Edexcel Physics A-level

Topic 10: Space

Notes

10 - Space

10.156 - Intensity and luminosity

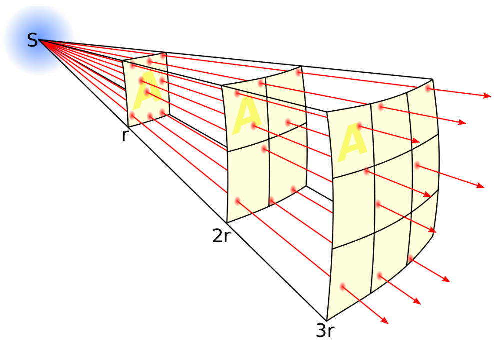
Luminosity (L) is the rate of light energy released or power output of a star.

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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10.157 - 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).

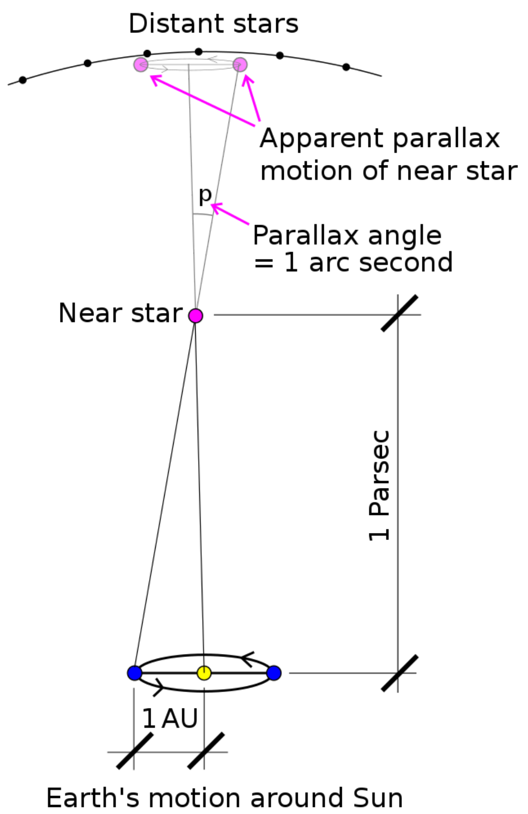
  1 pc = 2.06 x 10^5 AU = 3.08 x 10^{16} m = 3.26 ly
- **Light year (ly) -** The distance that an EM waves travels in a year in a vacuum.

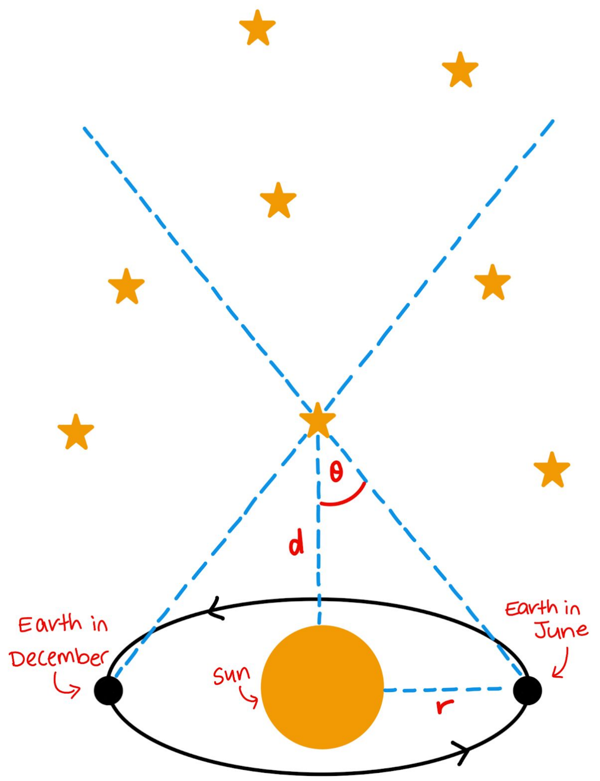
  1 ly = 9.46 x 10^{15} m

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

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

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





10.158 - 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:

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

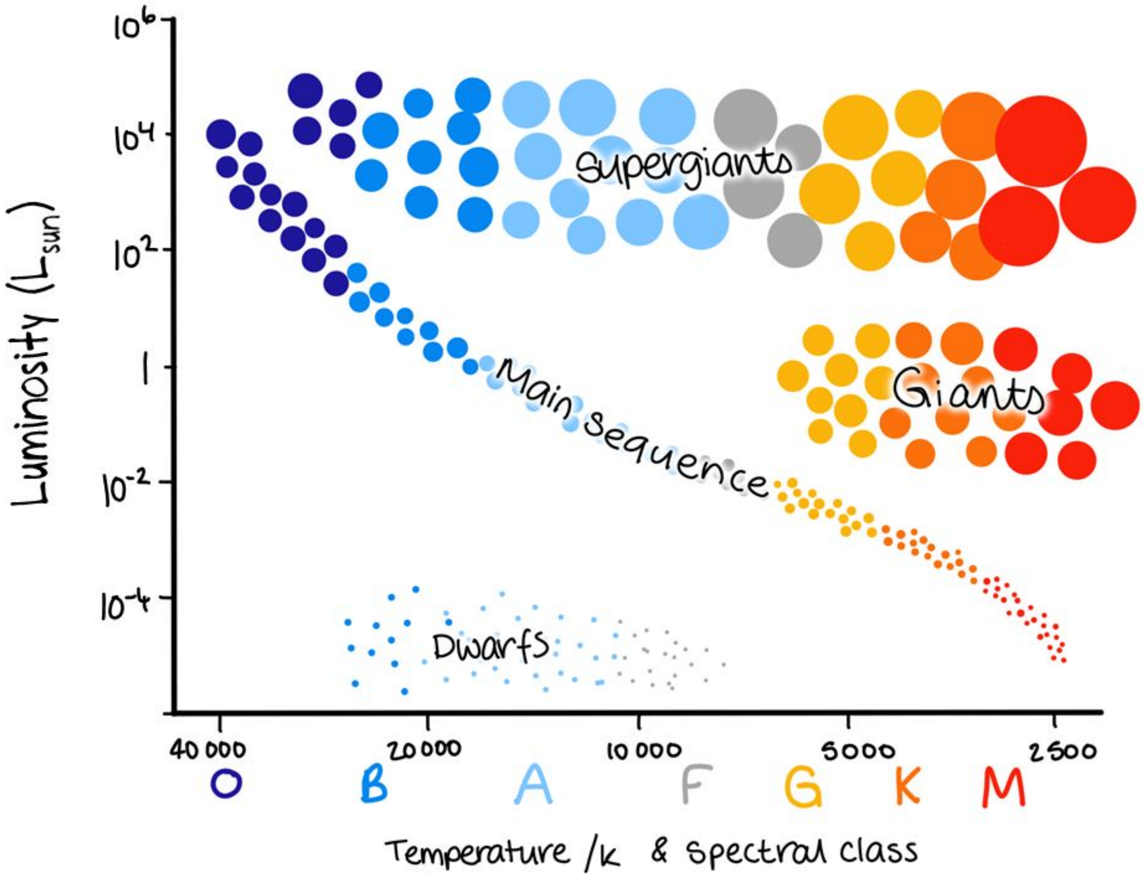
Where **I** is intensity, **L** is luminosity and **d** is the distance from the source (star).

10.159 - 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.

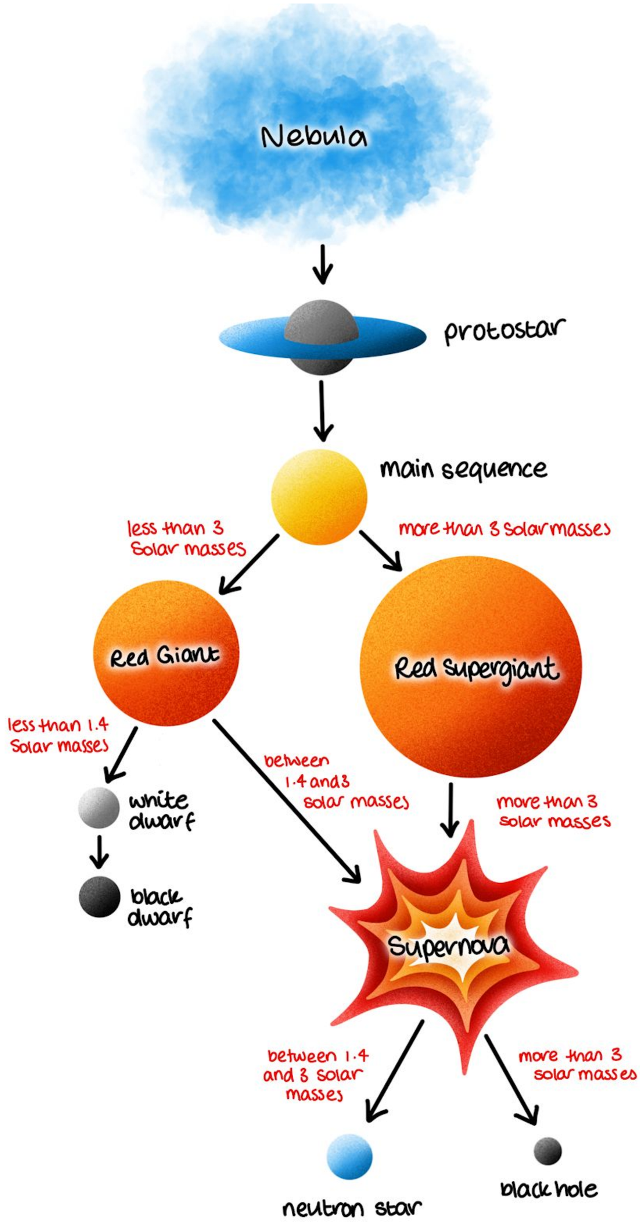


You must be able to draw and interpret a HR diagram, like the one above.

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.

10.160 - 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.

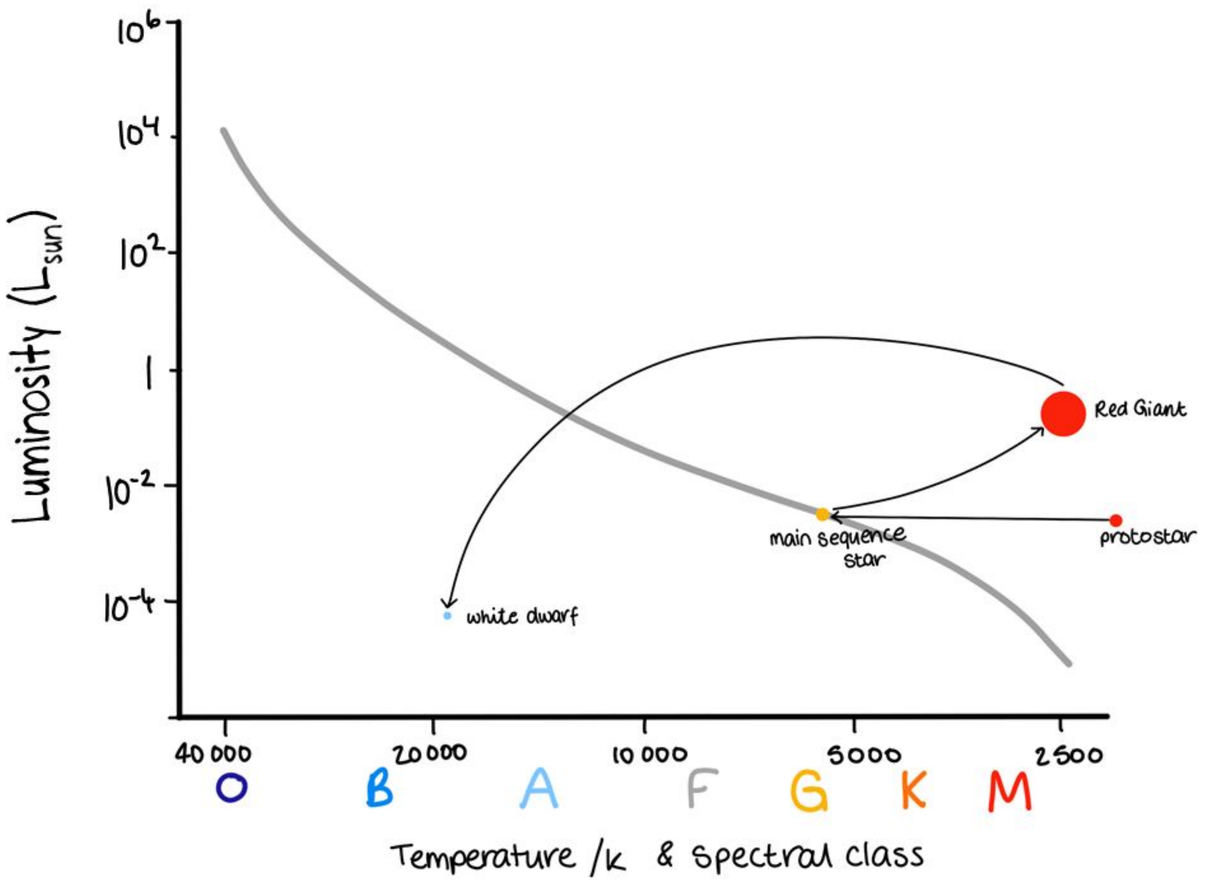
6. **Supernova (for a star > 1.4 solar masses)**
    - When **all fuel runs out**, fusion stops and the core collapses inwards very suddenly and **becomes rigid** (as the matter can no longer be forced any closer together).
    - The outer layers of the star fall inwards and **rebound** off of the core, 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.

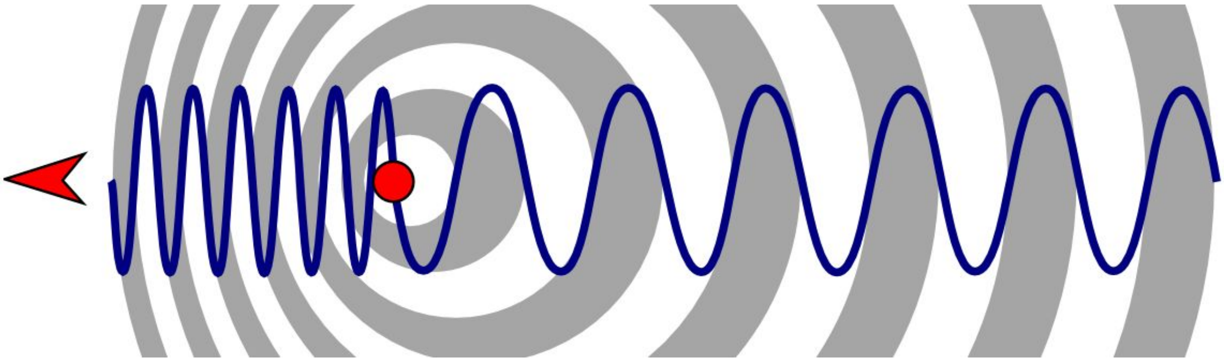
You can observe the life cycle of star by looking at a HR diagram, for example, consider a **main sequence star**:

1. The star begins as a **protostar**, which gradually **heats up**, moving to the left on the HR diagram. Once it reaches temperatures which allow fusion to occur, it becomes a **main sequence star**.
2. 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.
3. 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.



10.161 - 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.



10.162 - Red shift

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:

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

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)
Δλ = 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). When considering objects at **cosmological distances**, you can use Hubble's law, which is described below.

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:

$$v = H_0 d$$

Where **v** is the recessional velocity (km s^{-1}), $\mathbf{H_0}$ is the Hubble constant (around 70 km s^{-1} Mpc^{-1}), and **d** is its distance from Earth (**Mpc = megaparsec**)

10.163 - The age and ultimate fate of the universe

The **redshift** of distant objects shows that they are moving away from us, suggesting that the universe is 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.

By using the Hubble's law equation, you can estimate the age of the universe, as shown below:

1. **Rearrange** $v = H_0 d$ as follows:

$$\frac{v}{H_0} = d$$
$$\frac{1}{H_0} = \frac{d}{v}$$

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

$$t = \frac{1}{H_0}$$

Therefore, if you can correctly calculate the value of the Hubble constant, you can find the age of the universe. By using 70 km s^{-1} Mpc^{-1} as H_0, you get the value of t to be around 14 billion years.

However, the **value of H_0 varies quite a bit depending on the method used to find it**, which results in quite a large variation in the calculated age of the universe. As experimental methods improve, the measured value of H_0 keeps changing, meaning that there is no exact known value for the age of the universe, as this also changes.

By considering the centripetal force exerted on stars in the outer orbits of a galaxy, you'd expect them to travel **slower** than stars closer to the galactic centre (as the centripetal force is inversely proportional to the distance from the centre), however this is **not** the case. It has been observed that all of the stars in the galaxy tend to travel at the same speed regardless of how far away they are from the centre of the galaxy. This result suggests that the stars have a larger mass than they appear to, which allows them to travel at the speed that they are. This extra mass is believed to be caused by **dark matter**, which is **yet to be detected** as it does not emit or interact with light.

The image below shows three galaxy cluster collisions; in blue is the distribution of dark matter.

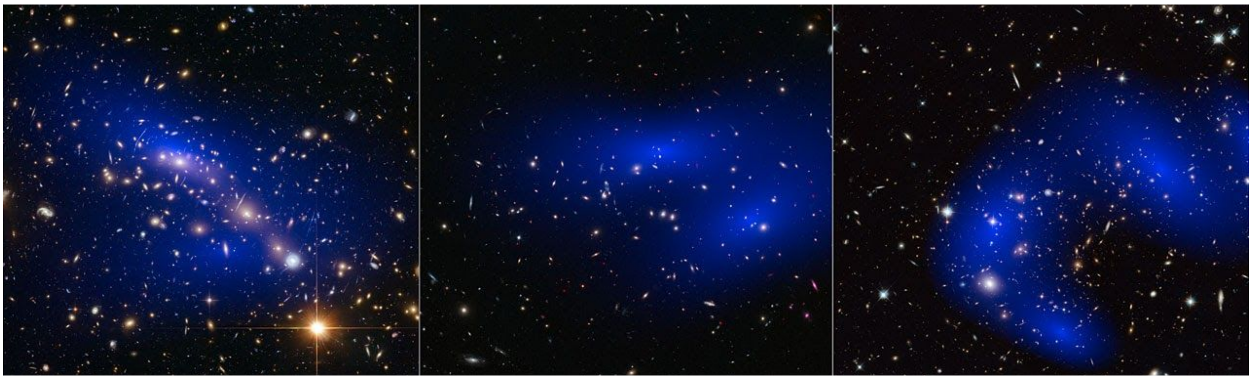


Image source: ESA/Hubble, CC BY 4.0, Image is cropped

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, a certain type of 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.