = \frac{r}{\theta}$$ As tan θ ≈ θ for small θ

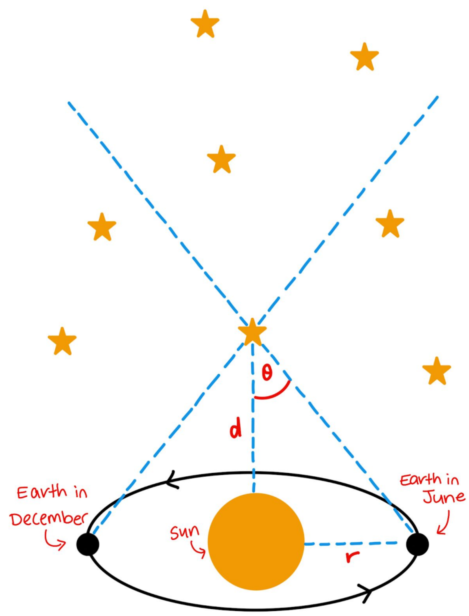
Where d and r are in metres and θ is in radians.

Using the equation above you can derive the following equation for finding d in parsecs, though note very carefully the changes in units.

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

Where d is in parsecs and θ is in arcseconds.





3.9.2.3 - Classification by temperature, black-body radiation

A **black body radiator** is a **perfect emitter and absorber of all possible wavelengths of radiation**.

- ➔ Stars can be approximated as black bodies.

Stefan's law - the power output (luminosity/P) of a black body radiator is **directly proportional** to its **surface area (A)** and its **(absolute temperature)^4**.

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

Where T is the absolute temperature and σ is the **Stefan constant** (5.67×10^{-8} W m^{-2} K^{-4}).

This law can be used to **compare** the power output, temperature and size of stars.

Wien's displacement law - the peak wavelength (λ_{max}) of emitted radiation is **inversely proportional** to the **absolute temperature (T)** of the object.
The peak wavelength (λ_{max}) is the wavelength of light released at maximum intensity.

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

Where the unit mk is **metres-Kelvin**, not milliKelvin.

Wein's law shows that the peak wavelength of a black body **decreases** as it gets hotter meaning **the frequency increases so the energy of the wave increases** (as expected).
This law can be used to **estimate** the temperature of black-body sources.

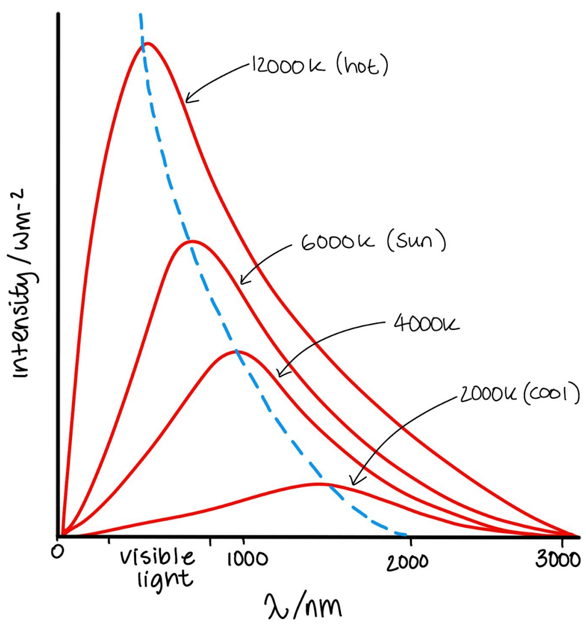
The graph to the right shows **black body curves** (graphs of intensity against wavelength of radiation emitted) for objects of various temperatures. As you can see, following Wein's law, as the temperature of the body increases, the peak wavelength decreases.

It is important to note that the intensity of light emitted by a star follows the **inverse square law**, meaning **intensity is inversely proportional to the distance between the star and the observer.**
It is assumed that light is emitted **equally in all directions** from a point, so will spread out (in the shape of a sphere).

Therefore, this can be shown in the following formula:

$$I = \frac{P}{4\pi d^2}$$

Where P is the power output by the star and d is the distance from the star.



3.9.2.4 - Principles of the use of stellar spectral classes

Stars can be classified into **spectral classes** based on the strength of absorption lines as shown in the table below. These **absorption lines are dependent on the temperature** of the star. This is because the energy of the particles which make up the star is dependent on its temperature.

Hydrogen Balmer lines are absorption lines that are found in the spectra of **O, B and A type stars**. They are caused by the excitation of hydrogen atoms from the **n = 2 state** to higher/lower energy levels. If the temperature of a star is **too high**, the majority of hydrogen atoms will become **excited to higher levels than n = 2** or electrons might even become ionised, so hydrogen balmer lines will not be present. If the temperature of a star is **too low**, the hydrogen atoms are **unlikely to become excited,** or may not be present at all, so hydrogen balmer lines will not be present.

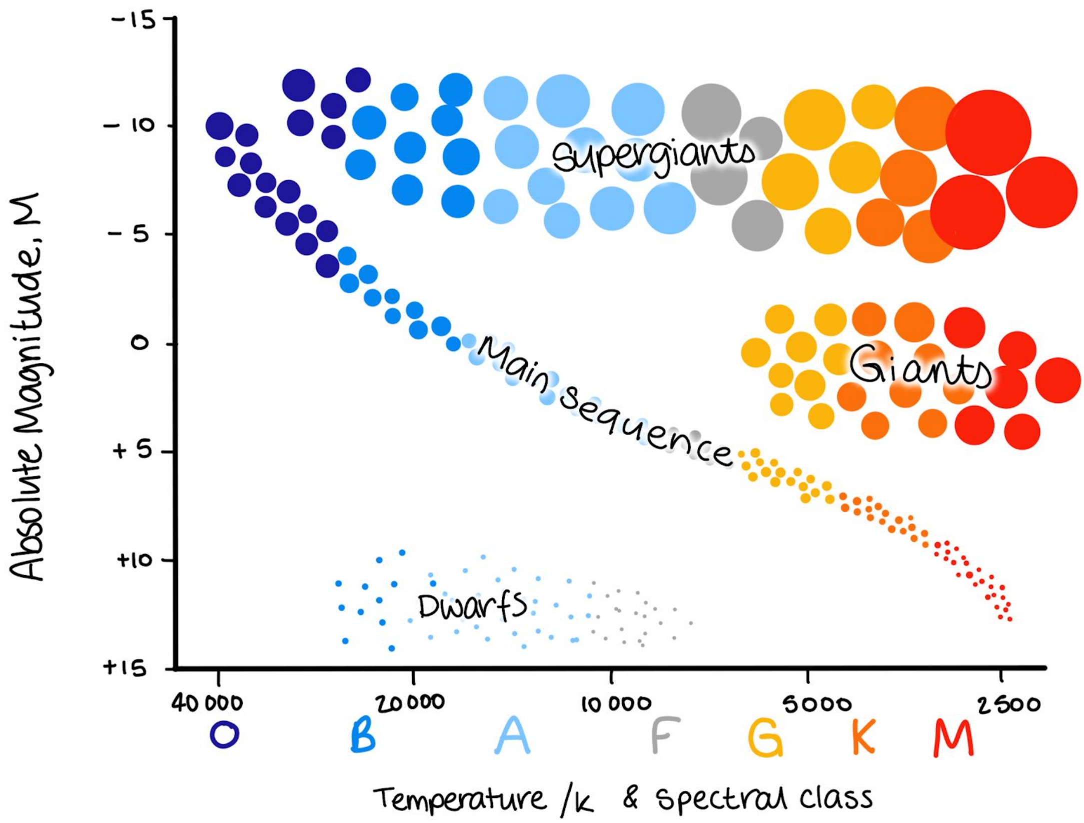
Therefore the **intensity of hydrogen balmer lines is dependent on temperature**.

Spectral Class	Colour	Temperature Range (K)	Prominent Absorption Lines	Prominence of hydrogen balmer lines
O	Blue	25 000 - 50 000	He^+, He, H	Weak
B	Blue	11 000 - 25 000	He, H	Slightly stronger than O
A	Blue/White	7 500 - 11 000	H, ionised metals	Strongest
F	White	6 000 - 7 500	Ionised metals	Weak
G	Yellow/White	5 000 - 6 000	Ionised and neutral metals	None
K	Orange	3 500 - 5 000	Neutral metals	None
M	Red	< 3 500	Neutral atoms, Titanium Oxide	None

3.9.2.5 - The Hertzsprung-Russell (HR) Diagram

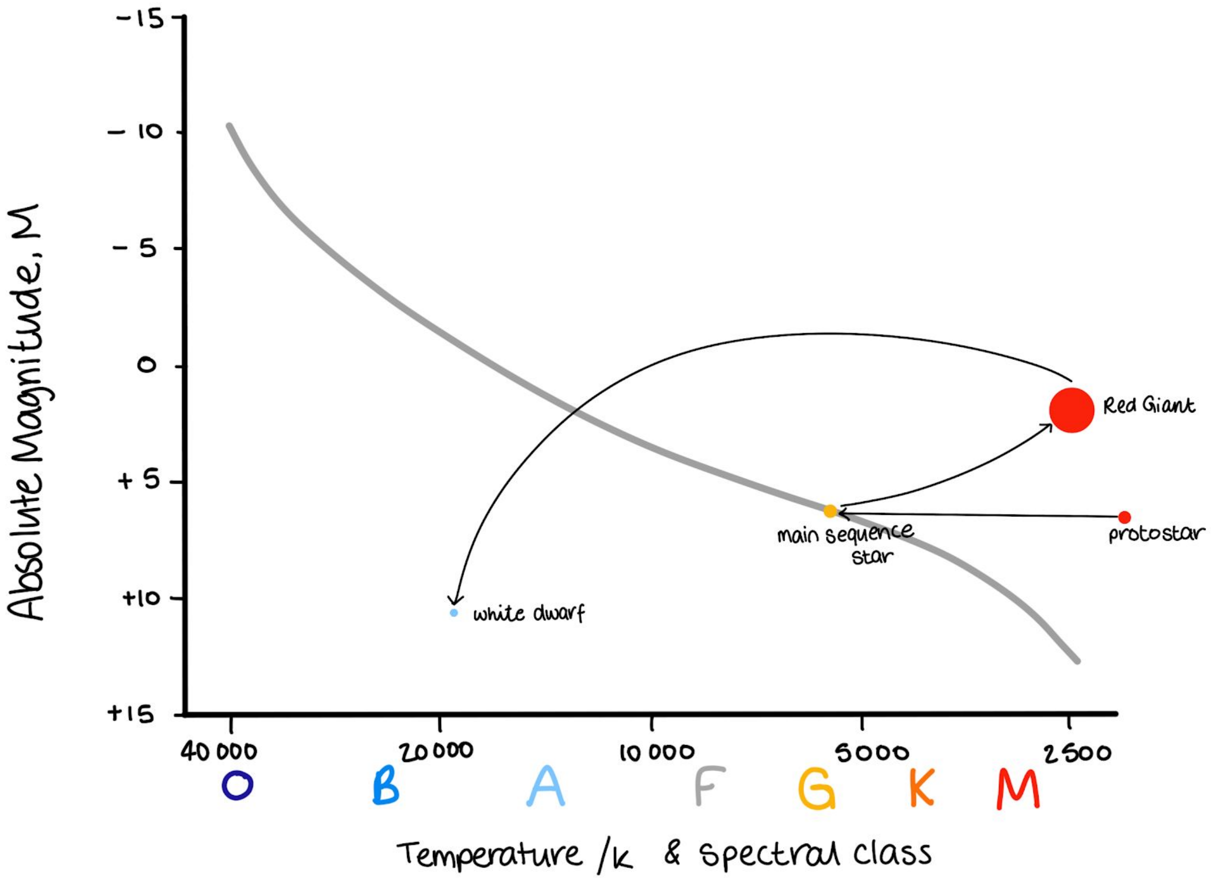
You need to be familiar with the HR diagram as shown below.
Note that the temperature scale on a HR diagram is **logarithmic** – it **halves** at every interval. The absolute magnitude scale also goes from positive at the bottom to negative at the top because the brightest stars have negative absolute magnitudes.

The **sun** is a **main sequence** star, its spectral class is **G** and its absolute magnitude is **4.83**. Using this information you can deduce where the sun would lie on the below HR diagram.



You need to be able to show the evolutionary path of a Sun-like star (labelled as "main sequence star") on a HR diagram:

1. Once the **main sequence star** uses up all the hydrogen in its core, it will move up and to the right on the HR diagram as it becomes a **red giant**. A red giant is **brighter and cooler** than a main sequence star.
2. Once the **red giant** uses up all the helium in its core, it will eject its outer layers and will move down and to the left on the HR diagram as it becomes a **white dwarf**. A white dwarf is **hotter and dimmer** than a main sequence star.



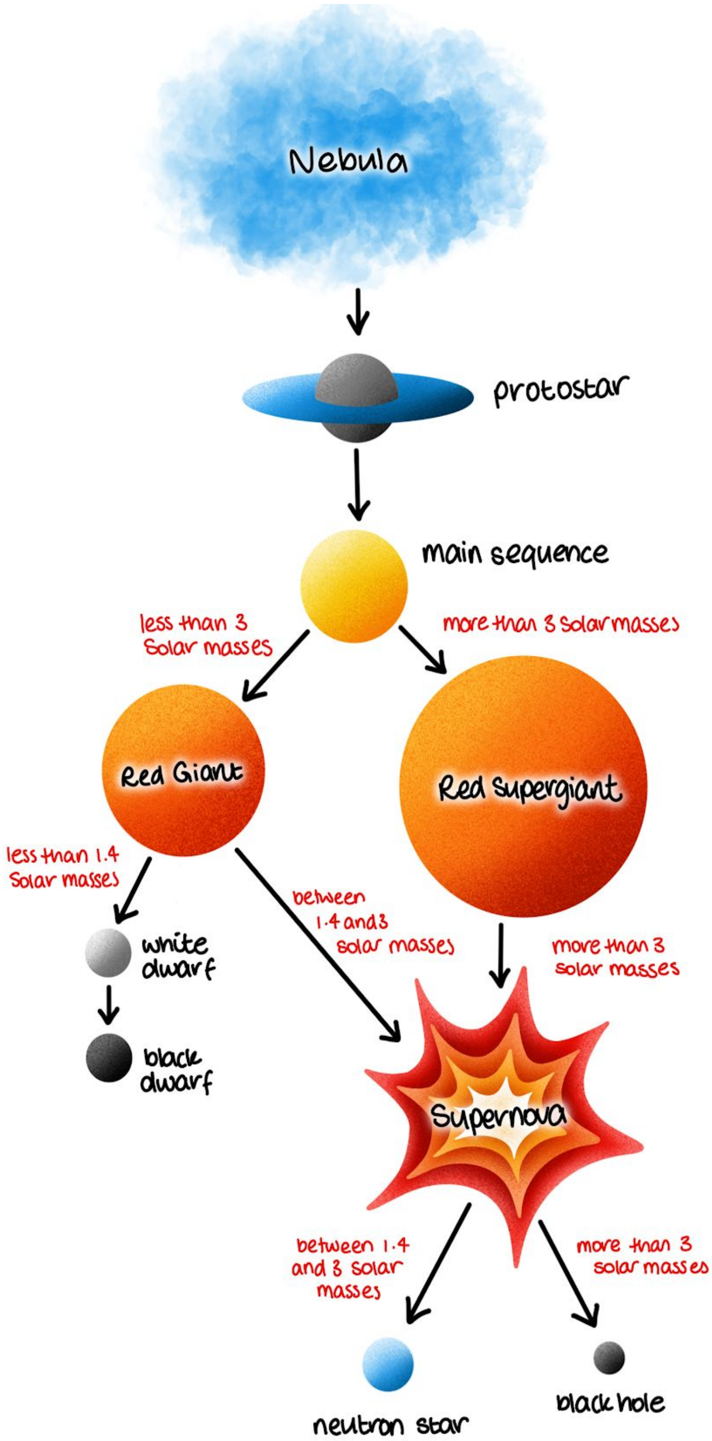
Absolute Magnitude, M
-15
-10
-5
0
+5
+10
+15
Red Giant
main sequence star
protostar
white dwarf
40 000
20 000
10 000
5000
2500
O
B
A
F
G
K
M
Temperature /K & spectral class

3.9.2.6 - Supernovae, Neutron Stars and Black Holes

One **solar mass** is the mass of the sun and is equal to 2×10^{30} **kg**.

The stages of stellar evolution:

1. **Protostar**
   - Clouds of **gas and dust** (nebulae) have fragments of varying masses that **clump together under gravity.**
   - The irregular clumps **rotate** and a gravity/conservation of angular momentum spins them inwards to form a **denser centre** – a **protostar.**
   - The protostar is surrounded by a disc of material (a **circumstellar disc**).
   - When the protostar gets hot enough, it begins to **fuse elements**, producing a strong **stellar wind** that blows away any surrounding material.
2. **Main Sequence**
   - The inward force of gravity and the outward force due to fusion are in **equilibrium** – the star is **stable.**
   - Hydrogen nuclei are fused into helium.
   - The **greater the mass** of the star, the **shorter its main sequence period** because it uses its fuel more quickly.
3. **Red Giant (for a star < 3 solar masses)**
   - Once the hydrogen runs out, the **temperature of the core increases** and begins **fusing helium nuclei** into heavier elements (E.g. Carbon, Oxygen and Beryllium).
   - The outer layers of the star **expand** and **cool.**



4. **White Dwarf (for a star < 1.4 solar masses)**
    - When a red giant has used up all its fuel, **fusion stops** and the **core contracts as gravity is now greater** than the outward force.
    - The **outer layers are thrown off**, forming a planetary nebula around the remaining core.
    - The core becomes **very dense** (around 10^8 - 10^9 kg m^{-3}).
    - A white dwarf will eventually cool to a **black dwarf.**
5. **Red Supergiant (for a star > 3 solar masses)**
    - When a **high-mass** star runs out of hydrogen nuclei, the same process for a red giant occurs, but on a larger scale.
    - The collapse of red supergiants in a supernova (see below) causes **gamma ray bursts.**
    - Red supergiants can fuse **elements up to iron.**
6. **Supernova (for a star > 1.4 solar masses)**
    - When **all fuel runs out**, fusion stops and the **core collapses inwards** very suddenly and **becomes rigid** (as the matter can no longer be forced any closer together).
    - The outer layers of the star fall inwards and **rebound** off of the core, launching them out into space in a **shockwave.**
    - As the shockwave passes through surrounding material, elements **heavier than iron** are fused and flung out into space.
    - The remaining core depends on the mass of the star.
    - A defining characteristic of a supernova is its **rapidly increasing absolute magnitude.**
    - Supernovae may release around **10^{44}** J of energy, which is the same amount of energy as the **sun outputs in its 10 billion year lifetime**.
7. **Neutron Star (for a star between 1.4 and 3 solar masses)**
    - When the core of a large star collapses, **gravity is so strong** that it **forces protons and electrons together to form neutrons.**
    - A neutron star is incredibly dense – about 10^{17} kg m^{-3} (the **density of nuclear matter**).
    - **Pulsars** are **spinning neutron stars** that emit beams of radiation from the magnetic poles as they spin (up to 600 times per second).
8. **Black Hole (for a star > 3 solar masses)**
    - When the core of a giant star **collapses**, the neutrons are unable to withstand gravity forcing them together.
    - The gravitational pull of a black hole is so strong that not even light can escape.
    - The **event horizon** of a black hole is the point at which the **escape velocity becomes greater than the speed of light .**
    - The **Schwarzchild radius** is the **radius of the event horizon**, and can be calculated using the formula:

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

Where G is the gravitational constant, M is the mass of black hole and c is the speed of light in a vacuum.

A **binary system** is one where two stars orbit a common mass.

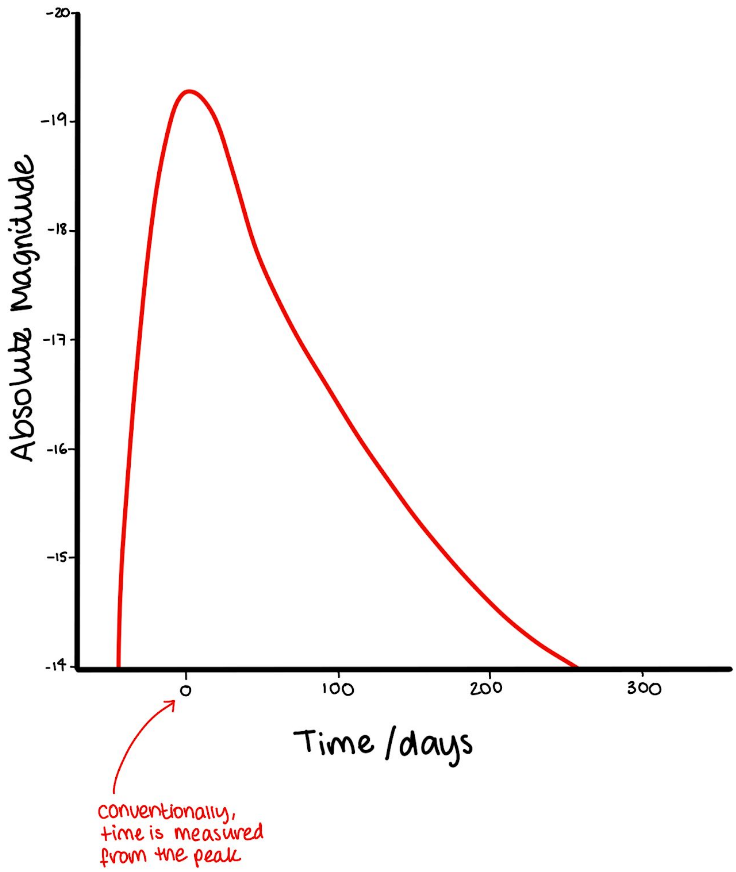
There are two types of **supernovae**:

- ➔ **Type I -**
  When a star **accumulates matter** from its companion star in a binary system and **explodes after reaching a critical mass**.
- ➔ **Type II -**
  The death of a high-mass star after it **runs out of fuel**.

A **Type 1a supernova** is a **Type I supernova with a white dwarf**. When the companion star in the binary system runs out of hydrogen, it expands, allowing the white dwarf to begin accumulating some of its mass. When the white dwarf star reaches a **critical mass**, fusion begins and becomes unstoppable as the mass continues to increase, eventually causing the white dwarf to explode in a supernova.

All types of supernovae occur at the **same critical mass**, meaning they all have a very **similar peak absolute magnitude** (about -19.3) and produce **very consistent light curves**, allowing astronomers to use them as **standard candles** to calculate distances to far-off galaxies (they can be seen up to 1000Mpc away).

Below is the light curve for a typical 1a supernova:



Scientists believe that there are **supermassive black holes** at the centre of every galaxy. This is because stars and gas near the centre of galaxies appear to be **orbiting very quickly**. They concluded that there must be a supermassive object at the centre with a **very strong gravitational field** attracting them.

Supermassive black holes can form from:

- The **collapse of massive gas clouds** while the galaxy was forming
- A **normal black hole** that **accumulated huge amounts of matter** over millions of years
- **Several normal black holes merging** together.

Hubble's law (covered in section 3.9.3.2) shows that the universe is expanding.

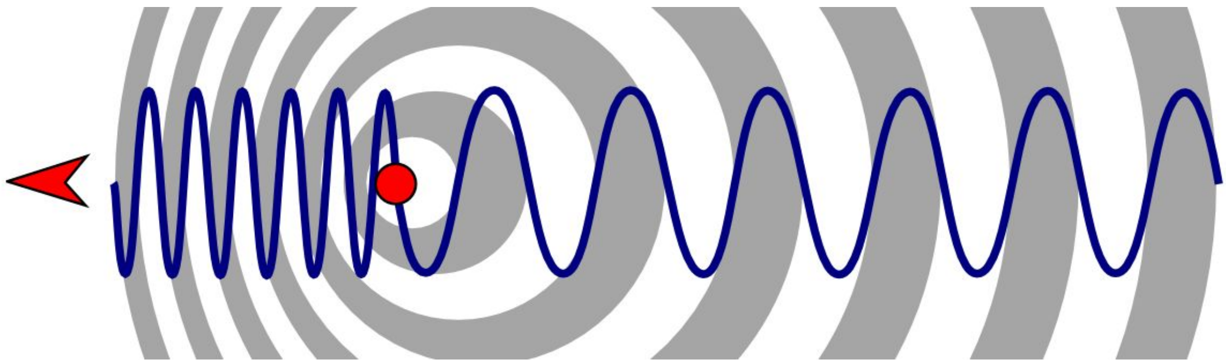
If the expansion of the universe was slowing down, **more distant objects would be observed to be receding more quickly**, since expansion was faster in the past. Note that the light from more distant objects would take longer to reach us so would appear to be in the past. Objects would also appear brighter than predicted as they would be closer than expected. However, type 1a supernovae have been seen to be **dimmer than they were expected to be**, meaning they are **more distant than Hubble's law predicted**. This suggests that **the expansion of the universe is accelerating** and it is actually older than Hubble's law estimates.

Dark energy is thought to be the reason behind the universe accelerating. It is described as having an **overall repulsive effect throughout the whole universe**. Since gravity follows the **inverse square law**, it decreases with distance. Dark energy however remains **constant** all throughout the universe, meaning it has a greater effect than gravity and is therefore **causing expansion speed to increase**.
Dark energy is **controversial** because **there is evidence for its existence but no one knows what it is or what is causing it**.

3.9.3 Cosmology

3.9.3.1 - Doppler effect

The **Doppler effect** is the **compression or spreading out of waves** that are emitted or reflected by a **moving source**. As the source is moving, the wavelengths in front of it are compressed and the wavelengths behind are spread out as shown in the diagram below. An example of the doppler effect can be heard in the sound of a car moving past you.



The Doppler effect causes the line spectra of distant objects to be shifted either towards the **blue** end of the visible spectrum when they move **towards the Earth** (**blue-shift**) or towards the **red** end of the spectrum when they move **away from the Earth** (**red-shift**).

Red-shift is used as evidence for the **expanding universe**, as distant objects are red-shifted. The more distant the object, the **greater its red-shift**.

The **red shift (z)** of an object can be calculated using the following equations:

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

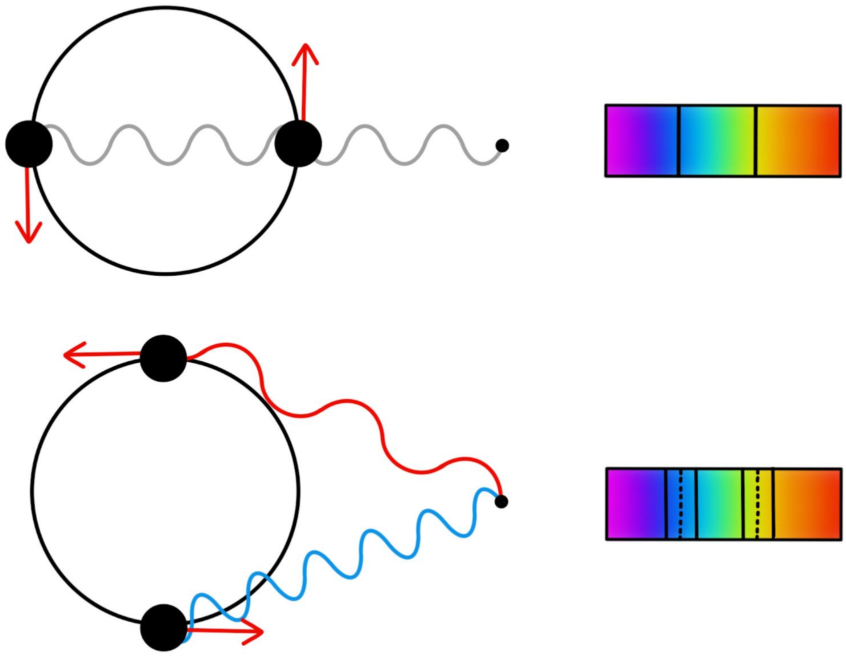
v = the object's receding velocity (m/s)
c = the speed of light in a vacuum (m/s)
Δf = the change in frequency of the emitted radiation (Hz)
f = the original frequency of the emitted radiation (Hz)
$\Delta\lambda$ = the change in wavelength of the emitted radiation (m)
λ = the original wavelength of the emitted radiation (m)

Note that this formula can **only be used when v is much smaller than c** (since the formula was derived without taking into account any relativistic effects, which occur when objects are moving close to the speed of light).

The **wavelength ratio is negative** because **wavelength is inversely proportional to frequency** – as the frequency of a wave increases, the wavelength decreases.
The **z value (also known as red shift) is positive** for **red-shift**, and **is negative** for **blue-shift**.

The Doppler effect can be used to identify **binary star systems**, where **two stars** are orbiting a **common** centre of mass. **Spectroscopic binaries** are binary star systems in which the stars are **too close to be resolved** by a telescope, meaning the only way to identify them is by using the Doppler shifts of each star.

Spectroscopic binaries being identified from the Doppler shift in their line spectra:

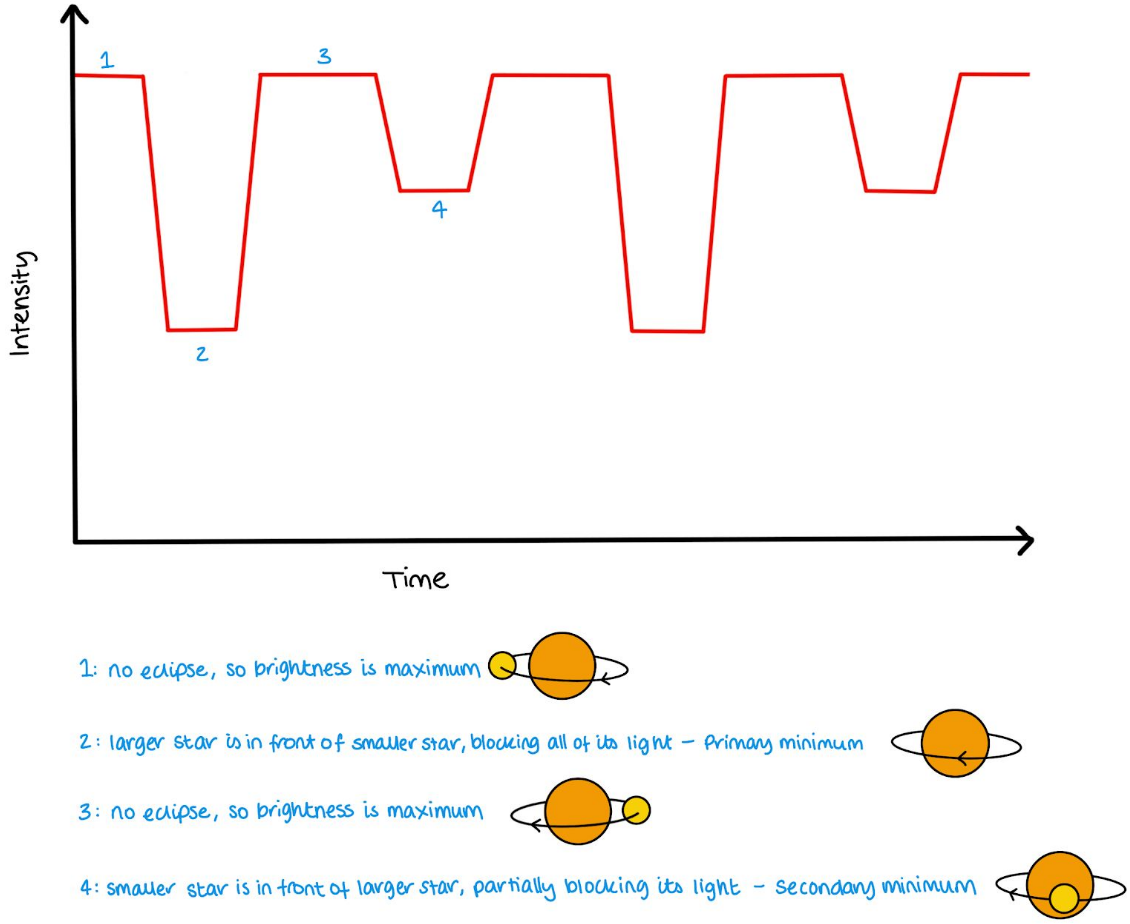


As the stars **eclipse** each other, they are travelling **perpendicular** to the line of sight from the observer, so there is **no Doppler shift** in their emitted radiation.
However, when one star is travelling away from the observer, the other is travelling towards the observer. This causes each spectral line to be **split into two**, where one is **blue-shifted** and the other is **red-shifted**.

Eclipsing binaries are when the plane of the orbit of the stars is in the line of sight from Earth to the system, meaning that the stars **cross in front of each other** as they orbit. These can be identified from their characteristic light curves as seen on the next page.

Quasars are objects which have **very large red shifts**, suggesting they are very far away, however they are also extremely bright. Using the **inverse square law**, you can show that the power output of a quasar must be around that of an entire galaxy.

Typical light curve of eclipsing binaries:



3.9.3.2 - Hubble's Law

Hubble's law states that **a galaxy's recessional velocity is directly proportional to its distance from the Earth**. It essentially states that the **universe is expanding from a common starting point**.

This can be summed up in the formula:

$$v = Hd$$

Where v is the recessional velocity (km s^{-1}), H is the Hubble constant (65 km s^{-1} Mpc^{-1}, also sometimes written as H_0), and d is its distance from Earth (**Mpc = megaparsec**)

You can use Hubble's law to **estimate the age of the universe** as follows:

1. **Rearrange** $v = Hd$ as follows:

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

2. Using **distance = velocity x time** (rearranged to $t = \frac{d}{v}$), you can equate time and the reciprocal of Hubble's constant:

$$t = \frac{1}{H}$$

3. However, for this to work, you also need to convert H to **SI units**:
   a. Multiply by 1000 **converting from km to m**

   $$65 \times 1000 = \mathbf{65\ 000\ m\ s^{-1}\ Mpc^{-1}}$$

   b. Divide by 1 Mpc (megaparsec) in metres, to **convert from parsecs to metres**

   $$\frac{65000}{3.08 \times 10^{22}} = \mathbf{2.1 \times 10^{-18}\ m\ s^{-1}\ m^{-1}}$$

   Note: **the metres cancel out** so the unit is just s^{-1}, hence the reciprocal of H gives time

4. You can now substitute your value of H in SI units, into the equation derived above.

$$t = \frac{1}{H} = \frac{1}{2.1 \times 10^{-18}} \approx 4.74 \times 10^{17}$$

5. Convert from **seconds to years**:

$$(4.74 \times 10^{17}) \div 3600 \div 24 \div 365 \approx 1.5 \times 10^{10} = 15\ \textit{billion years}$$

As the universe is currently expanding, it would be reasonable to assume that the universe began from **one point** – a **singularity that was infinitely small and infinitely hot**. The **Big Bang Theory** suggests that the universe began with a **huge explosion** from this point. When the Big Bang happened, it is thought that there was high-energy radiation everywhere, and as the universe expanded and cooled, this radiation would have lost energy and been red-shifted. The remains of this radiation is what we call **Cosmological Microwave Background Radiation (CMBR)**, which is microwave radiation that has been detected from all directions in space. This provides **evidence for the Big Bang**.

During the early stages of the Big Bang, **nuclear fusion** converted hydrogen nuclei into helium nuclei. However, this only lasted for a very short period of time before the universe cooled too much and nuclear fusion stopped. **Approximately** ¼ of all of the existing hydrogen nuclei were fused into helium, resulting in a **relative abundance ratio of H:He of 3:1**. The relative abundance by mass of different elements observed today is approximately **73% hydrogen, 25% helium and 2% everything else**. This provides **further evidence for the Big Bang**.

3.9.3.3 - Quasars

A **quasar** is an **active galactic nucleus** – **a supermassive black hole surrounded by a disc of matter** which, as it falls into the black hole, causes **jets of radiation** to be emitted from the poles. Below is an artist's impression of a particular quasar (ULAS J1120+0641).

Image source: ESO/M. Kornmesser,

Quasars are characterised by the following features:

- Extremely **large optical red-shifts**
- Very **powerful** light output
- Their size being **not much bigger than a star**

Quasars are thought to be some of the **most distant measurable objects** in the known universe. You can estimate the power output of quasars using the **inverse square law for intensity** (see topic 3.9.2.1) by using the amount of doppler shift experienced by the quasar to find their distance from Earth.

The inverse square law shows that quasars are **extremely powerful** and can have the **same energy output as several galaxies**.

The first quasar to be discovered was 3C 273, which was thought to be a dim star, but it had **much greater radio emissions than expected**. It was later found to be 26 billion light years away and **1000 times more luminous than the Milky Way**.

3.9.3.4 Detection of Exoplanets

Exoplanets are **planets that are not within our solar system**; they orbit other stars.
They can be difficult to detect directly as they tend to be **obscured by the light of their host stars**.

There are two methods of detecting exoplanets you need to know about:

- ➔ **Radial velocity method -**
  This is very similar to the method of detecting spectroscopic binaries. The star and planet orbit a **common centre of mass**, which causes the star to **'wobble'** slightly. This **causes a Doppler shift in the light received from the star** (this method is sometimes referred to as the 'wobble effect' for this reason). The effect is most noticeable with **high-mass planets** since they have a greater gravitational pull on the star. The line spectrum of the star is blue-shifted when it moves towards the Earth, then red-shifted when it moves away. This shows that there is something else near the star that is exerting a gravitational force on it – the exoplanet. The **time period (T)** of the planet's orbit is **equal to the time period of the Doppler shift**.

- ➔ **Transit method -**
  This involves observing the **intensity of the light output** of a star. If a planet **crosses in front of a star** (**'transits'**), the intensity dips slightly. If the intensity of a star dips **regularly**, it could be a sign that there is an exoplanet orbiting it. If there are variations in the regularity of the dips, there may be several planets orbiting the same star which have a gravitational effect on the transiting planet.

  The **size** and the **orbital period** of the planet can be determined from the **amount** that the intensity falls by and the **duration** of the dip respectively. However, the application of this method is limited since it **only works if the line of sight to the star is in the plane of the planet's orbit**, which is **more likely for planets with small orbits**. This is because most orbits are **inclined** (do not pass in front of the star when observed from the Earth), and smaller orbits mean that parts of the planet are more likely to cross in front of the star and block some of its light.

Typical light curve of a star with a transiting planet: