Edexcel IAL Physics A-level

Topic 5.6: Astrophysics and Cosmology

Notes

5.6 - Astrophysics and Cosmology

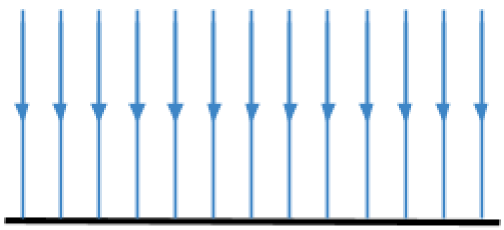
5.6.154 - Gravitational fields

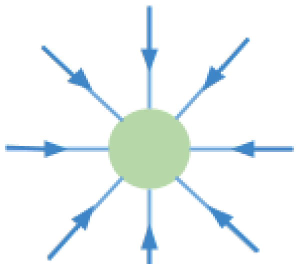
A **force field** is an area in which an object experiences a **non-contact force**. Force fields can be represented as **vectors**, which describe the direction of the force that would be exerted on the object, from this knowledge you can deduce the direction of the field. They can also be represented as diagrams containing **field lines**, the distance between field lines represents the strength of the force exerted by the field in that region.

A gravitational **field** is a **force field** in which objects with mass experience a force.

5.6.155 - Gravitational field strength

There are two types of gravitational field; a **uniform field** or **radial field**. These can be represented as the following field lines:





The arrows on the field lines show the direction that a force acts on a mass. A **uniform field** exerts the **same** gravitational force on a mass everywhere in the field, as shown by the parallel and equally spaced field lines. In a **radial field** the **force exerted depends on the position** of the object in the field, e.g in the diagram above, as an object moves further away from the centre, the magnitude of force would decrease because the distance between field lines increases. The Earth's gravitational field is radial, however very close to the surface it is almost completely uniform.

Gravitational field strength (g) is the force per unit mass exerted by a gravitational field on an object. This value is constant in a uniform field, but varies in a radial field. The general formula for calculating the gravitational field strength is:

$$g = \frac{F}{m}$$

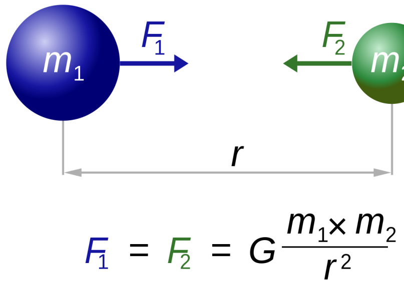
Where **F** is the force exerted on the object and **m** is the mass of the object.

5.6.156 - Newton's law of universal gravitation

Gravity acts on any objects which have **mass** and is **always attractive**.
Newton's law of gravitation shows that the magnitude of the gravitational force between two masses is **directly proportional to the product of the masses**, and is **inversely proportional to the square of the distance between them**, (where the distance is measured between the two centres of the masses).

$$F = \frac{Gm_1m_2}{r^2}$$

Where **G** is the gravitational constant, $\mathbf{m_1/m_2}$ are masses and **r** is the distance between the centre of the masses.



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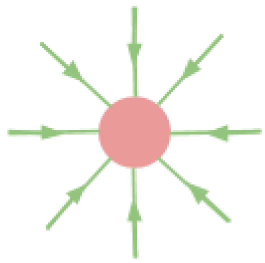
5.6.157 - Gravitational field strength in a radial field

An example of a radial gravitational field, is the one formed by a point mass.



The gravitational field strength (g) in a radial field **varies** and you can derive an equation for the gravitational field strength at a point in the field using Newton's law of gravitation and the general formula for **gravitational field strength** as shown below:

$$F = \frac{Gm_1m_2}{r^2} \qquad g = \frac{F}{m_2}$$

Rearrange the general formula so that its subject is the force exerted (F). Note that this just gives us the equation for calculating the weight of an object, where m_2 is its mass.

$$F = m_2g$$

You can now set Newton's law of gravitation and the equation above equal to each other, and cancel down to get an equation for gravitational field strength.

$$m_2g = \frac{Gm_1m_2}{r^2}$$

$$g = \frac{Gm_1}{r^2}$$

Where m_1 is the mass of the object creating the gravitational field.
This can be re-written more clearly as:

$$g = \frac{Gm}{r^2}$$

Where **g** is the gravitational field strength, **G** is the gravitational constant, **m** is the mass of the object causing the gravitational field and **r** is the distance from the centre of the mass.

5.6.158 - Gravitational potential

Gravitational potential (V) at a point is the work done per unit mass when moving an object from infinity to that point. Gravitational potential **at infinity is zero**, and as an object moves from infinity to a point, energy is released as the gravitational potential energy is reduced, therefore **gravitational potential is always negative**.

$$V = -\frac{GM}{r}$$ (For a radial field)

Where **M** is the mass of the object causing the field, **r** is the distance between the centres of the objects.

The **gravitational potential difference(ΔV)** is the energy needed to move a unit mass between two points and therefore can be used to find the work done when moving an object in a gravitational field.

$$Work\ done = m\Delta V$$ Where **m** is the mass of the object moved.

5.6.159 - Comparing electric and gravitational fields

The table below describes some of the similarities and differences between electric and gravitational fields:

Similarities	Differences
Forces both follow an inverse-square law	In gravitational fields, the force exerted is always attractive, while in electric fields the force can be either repulsive or attractive.
Use field lines to be represented and can both be either uniform or radial	
Use equations of a similar form to find the force exerted and field strength (though use different values)	Electric force acts on charge, while gravitational force acts on mass.

5.6.160 - Orbital motion

Kepler's third law is that the **square of the orbital period (T) is directly proportional to the cube of the radius (r)**: $T^2 \propto r^3$. This can be derived through the following process:

1. When an object orbits a mass, it experiences a **gravitational force** towards the centre of the mass, and as the object is moving in a circle, this gravitational force acts as the **centripetal force**. Therefore we can **equate** the equations of centripetal force and gravitational force:

$$Centripetal\ force = \frac{mv^2}{r} \qquad Gravitational\ force = \frac{GMm}{r^2}$$

$$\frac{mv^2}{r} = \frac{GMm}{r^2}$$

2. Rearrange the equation to make it v^2 the subject.

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

3. Velocity is the rate of change of displacement, therefore you can find v in terms of radius (r) and orbital period (T):

$$v = \frac{2\pi r}{T} \quad \Rightarrow \quad v^2 = \frac{4\pi^2 r^2}{T^2}$$

Because the diameter of a circle is $2\pi r$, and the object will travel this distance in one orbital period.

4. Substitute the equation for v^2 in terms of r and T, into the original equation (from step 2).

$$\frac{4\pi^2 r^2}{T^2} = \frac{GM}{r}$$

5. Rearrange to make T^2 the subject.

$$T^2 = \frac{4\pi^2}{GM} \times r^3$$

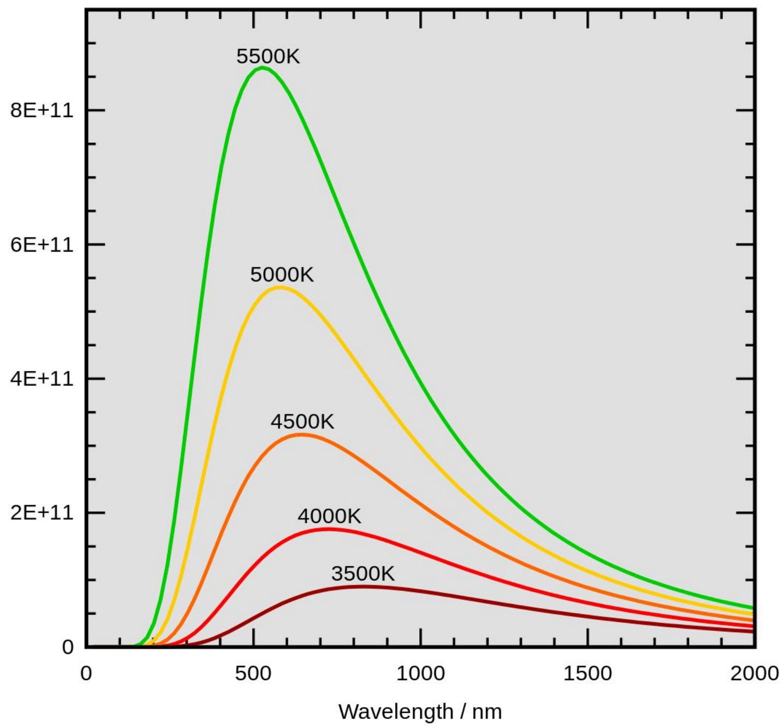
As $\frac{4\pi^2}{GM}$ is a constant, this shows that $T^2 \propto r^3$ (**T^2 is directly proportional to r^3**).

You must be able to apply Newton's laws of motions and gravitation to orbital motion as shown above. It is important to keep in mind that if an orbit is circular, all the equations you learnt to do with **circular motion** will apply.

5.6.161 - Black body radiators and their radiation curves

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

Radiation curves are graphs of intensity against wavelength of radiation emitted by objects at different temperatures. Below is an example of a radiation curve for a black body radiator.



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5.6.162 - The Stefan-Boltzmann law

Stefan's law states that the power output (also known as **luminosity (L)**) of a black body radiator is **directly proportional** to its **surface area (A)** and its **(absolute temperature)**^{4}.

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

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.

5.6.163 - Wien's law

Wien's displacement law states that 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.

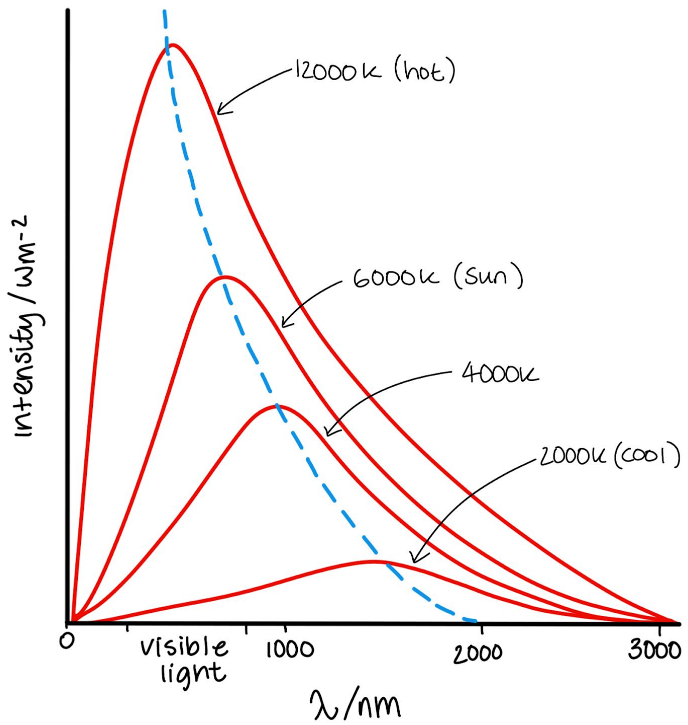
$$\lambda_{max} T = constant = 2.898 \times 10^{-3} m\ K$$

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.

You can see **Wien's law** being followed in the black-body curve below - as the temperature of the body increases, the peak wavelength decreases.



5.6.164 - Intensity and luminosity

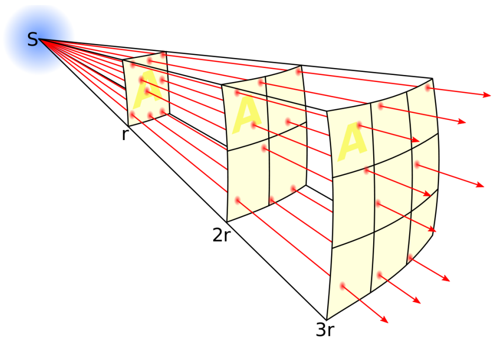
Luminosity (L) is the rate of light energy released or power output of a star.

Intensity (I) is the power received from a star (its luminosity) per unit area and has the unit, W m^{-2}. 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 intensity of a star follows the **inverse square law**, meaning it is inversely proportional to the square of 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 by the equation below:

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

Where **I** is intensity, **L** is luminosity and **d** is the distance from the source (star).



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5.6.165 - Trigonometric parallax

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 one of the diagrams below). You can find the angle of parallax by measuring the angle to a star and seeing how this angle changes as the Earth changes position. 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 should be aware of:

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

  1 AU = 1.5 x 10^{11} m
- **Parsec (pc) -** The distance at which the angle of parallax is 1 arcsecond (1/3600th of a degree).

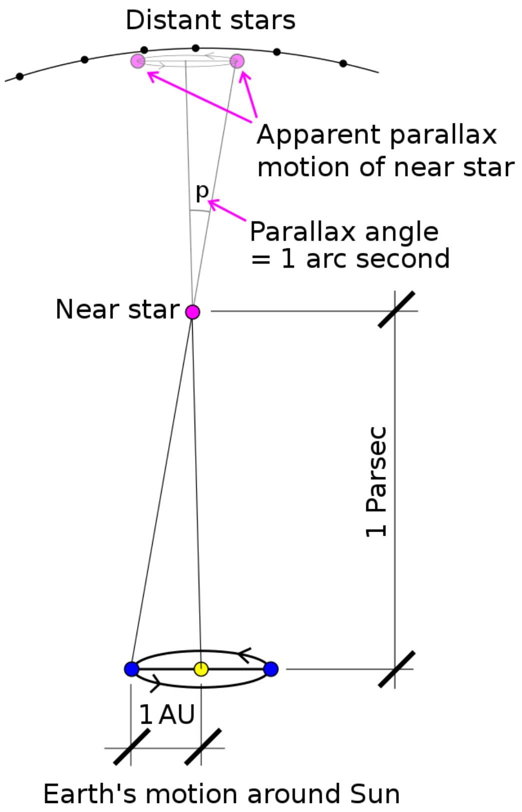
  1 pc = 2.06 x 10^{5} AU = 3.08 x 10^{16} m = 3.26 ly
- **Light year (ly) -** The distance that an EM waves travels in a year in a vacuum.

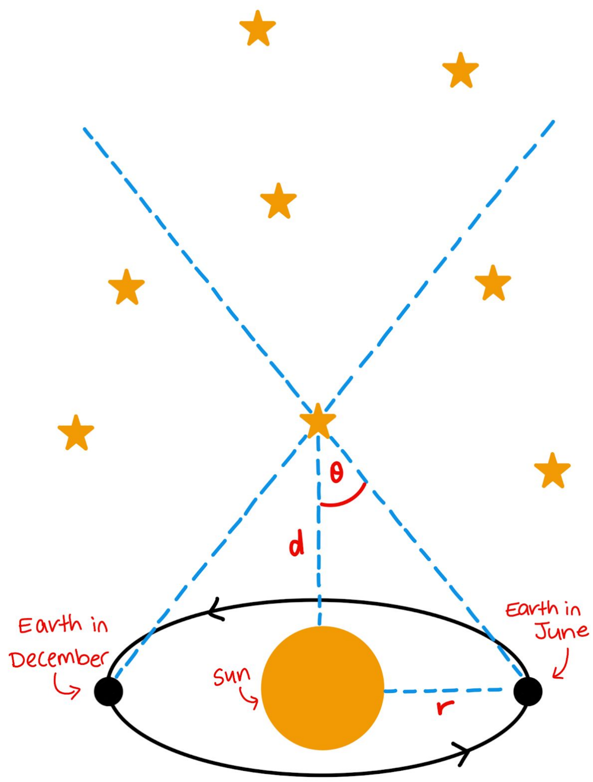
  1 ly = 9.46 x 10^{15} m

You can use the angle of parallax (θ) to find the distance, **d** (as shown in the diagram below on the right), using trigonometry.

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

Where **d** and **r** are in metres and **θ** is in radians. These are labelled on the diagram below on the right.





5..6.166 - Standard candles

You can also determine astronomical distances by measuring the intensity detected from **standard candles**, which are objects of **known luminosity**.

This can be done by measuring the intensity detected from the light source on Earth and using the inverse square law equation described above to calculate its distance away:

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

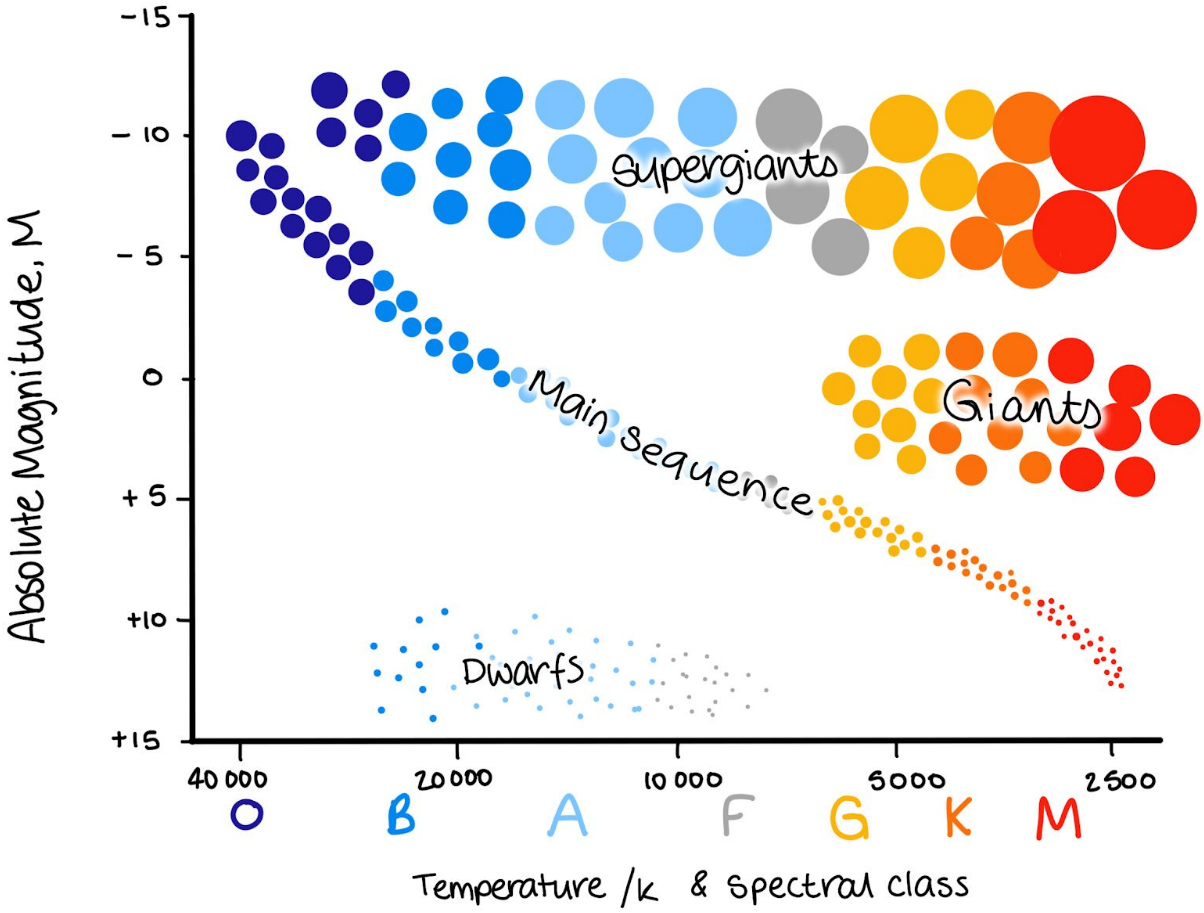
Where **I** is intensity, **L** is luminosity and **d** is the distance from the source (star).

5.6.167 - Hertzsprung-Russell diagram (stellar luminosity and temperature)

Stars belong to different **spectral classes** depending on their **temperature**. The table below describes star spectral classes and the temperature range of stars which fall into that class.

Spectral Class	Colour	Temperature Range (K)
O	Blue	25 000 - 50 000
B	Blue	11 000 - 25 000
A	Blue/White	7 500 - 11 000
F	White	6 000 - 7 500
G	Yellow/White	5 000 - 6 000
K	Orange	3 500 - 5 000
M	Red	< 3 500

The **Hertzsprung-Russell** (HR) diagram shows the stellar luminosity of a star against its temperature. By looking at the position of a star on the HR diagram, you will likely be able to tell what **spectral class** that star belongs to.

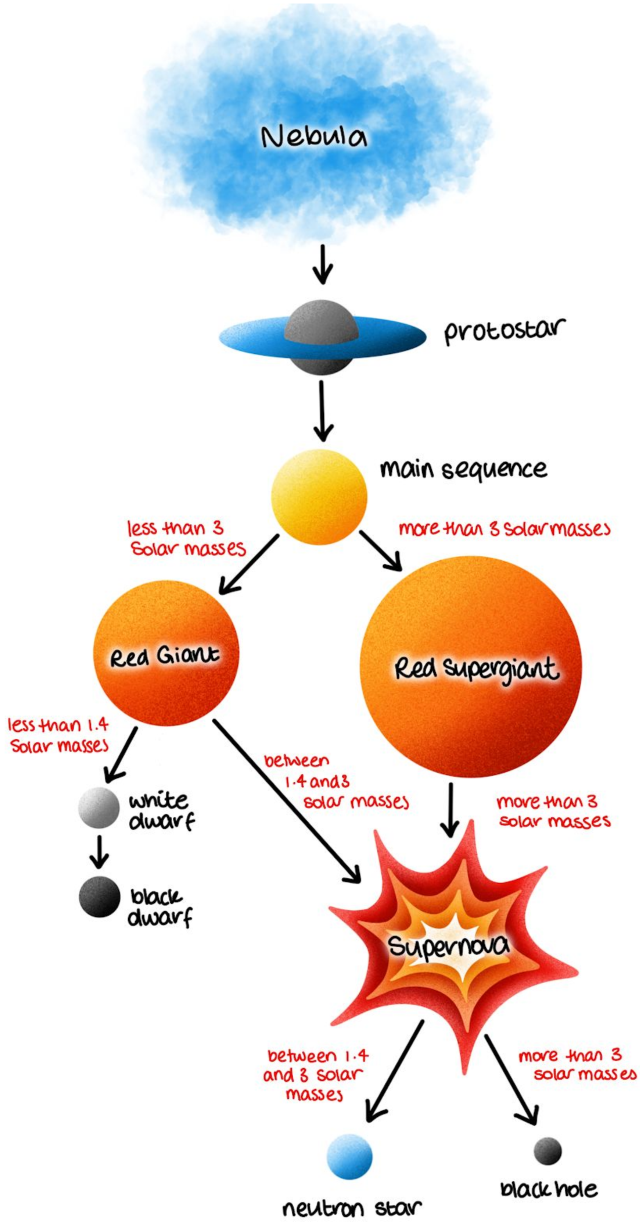


You must be able to draw and interpret a HR diagram, like the one above.

Most stars fall on the diagonal line crossing the HR diagram labelled "Main sequence". Stars in the main sequence are stable and will stay in this state for most of the lifetime. You can see that this diagonal main sequence line shows the link between the luminosity of a star and its temperature. Note that the temperature decreases as you move along the scale to the right.

5.6.168 - Hertzsprung-Russell diagram (life cycle of stars)

The **lifecycle of stars depends on their mass**, and the diagram below shows the life cycle of stars depending on their mass in solar masses, however you don't need to be aware of these exact amounts.



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 gravity/conservation of angular momentum spins them inwards to form a **denser centre** – a **protostar.**

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 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.

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.

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.

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.

What is the relation of the HR diagram to the life cycle as described above?