Cambridge (CIE) IGCSE Physics

Your notes

Stars & The Universe

Contents

The Sun as a star

- The Sun is a **medium-sized star** which lies at the **centre** of the Solar System
- It consists mostly of the two elements **hydrogen** and **helium**
- It radiates most of its energy in the **infrared**, **visible** and **ultraviolet** regions of the electromagnetic spectrum

Our Sun

The Sun is a medium-sized star consisting of mostly hydrogen and helium

Nuclear fusion in stars

Extended tier only

- Stars are huge balls of (mostly) **hydrogen** gas
- In the centre of a star, hydrogen nuclei undergo **nuclear fusion** to form helium nuclei
- An equation for a possible fusion reaction is:

$$^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{H} \rightarrow ^{4}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n}$$

- Where $^{2}_{1}\mathrm{H}$ (deuterium) and $^{3}_{1}\mathrm{H}$ (tritium) are both isotopes of hydrogen
  - These are formed through other fusion reactions in the star
- A huge amount of **energy** is released in the reaction
- All stable stars are **powered** by nuclear fusion reactions

Your notes

Examiner Tips and Tricks

It is useful to remember that hydrogen is the fuel within stars, but the details of the reaction between deuterium and tritium is not required at this level.

The Milky Way

The Universe

- The Universe is defined as

A large collection of billions of galaxies

- It is also the name given to the entirety of space

Galaxies

- A galaxy is defined as

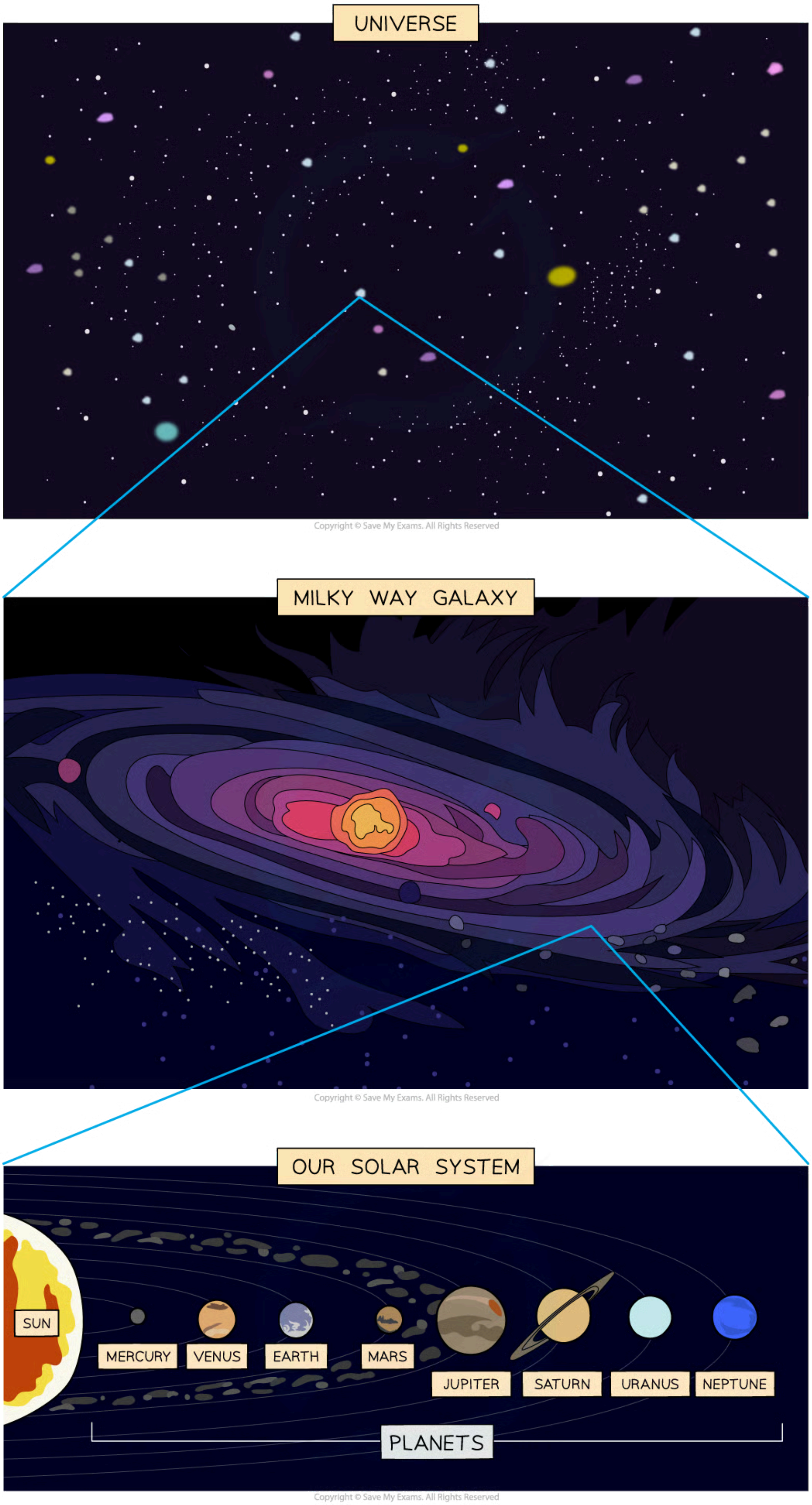
A large collection of billions of stars

- Stars are large astronomical objects, such as the Sun

The Milky Way

- **The Milky Way** is one of many billions of galaxies making up the Universe
- **The Sun** is one of many billions of stars making up the Milky Way
- Other stars in the Milky Way galaxy are **much further away** from Earth than the Sun is
- Some of these stars also have **planets** which orbit them

Hierarchy of the Universe


UNIVERSE
MILKY WAY GALAXY
OUR SOLAR SYSTEM
SUN
MERCURY
VENUS
EARTH
MARS
JUPITER
SATURN
URANUS
NEPTUNE
PLANETS

The Universe is a large collection of galaxies and a galaxy is a large collection of stars. The Sun is a star at the centre of our Solar System in the Milky Way galaxy

Your notes

Astronomical distances

- Astronomical distances, such as the distances between stars and galaxies, are extremely **large**
- To describe these distances, astronomers use a special unit called the **light year**
- One light-year is defined as:

The distance travelled by light in one year

- The **diameter of the Milky Way** is approximately **100 000 light-years**
- This means that light would take 100 000 years to travel from one side of the Milky Way to the other

Extended tier only

- One light year is equal to 9.5×10^{12} km, or $\mathbf{9.5 \times 10^{15}}$ **m**

Worked Example

The centre of our galaxy is 30 000 light years away.

(a) How long does it take light to reach the Earth?

Extended tier only

(b) Calculate this distance in km.

Answer:

(a)

- The centre of our galaxy is 30 000 light years away
- It takes light 30 000 years to reach the Earth from the centre of our galaxy

(b)

Extended tier only

Step 1: Write down the known quantities:

- The centre of our galaxy is 30 000 light years away
- 1 light year = 9.5×10^{12} km

Step 2: Calculate the distance in km:

$$\text{distance} = 30\,000 \times (9.5 \times 10^{12})$$

$$\text{distance} = 2.85 \times 10^{17}\ \text{km}$$

Your notes

Your notes

Star formation

Extended tier only

- Stars go through a sequence of evolutionary stages, known as the **life cycle** of a star
- All stars follow the same initial stages:

nebula → protostar → stable star

Nebula

- Stars form from a giant interstellar **cloud of gas and dust** called a nebula

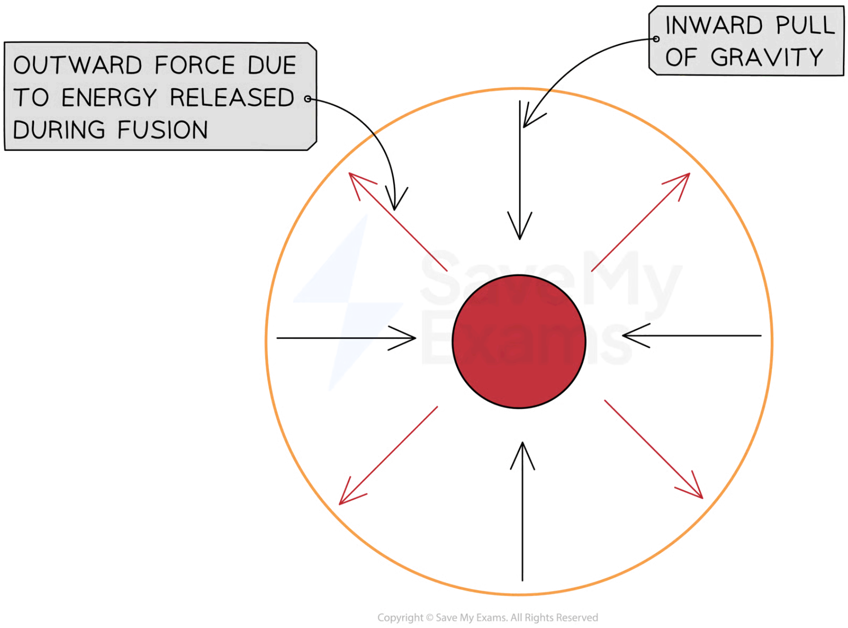
Protostar

- The **gravitational attraction** within a nebula pulls the particles **closer together** until a hot ball of gas forms, known as a **protostar**
- As the particles are pulled closer together, the **density** of the protostar **increases**
- This results in **more frequent collisions** between the particles, which causes the **temperature** to **increase**

Stable star

- Once the protostar becomes hot enough, **nuclear fusion** reactions occur within its core
  - The hydrogen in the core of the star is converted into helium
  - Every fusion reaction releases heat and light, which keeps the core of the star hot
- Once a star initiates fusion, it is known as a **stable star**
- During this stage, the star is in **equilibrium** as the forces acting on it are balanced
- Gravitational forces act **inwards**
  - This is an attractive force which pulls the outer layers inwards
- Thermal pressure acts **outwards**
  - This is exerted by the expanding hot gases inside the star as energy is released during fusion

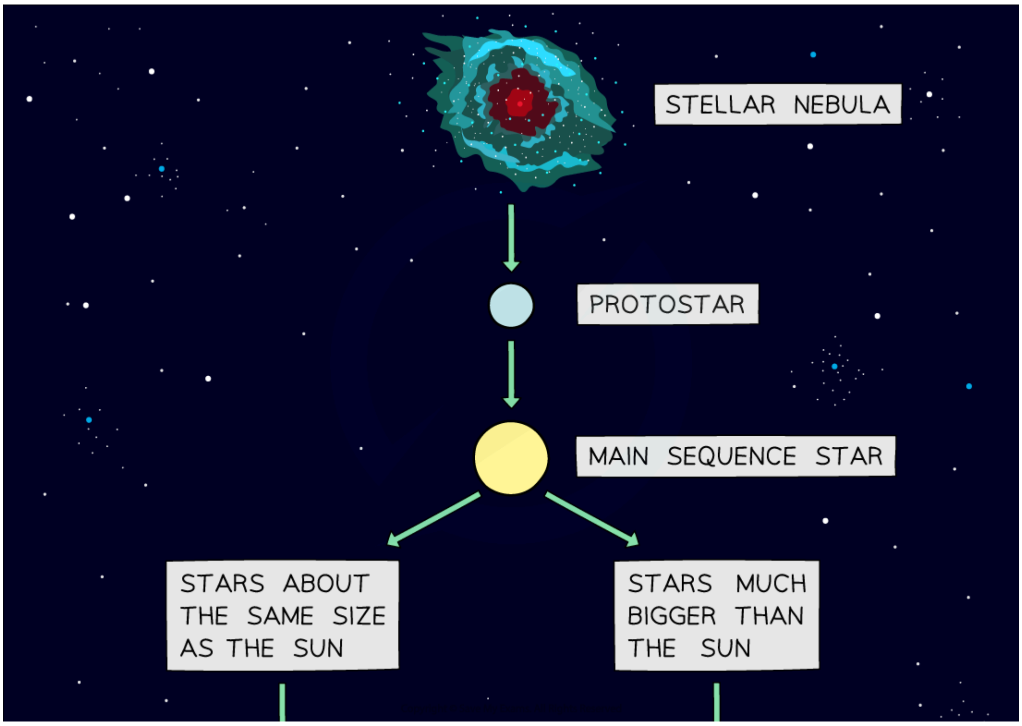
Balanced forces in a stable star

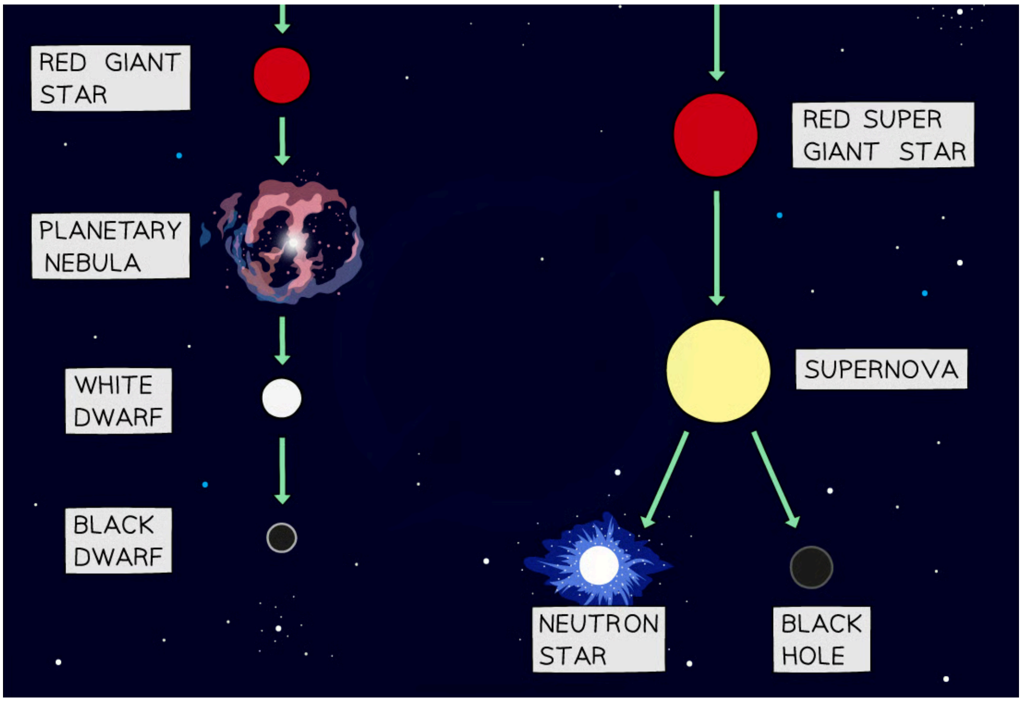


The outward and inward forces within a star are in equilibrium. The centre red circle represents the star's core and the orange circle represents the star's outer layers

- Once a stable star is formed, the final stages of its life cycle depend on its **mass**
- The different life cycles are shown below

Summary of the life cycles of stars





Flow diagram showing the life cycle of a star which is the same size as the Sun (solar mass) and the lifecycle of a star which is much more massive than the Sun

Your notes

Your notes

Life cycle of low mass stars

Extended tier only

- A low-mass star is one with a mass of up to about eight times that of the Sun
- After the main sequence, a low-mass star finishes its life cycle in the following evolutionary stages:

red giant → planetary nebula → white dwarf

Red giant

- After several **billion** years, the hydrogen fuel used for nuclear reactions begins to run out
- Once this happens, the rate of fusion decreases, which causes the core to shrink and heat up
  - As the energy produced by fusion decreases, the inward force due to gravity becomes **greater** than the outward force due to the thermal pressure
- Eventually, the star becomes a **red giant** when the core becomes hot enough for **helium** to fuse into **carbon**
- The energy released by re-ignited fusion reactions causes the outer layers of the star to **expand** and **cool**

Planetary nebula

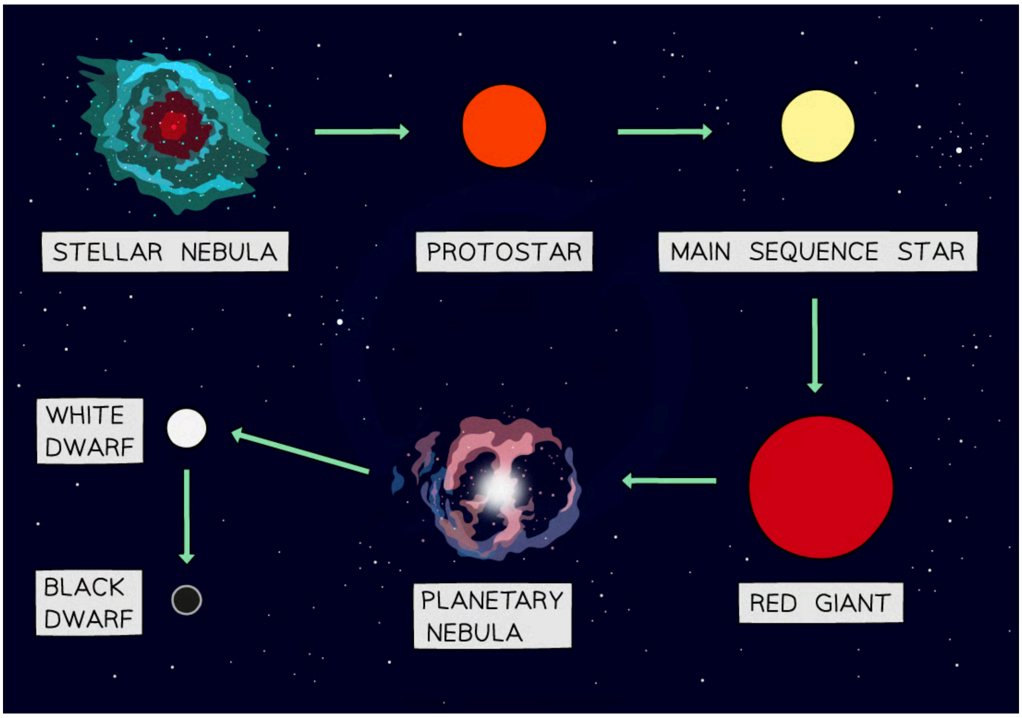
- Once the helium in the core runs out, fusion reactions cannot continue
- The star becomes **unstable** and the core collapses under its own gravity
- The outer layers are ejected into space as a **planetary nebula**

White dwarf

- The collapsed core of the red giant is called a **white dwarf**
- The white dwarf **cools** down over time and as a result, the amount of **energy** it emits **decreases**

The life cycle of a low-mass star

Your notes



The life cycle of a star that is similar to our Sun

Examiner Tips and Tricks

A low mass star is any star that will eventually become a **white dwarf**. You may see different sources giving different ranges of masses for stars within this category, or terms such as low mass stars (up to 2 solar masses) or intermediate mass stars (between 2 and 8 solar masses). Note that you do not need to know these numbers or categories, only that all these stars will follow the **same** evolutionary stages.

Life cycle of high mass stars

Extended tier only

- A high-mass star is one with a mass of more than about eight times that of the Sun
- After the main sequence, a high-mass star finishes its life cycle in the following evolutionary stages:

red supergiant → supernova → neutron star (or black hole)

Red supergiant

- After several **million** years, the hydrogen in the core begins to run out
- Similar to a low-mass star, the rate of fusion decreases and the core shrinks and heats up

- The star becomes a **red supergiant** when the core becomes hot enough for helium fusion to start
- This causes the outer layers of the star to **expand** and **cool**
- In the core of the star, **helium** fuses into **carbon**
  - This is followed by further fusion reactions in which successively heavier elements, such as nitrogen and oxygen, are formed
- During this stage, the core collapses and expands repeatedly as fusion reactions start and stop

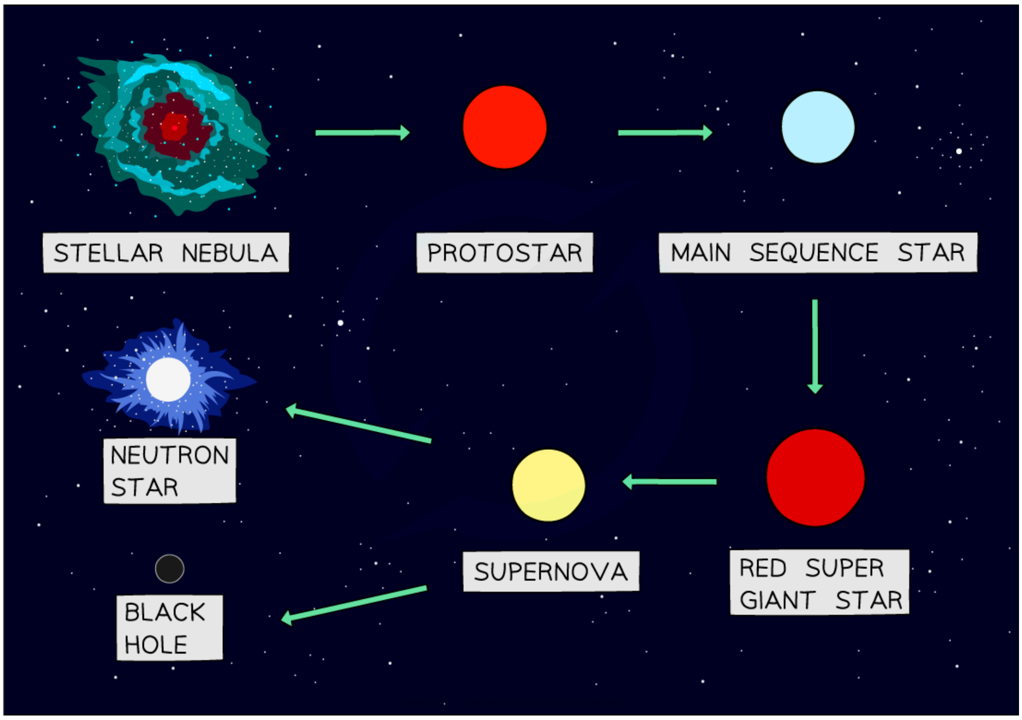
Supernova

- Eventually, fusion reactions inside the red supergiant cannot continue once **iron** is formed
- The core of the star will **collapse rapidly** and initiate a **gigantic explosion** called a **supernova**
- At the centre of this explosion, a **dense** body called a **neutron star** will form
- The **outer layers** of the star are **ejected** into space forming **new clouds** of dust and gas (**nebula**)
- The nebula from a supernova may form new **stars** with orbiting **planets**
  - The heaviest elements (elements heavier than iron) are formed during a supernova and are ejected into space
  - These nebulae may form new planetary systems

Neutron star (or black hole)

- In the case of the **most massive stars**, the neutron star that forms at the centre will continue to **collapse** under the force of **gravity** until it forms a **black hole**
- A black hole is an **extremely dense** point in space that not even **light** can escape from

The life cycle of a high-mass star



The life cycle of a star much larger than our Sun

Examiner Tips and Tricks

A high mass star is a one that will **not** eventually become a white dwarf. Make sure you understand that most high mass stars become neutron stars and only the highest mass stars become black holes.

Your notes

Your notes

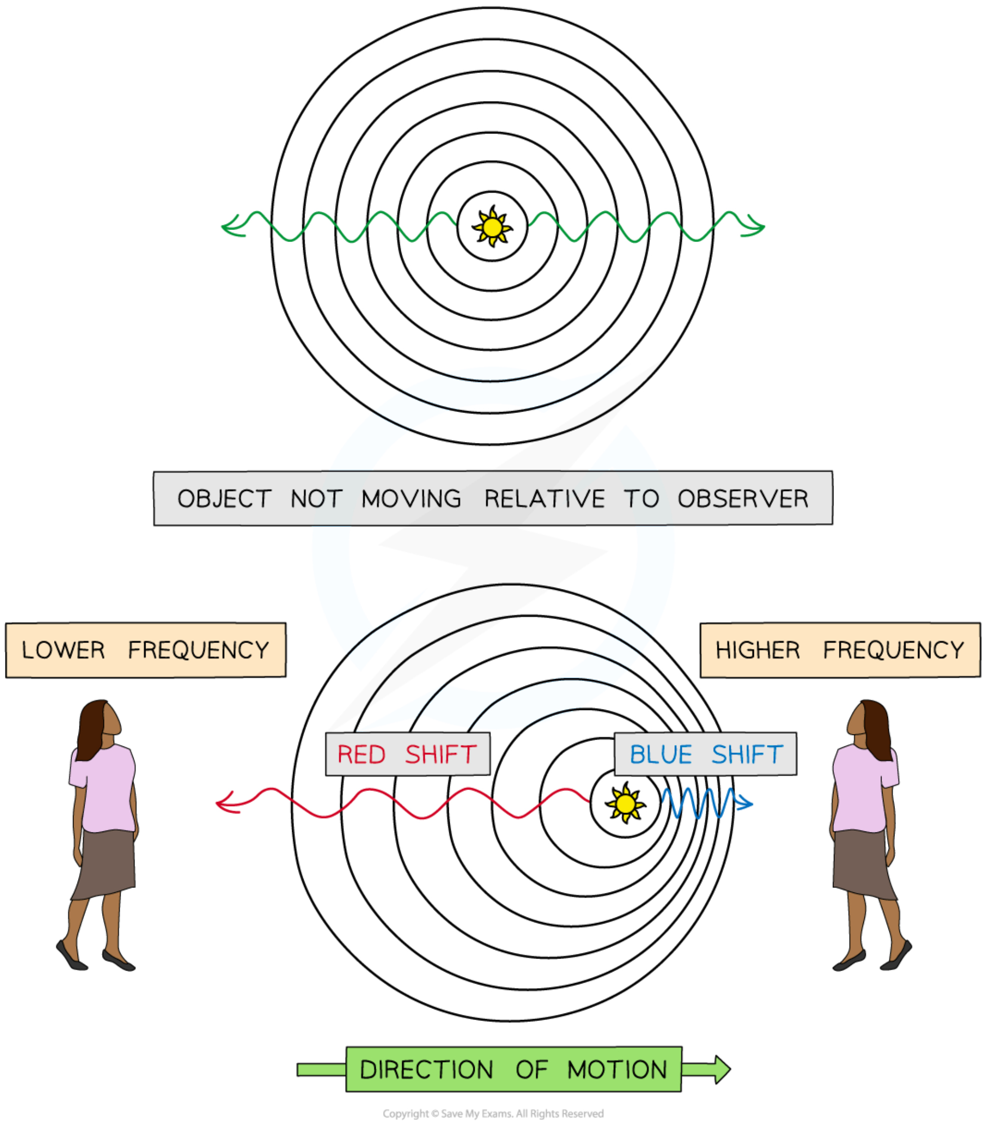
Galactic redshift

- When a stationary object emits waves, they spread out **symmetrically**
- If the source of the waves moves, the waves can become squashed together or spread out
- This change in wavelength is known as the **Doppler effect**
- This effect applies to **both** sound waves and electromagnetic radiation (i.e. light waves)

Doppler effect of light

- If a source of light moves **towards** an observer, the observed wavelength **decreases**
  - The wavelength of light **shifts** towards the **blue** end of the spectrum
  - This is called **blueshift**
- If a source of light moves **away** from an observer, the observed wavelength **increases**
  - The wavelength of light **shifts** towards the **red** end of the spectrum
  - This is called **redshift**

Redshift and blueshift of light

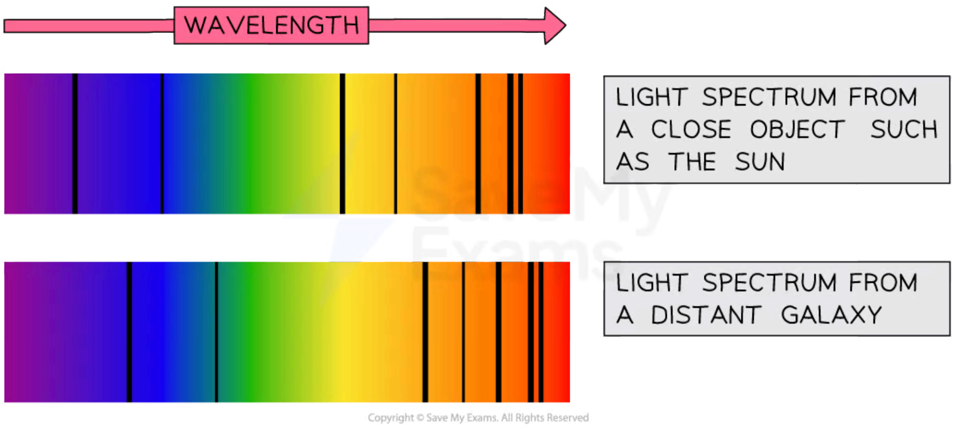


When a light source moves away from an observer, redshift is observed, and when a light source moves towards an observer, blueshift is observed

Observing redshift in distant galaxies

- When astronomers compare light from glowing hydrogen in **distant galaxies** with light from glowing hydrogen on **Earth**, the light appears to be **redshifted**
- This means the observed wavelength has **increased** as the light travelled from the galaxy to the Earth
- This shows that distant stars and galaxies are **moving away** (receding) from the Earth

Redshift of light from a distant galaxy



Light emitted from glowing hydrogen in distant objects appears to be shifted towards the red end of the spectrum, showing they are moving away from Earth

- The greater the observed redshift:
  - the **greater** the **distance** to a galaxy
  - the **faster** the galaxy is moving **away** from Earth

Examiner Tips and Tricks

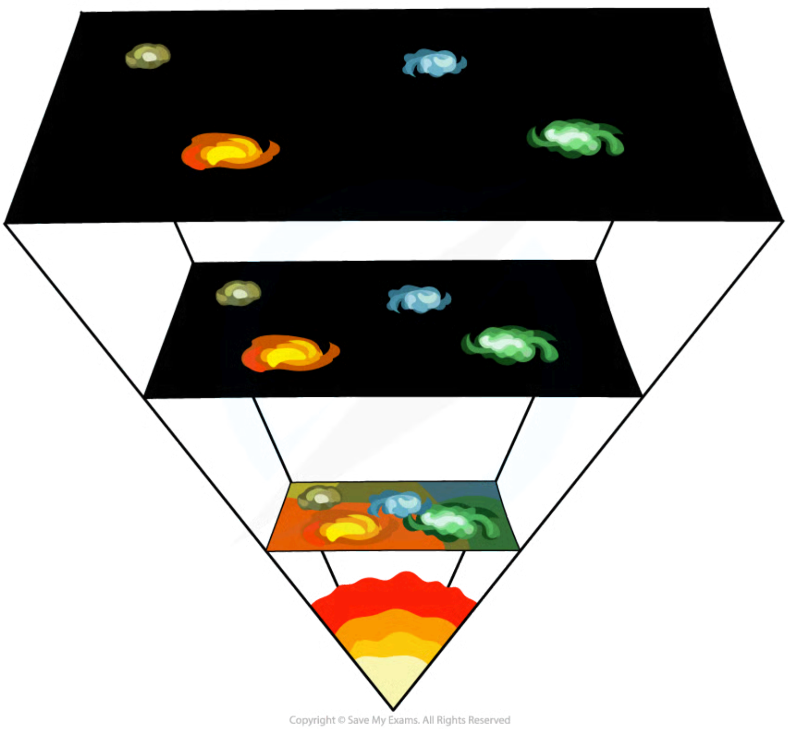
You need to know that in the visible light spectrum, **red light** has the **longest wavelength** and the **smallest frequency**.

Your notes

Evidence for the Big Bang Theory

- Around 14 billion years ago, the Universe began from a **single point** that was **extremely hot** and **dense**
- A giant explosion, known as the **Big Bang**, caused the Universe to **expand** outwards
- As each point **moved away** from the others, the Universe began to cool
- As a result of the initial explosion, the Universe **continues to expand**

The Big Bang Theory



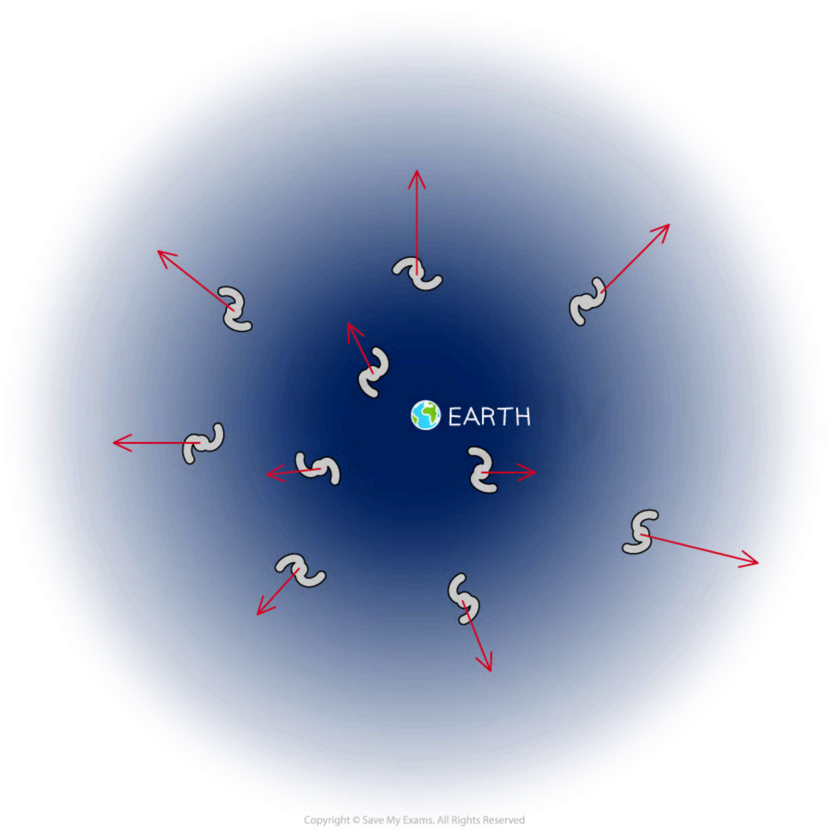
Tracing the expansion of the Universe back to the beginning of time leads to the idea it must have begun with a "Big Bang"

Evidence from galactic redshift

- Galactic redshift indicates that distant galaxies are moving **away** from us
- If galaxies are moving away from us, this means the Universe must be **expanding**

Expansion of the Universe

Your notes



Observations of light from galaxies show they are moving away from us which means the Universe is expanding

- Redshift provides evidence for the Big Bang because:

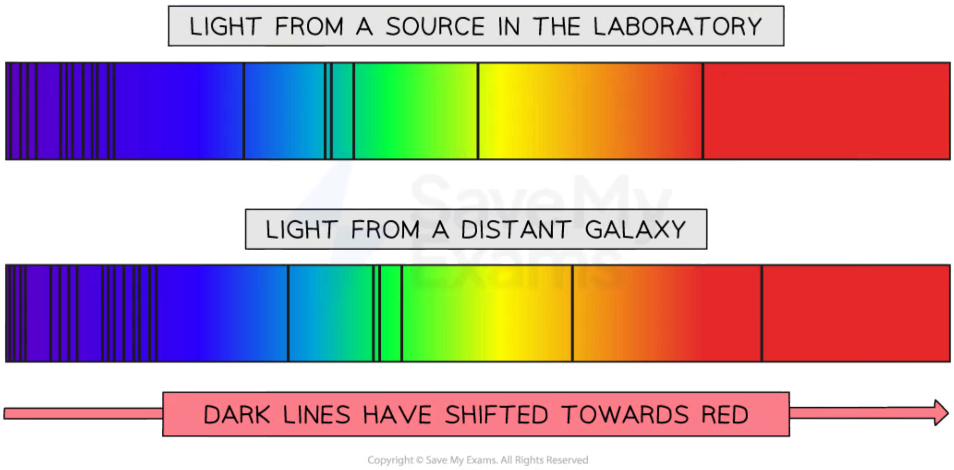
1. Observations show that distant galaxies are all moving away from us

- We see that light from glowing hydrogen in stars from distant galaxies is redshifted in comparison with light from glowing hydrogen on Earth

2. Observations show that the further away a galaxy is, the faster it is moving away from us

- The spectra of light from more distant galaxies are more redshifted than closer galaxies due to the expansion of space itself

Galactic redshift spectra

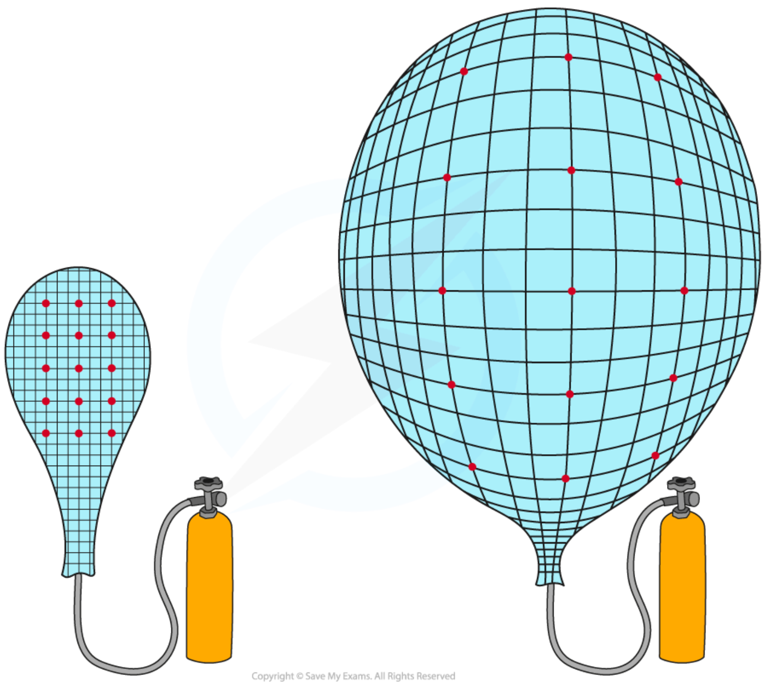


The dark lines (representing glowing hydrogen) have shifted towards red wavelengths due to the stretching of light as it travelled through space that was expanding

Examiner Tips and Tricks

Make sure that you understand that the stretching of the wavelength of light is due to the expansion of the Universe, not the motion of stars and galaxies themselves.

This can be visualised by imagining a balloon with equally spaced points on it. The balloon represents space and the points represent galaxies.



Your notes

When the balloon is deflated (i.e. the Universe was smaller), the points (galaxies) are closer together and are at an equal distance apart.

As the balloon (Universe) expands, all the points (galaxies) become further apart **by the same amount**.

This is because the **space between the galaxies** itself has expanded.

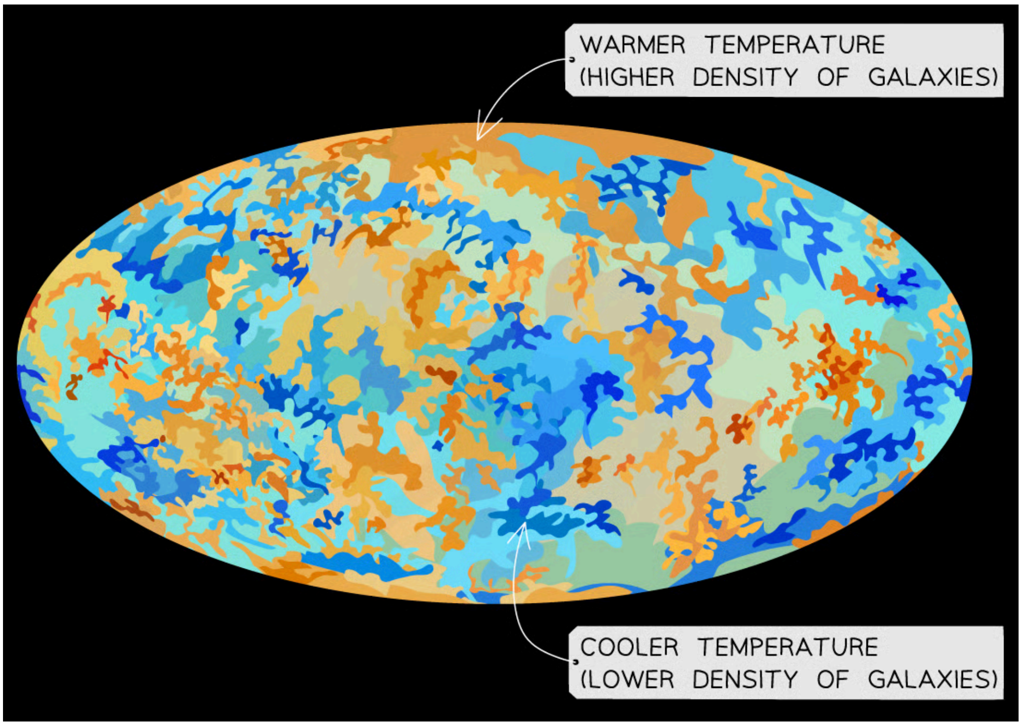
Your notes

Cosmic microwave background radiation

Extended tier only

- Cosmic microwave background radiation (CMBR) is a form of electromagnetic radiation that was emitted shortly after the beginning of the Universe
- It is detected **everywhere** throughout the Universe
  - The CMBR map is the closest image that exists to a map of the Universe
- It shows that the temperature of the Universe, and therefore the objects in it, are more or less **uniformly spread out**

CMBR map of the Universe



The CMBR map shows areas of higher and lower temperature in the Universe. Regions with higher temperatures have a higher concentration of galaxies, Suns and planets

Evidence from cosmic microwave background radiation

- Cosmic microwave background radiation provides evidence for the Big Bang because:

Your notes

1. Theory predicts the early Universe was extremely hot and dense

- Therefore, CMBR would have initially existed as short-wavelength gamma radiation
- The shorter wavelength in the past indicates the Universe must have been very hot in the beginning

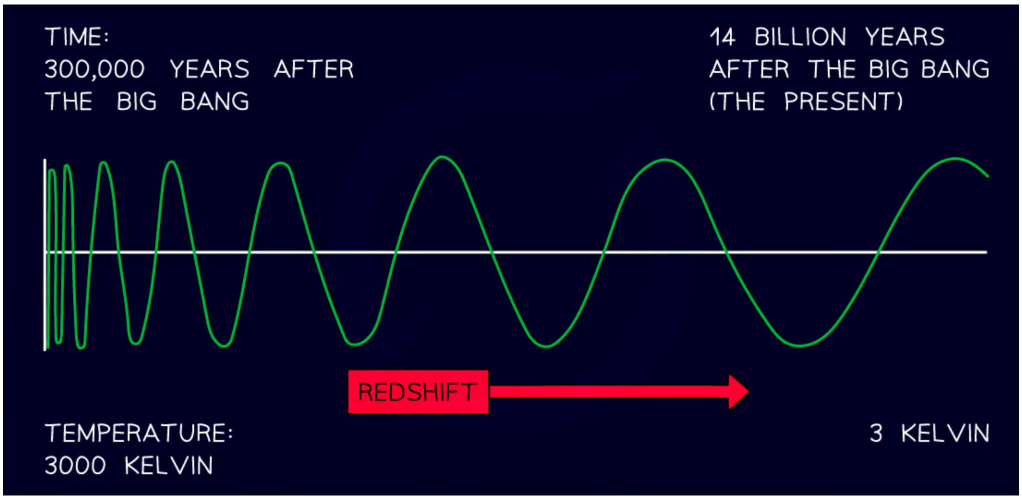
2. CMBR is consistent with radiation that has been stretched over time

- The Big Bang would have released a lot of energy in the form of extremely high-energy gamma radiation
- As the Universe expanded, the wavelength of the radiation **increased**
- Over time, it has been redshifted so much that it is now in the **microwave** region of the spectrum

3. CMBR can be interpreted as the radiation left over from the Big Bang

- The CMBR is extremely uniform which indicates the Universe was initially much smaller than it is now

Redshift of CMBR



CMBR is a result of high-energy radiation being redshifted over billions of years

Worked Example

Describe and explain what can be deduced about the history of the Universe from the CMBR.

Answer:

Step 1: Recall the features of the CMBR

- Microwave radiation is detected from all directions at a similar intensity

Step 2: State the source of this radiation

- This is the radiation produced just after the formation of the Universe

Step 3: Describe how the wavelength has changed and explain why

- When the Universe was formed, the radiation was high in energy and short in wavelength
- Now it has less energy and a longer wavelength
- This is because the Universe has expanded and cooled, causing the wavelength to increase

Step 4: Suggest what this tells us about the Universe in the beginning

- This suggests the Universe was initially very small and very energetic and has been expanding since

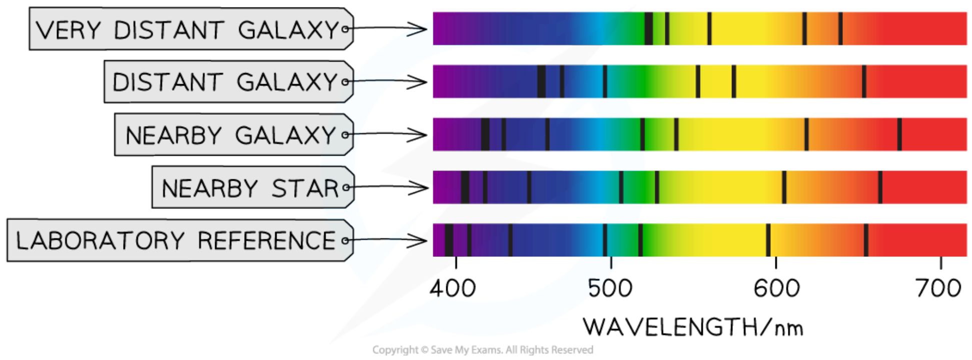
Your notes

The Hubble constant

Extended tier only

- When Edwin Hubble looked at the absorption spectra of distant galaxies, he determined a relationship between the **speed** of a galaxy and its **distance** from Earth

Comparing redshifts of galaxies



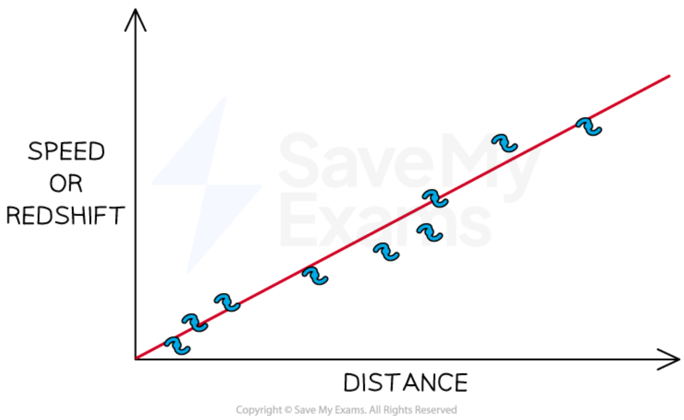
Hubble discovered that all galaxies show redshift, but the galaxies that are further away show a greater increase in redshift

- This is **Hubble's law**, which states

The speed of recession is proportional to the distance of the galaxy away from Earth

- 'Recession' speed means the speed at which something is moving away
- This means that the further away a galaxy is from Earth:
  - the **faster** it is moving away
  - the **greater** the increase in **redshift**

Relationship between redshift and galaxy distance



Hubble's law tells us the greater the distance to a galaxy, the greater the redshift, or the speed it moves away from Earth

Your notes

- Hubble's law can be expressed as an equation:

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

- Where:
  - H_0 = Hubble constant (per second)
  - v = recessional velocity of an object, the velocity of an object moving **away** from an observer (km/s)
  - d = distance between the object and the Earth (km)
- From this equation, the Hubble Constant H_0 can be defined as:

The ratio of the speed at which the galaxy is moving away from the Earth, to its distance from the Earth

- The accepted value of the Hubble constant is H_0 = **2.2 × 10^{-18} per second**

Examiner Tips and Tricks

Make sure to learn the currently accepted value of the Hubble constant.

You will be expected to know that the current estimate for H_0 is 2.2 × 10^{-18} per second

Measuring recession speed & distance

Extended tier only

- The Hubble constant H_0 can be determined from measurements of:
  - redshift of the light emitted by a galaxy
  - the brightness of supernovae in the galaxy

Measuring recession speeds of galaxies

- The speed of recession v of a galaxy (i.e. how fast it is moving away from the Earth) can be found from the change in wavelength of the galaxy's starlight due to redshift

Measuring distance using supernovae

- The distance d to a galaxy can be determined using the brightness of a supernova in that galaxy
- **Supernovae** are exploding stars

- Certain types of supernovae have the same peak level of brightness (**absolute magnitude**), meaning they can be used as **standard candles**
- These supernovae are so bright that they can be used for measuring distances to the most distant galaxies

Age of the Universe

Extended tier only

- Hubble's law can be rearranged to give the expression:

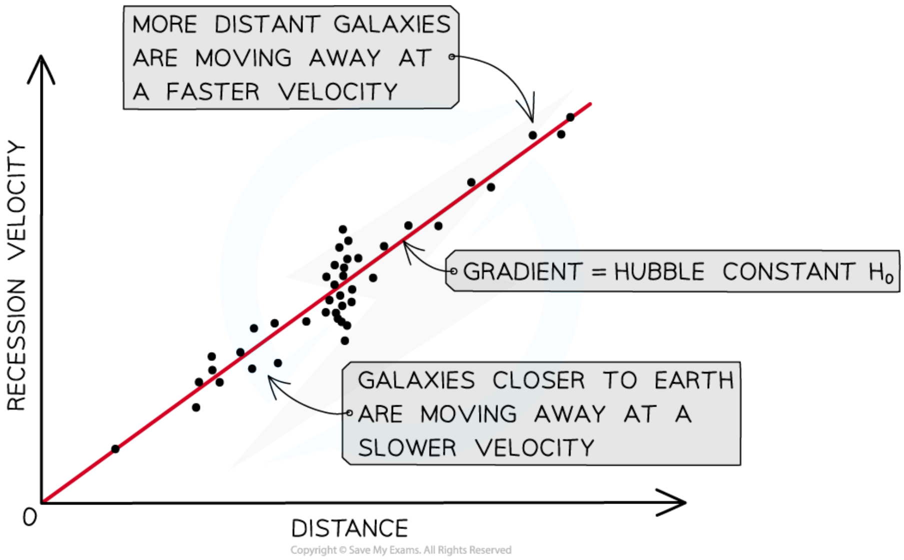
$$\frac{1}{H_0} = \frac{d}{v}$$

- Since time is equal to distance divided by speed, the term $\frac{1}{H_0}$ represents an estimate of the **age of the Universe**
- Hubble's law provides further **evidence** for the Big Bang
- **It shows that the Universe has been expanding since the beginning of time**
  - If we looked at time in reverse, we would see galaxies were closer together in the past
  - This suggests that the Universe must have originated from a single point and has been expanding outwards ever since

Hubble's law graph

- Using measurements from galactic redshift and brightness of supernovae, a graph of recession velocity against distance can be plotted

Graph of galaxy recession velocity against distance



A key aspect of Hubble's law is that the furthest galaxies appear to move away the fastest

Your notes

- The **gradient** of the graph represents the age of the Universe
  - When the distance equals zero, this represents all the matter in the Universe being at a single point
  - This is the singularity that occurred at the moment of the Big Bang
- Astronomers have used this formula to estimate the age of the Universe is about 13.7 billion years

Worked Example

A distant galaxy is 20 light-years away from Earth.

Use Hubble's law to determine the velocity at which the galaxy moves away from Earth.

Answer:

Step 1: List the known quantities

- Distance to the galaxy, d = 20 light-years
- 1 light year = 9.5×10^{15} m
- Hubble constant, H_0 = 2.2×10^{-18} per second

Step 2: Convert 20 light-years to m

- d = 20 ly = $20 \times (9.5 \times 10^{15}) = 1.9 \times 10^{17}$ m

Step 3: Substitute values into Hubble's Law

$$v = H_0 d$$

$$v = (2.2 \times 10^{-18}) \times (1.9 \times 10^{17}) = 0.418 \text{ m/s}$$

- The galaxy moves away from Earth at a velocity of 0.42 m/s

Examiner Tips and Tricks

If you are taking the Extended paper, remember that you have to learn the values for a light year and the Hubble constant!