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9.3 Cosmology

ASTROPHYSICS

AQA A Level Revision Notes

A Level Physics AQA

9.3 Cosmology

CONTENTS

9.3.1 The Doppler Shift of Light

The Doppler Effect of Light

- The Doppler shift for a light-emitting non-relativistic ($v << c$) source can be described using the equation:

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

- Where:
  - Δf = change in frequency (Hz)
  - f = reference frequency (frequency of the source) (Hz)
  - $\Delta \lambda$ = change in wavelength (m)
  - λ = reference wavelength (wavelength of the source) (m)
  - Δv = relative velocity of the source and observer (m s^{-1})
  - c = the speed of light (m s^{-1})
- The change in wavelength $\Delta \lambda$ is equal to:

$$\Delta \lambda = \lambda' - \lambda$$

- Where:
  - λ' = **observed** wavelength of the source (m)
- The **relative speed** between the source and observer along the line joining them is given by:

$$\Delta v = v_s - v_o$$

- Where:
  - v_s = velocity of the light **source** (m s^{-1})
  - v_o = velocity of the **observer** (m s^{-1})
- The velocity of the observer (usually from Earth) can be assumed to be **stationary**, i.e. $v_o = 0$
- The relative speed then simply becomes the speed of the source:

$$\Delta v = v_s = v$$

- Hence, the Doppler shift equation can be written as:

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

Redshift

- The fractional change in the wavelength $\frac{\Delta \lambda}{\lambda}$ is called the redshift and is given the symbol z
- In terms of wavelength, redshift is given by:

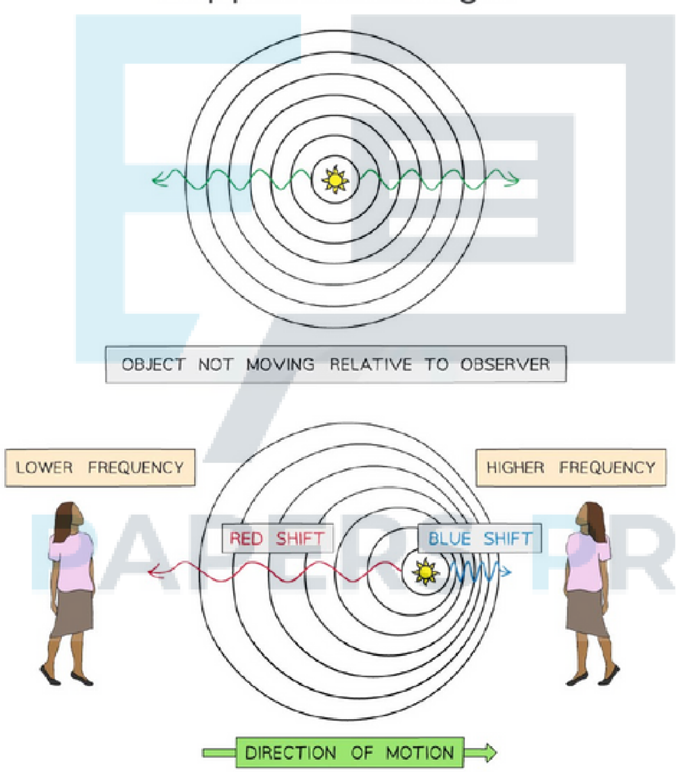
$$z = \frac{\Delta\lambda}{\lambda} = -\frac{v}{c}$$

- In terms of frequency, redshift is given by:

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

- This shows that if the source **moves away** from the observer then
  - The wavelength **increases**
  - The frequency **decreases**
- **Note:** the sign of z can cause some confusion, remember to look at the context - z is a measure of **redshift** so write it as positive for receding objects

Doppler Shift of Light



- Doppler shift can be observed in the spectra of stars and galaxies
- If the star is approaching the Earth, **blueshift** is observed (negative z)
  - The relative velocity v is positive
  - The change in wavelength $\Delta\lambda$ is negative
- If the star is receding from the Earth, **redshift** is observed (positive z)
  - The relative velocity v is negative
  - The change in wavelength $\Delta\lambda$ is positive

Worked Example

A stationary source of light is found to have a spectral line of wavelength 438 nm. The same line from a distant star that is moving away from the Earth has a wavelength of 608 nm.

Calculate the speed at which the star is travelling away from the Earth.

Answer:

Step 1: List the known quantities

- Unshifted wavelength, λ = 438 nm
- Shifted wavelength, λ' = 608 nm
- Change in wavelength, $\Delta\lambda$ = (608 – 438) nm = 170 nm
- Speed of light, $c = 3.0 \times 10^8$ m s^{-1}

Step 2: Write down the Doppler equation and rearrange for velocity v

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

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

Step 3: Substitute values to calculate v

$$v = \frac{(3.0 \times 10^8) \times 170}{438} = 1.16 \times 10^8 \text{ m s}^{-1}$$

Worked Example

The stars in a distant galaxy can be seen to orbit about a galactic centre. The galaxy can be observed 'edge-on' from the Earth.

Light emitted from a star on the left-hand side of the galaxy is measured to have a wavelength of 656.44 nm. The same spectral line from a star on the right-hand side is measured to have a wavelength of 656.12 nm.

The wavelength of the same spectral line measured on Earth is 656.28 nm.

(a)
State and explain which side of the galaxy is moving towards the Earth.
(b)
Calculate the rotational speed of the galaxy.

Answer:

(a)

- The light from the right-hand side (656.12 nm) is observed to be at a shorter wavelength than the reference line (656.28 nm)
- Therefore, the right-hand side shows blueshift and must, therefore, be moving towards the Earth

(b)

Step 1: List the known quantities

- Observed wavelength on LHS, λ_{LHS} = 656.44 nm
- Observed wavelength on RHS, λ_{RHS} = 656.12 nm
- Reference wavelength, λ = 656.28 nm
- Speed of light, $c = 3.0 \times 10^8$ m s^{-1}

Step 2: Calculate the average change in wavelength

- The magnitude of redshift or blueshift from each side is different, so you must calculate the average

$$\Delta\lambda = \frac{\lambda_{LHS} - \lambda_{RHS}}{2} = \frac{656.44 - 656.12}{2}$$

$$\Delta\lambda = 0.32 \text{ nm}$$

- Tip: you don't need to change the wavelengths from nm to m, as the units will cancel out later

Step 3: Write down the Doppler equation and rearrange for velocity v

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

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

Step 4: Substitute values into the velocity equation

$$v = \frac{(3 \times 10^8) \times 0.32}{656.28}$$

Rotational speed: $v = 1.46 \times 10^5 \text{ m s}^{-1} = 146 \text{ km s}^{-1}$

Exam Tip

You need to recall that, in the visible light spectrum, **red light** has a **longer wavelength** and a **lower frequency** compared to **blue light** which has a **shorter wavelength** and a **higher frequency**

9.3.2 Binary Star Systems

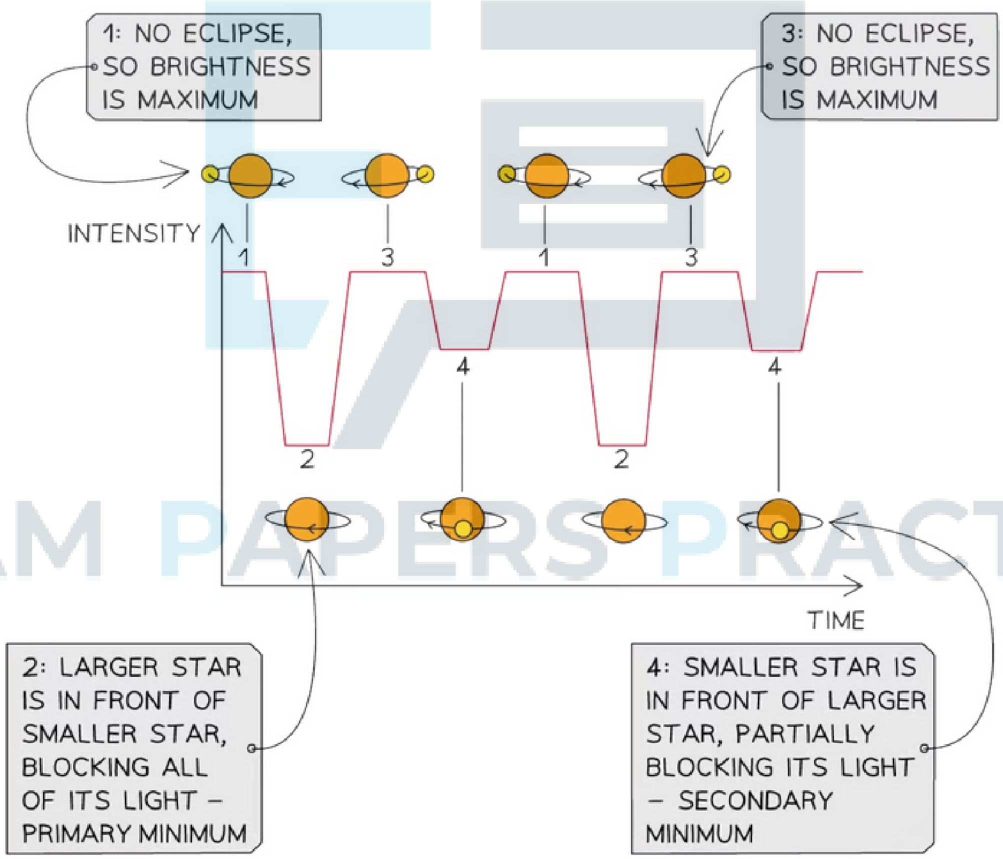
Binary Star Systems

- The Doppler effect can be used to identify eclipsing binary star systems
- An eclipsing binary star system is

Where two stars orbit around a common centre of mass with their orbital plane in the Earth's line of sight

- This means that, when observed from Earth, the stars cross in front of each other as they orbit, appearing to periodically eclipse one another
- They can be identified from their characteristic **light curves**

Light Curve of an Eclipsing Binary



The light intensity curve of an eclipsing binary shows periodic dips of two different sizes

- The **primary minima** (the larger dip) are caused by the larger star passing in front of the smaller star
- The **secondary minima** (the smaller dip) are caused by the smaller star passing in front of the large star

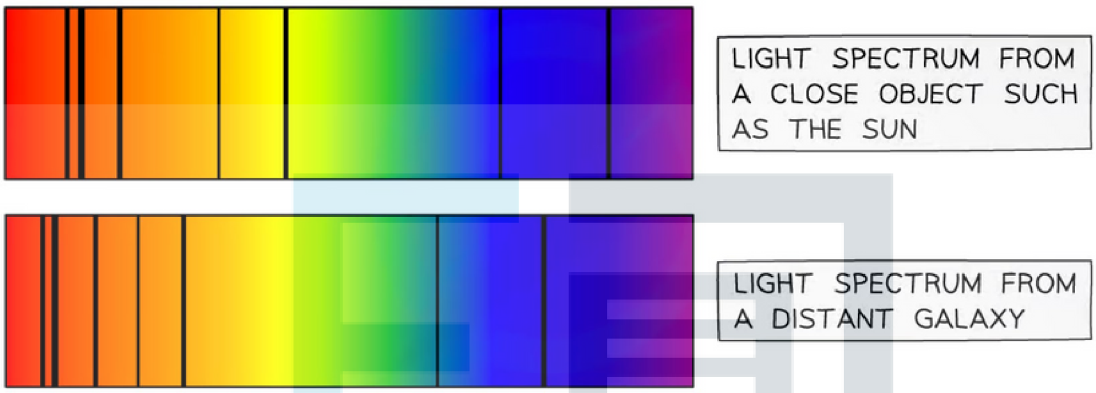
9.3.3 Galactic Redshift

Galactic Redshift

- When spectral lines from a distant galaxy are **redshifted**, this means:

  The lines have shifted towards a longer wavelength, or towards the red end of the spectrum

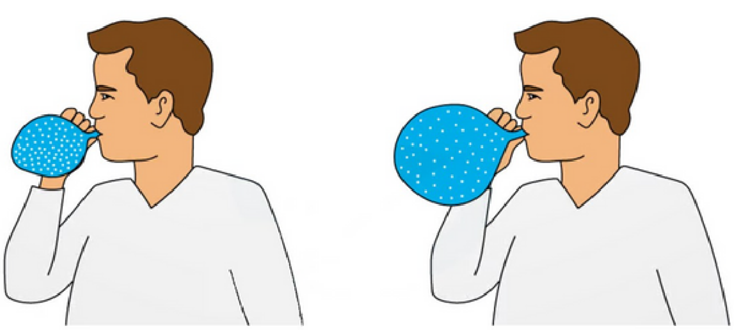
- This shift can be observed by comparing the spectra from the distant galaxy to a spectrum produced by a nearby object, such as our Sun, or a laboratory sample



Comparing the light spectrum produced by the Sun with light from a distant galaxy

An Expanding Universe

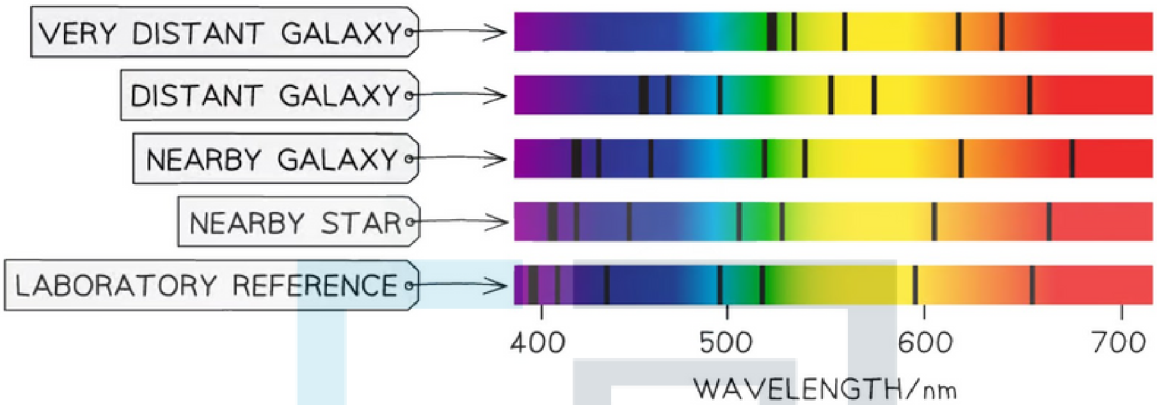
- After the discovery of redshift, astronomers began to realise that almost **all** the galaxies in the Universe are **receding**
  - This led to the idea that the space between the Earth and the galaxies must be **expanding**
- This expansion stretches out the light waves as they travel through space, shifting them towards the red end of the spectrum



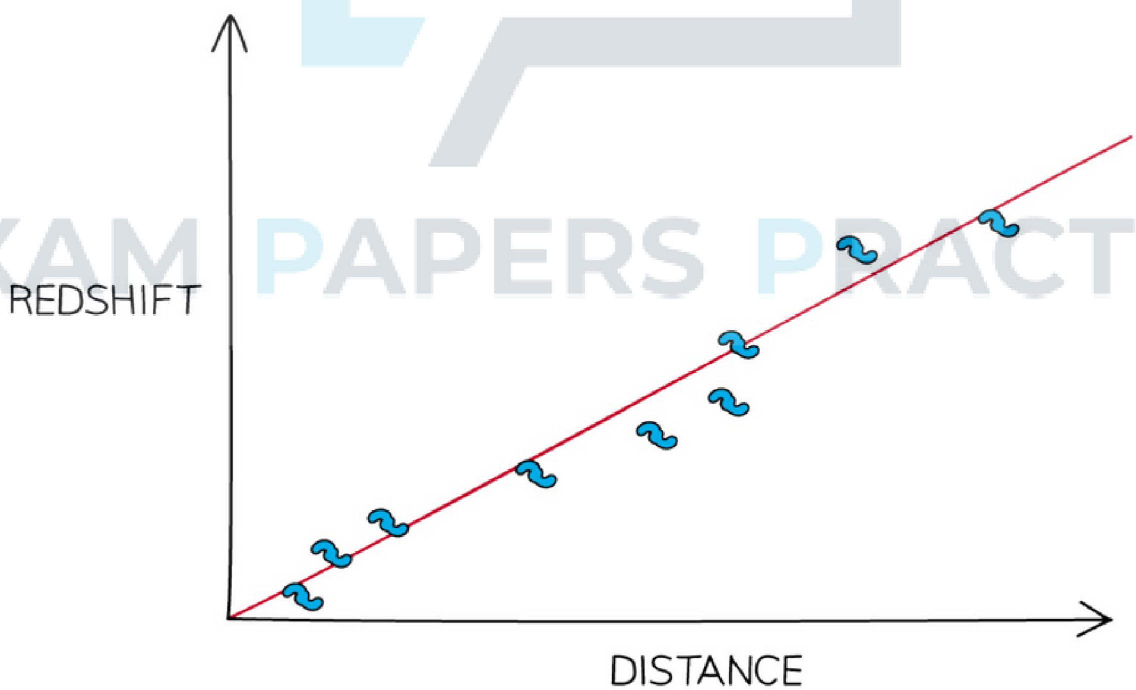
- The expansion of the Universe can be compared to dots on an inflating balloon
  - As the balloon is inflated, the dots all move away **from each other**
  - In the same way, as the rubber stretches when the balloon is inflated, space itself is **stretching out between galaxies**

- Just like the dots, the galaxies move away from each other, however, **they themselves** do not move

- Another observation from looking at the light spectra produced by distant galaxies is that the **greater** the **distance** to the galaxy, the **greater** the **redshift**
    - This means that the greater the degree of redshift, the **faster** the galaxy is moving away from Earth



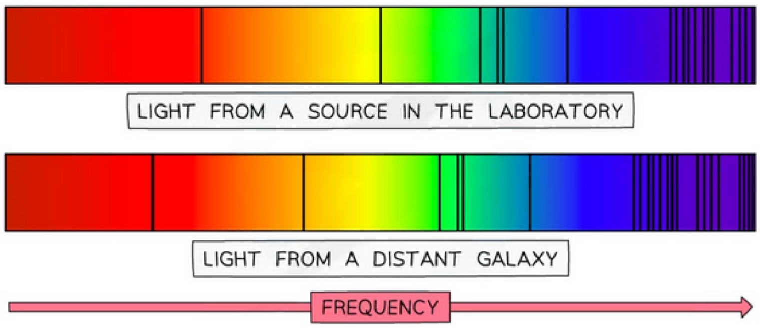
The further a galaxy is from Earth, the greater its redshift tends to be



The furthest galaxies appear to be redshifted the most and are receding the fastest

Worked Example

The spectra below show dark absorption lines against a continuous visible spectrum.



A particle line in the spectrum of light from a source in the laboratory has a frequency of 4.570×10^{14} Hz.

The same line in the spectrum of light from a distant galaxy is observed to have a frequency of 4.547×10^{14} Hz.

Calculate the speed of the distant galaxy, and state whether it is moving towards or away from the Earth.

Answer:

Step 1: Write down the known quantities

- Observed frequency, $f' = 4.547 \times 10^{14}$ Hz
- Original frequency, $f = 4.570 \times 10^{14}$ Hz
- Change in frequency, $\Delta f = (4.547 - 4.570) \times 10^{14} = -2.3 \times 10^{12}$ Hz
- Speed of light, $c = 3.0 \times 10^{8}$ m s^{-1}

Step 2: Write down the Doppler redshift equation

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

Step 3: Rearrange for speed v, and calculate

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

$$v = \frac{(3.0 \times 10^{8}) \times (-2.3 \times 10^{12})}{4.570 \times 10^{14}} = -1.5 \times 10^{6} \text{ m s}^{-1}$$

Step 4: Write a concluding sentence

- The relative velocity is **negative**, so the source is moving **away** from the Earth

OR

- The observed frequency is **less** than the emitted frequency (the light from a laboratory source), therefore, the source is **receding**, or moving away, from the Earth at $\mathbf{1.5 \times 10^6}$ $\mathbf{m\,s^{-1}}$

Exam Tip

Keep track of the minus signs in your calculation, as this gives you information about whether the object is moving away or towards the observer.

The speed of light is given in your data booklet, you will not need to memorise this value.

9.3.4 Hubble's Law

Hubble's Law

- Hubble's law states:

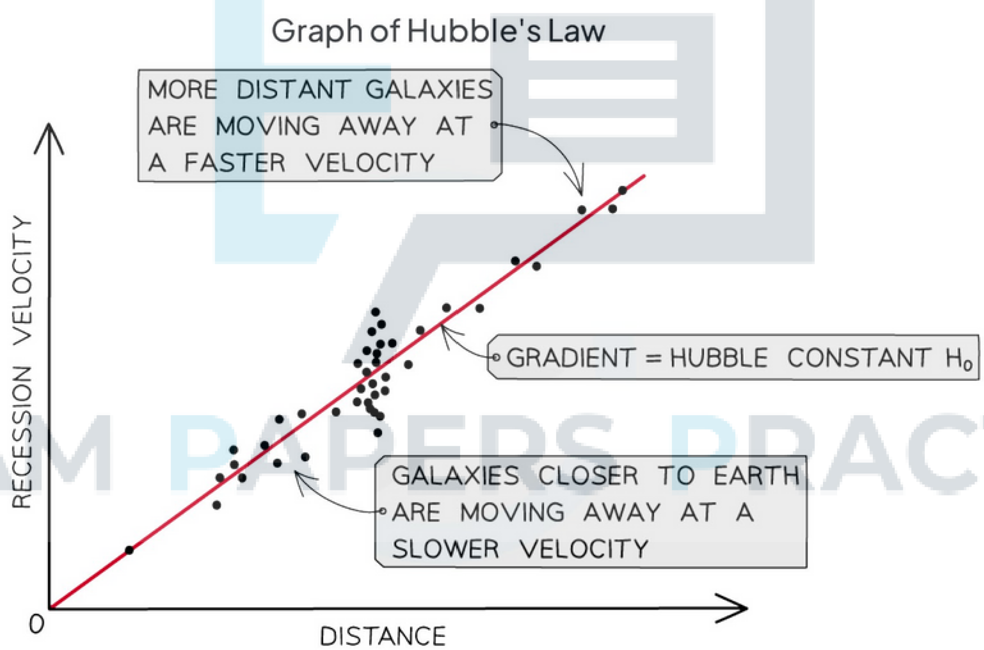
The recessional velocity of a galaxy is proportional to its distance from Earth

- This can be expressed mathematically as:

$$v = Hd$$

- Where:
  - v = recessional velocity of an object (km s^{-1})
  - H = Hubble constant (km s^{-1} Mpc^{-1})
  - d = distance between the object and the Earth (Mpc)

- Hubble's law shows that:
  - The further away a star is from the Earth, the faster it is moving away from us
  - The closer a star is to the Earth, the slower it is moving away from us



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

The Hubble Constant

- The constant of proportionality H in Hubble's law is known as the Hubble constant:

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

- The value for the Hubble constant has been estimated using data from thousands of galaxies, and other sources, such as standard candles

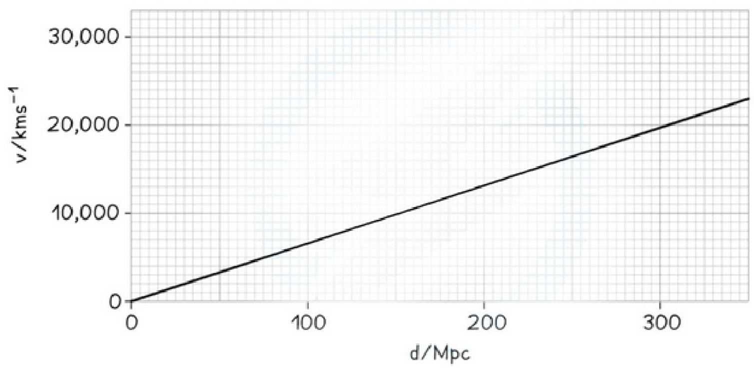
- Our current best estimate of the Hubble constant, based on CMB observations by the Planck satellite, is:

$$H = 67.4 \pm 0.5 \text{ km s}^{-1}\text{ Mpc}^{-1}$$

- **Note:** this value is constantly under review as more data is collected

Worked Example

The graph shows how the recessional velocity *v* of a group of galaxies varies with their distance *d* from the Earth.



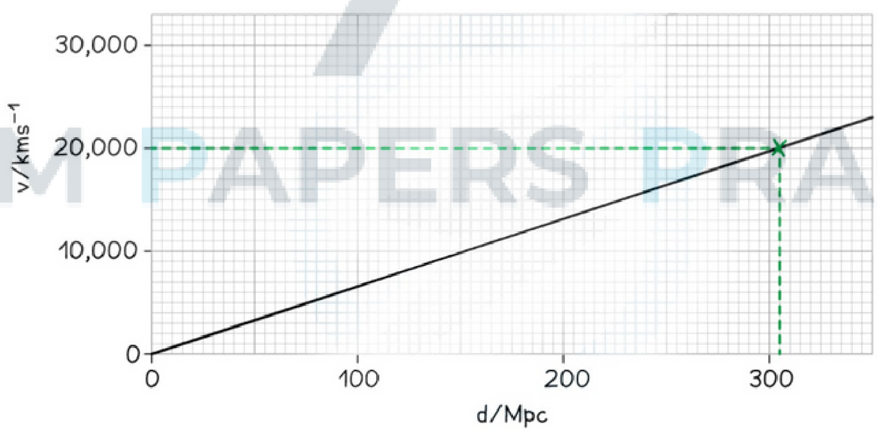
Use the graph to determine a value for the Hubble constant and state its unit.

Answer:

Step 1: Recall Hubble's Law and Hubble's constant

- Hubble's Law: $v = Hd$
- The gradient of the speed-distance graph = H

Step 2: Read values of v and d from the graph



- From the graph: v = 20 000 km s^{-1}
- From the graph: d = 305 MPc

Step 3: Calculate the gradient of the graph

$$H = \frac{20\,000 - 0}{305 - 0} = 65.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

Hubble constant: H = 66 km s^{-1} Mpc^{-1}

Exam Tip

The units for the quantities in Hubble's Law and for the Hubble Constant can change depending on the situation, Make sure you convert them to appropriate units and express your final answer correctly.

Estimating the Age of the Universe

- Hubble's Law is extremely important as it can give us an **estimate the age of the Universe**
- It can be used to find the **time** since the expansion began, and hence the age of the Universe
- We can calculate the time taken to reach a distant object from the Earth if we know
  - How **far away** it is
  - Its **recessional speed**

- This requires a couple of assumptions:
  - All points in the Universe were initially together
  - The recessional speed of a galaxy is and has always been, constant

- Comparing the equation for speed, distance and time:

$$time = \frac{distance}{speed} = \frac{d}{v}$$

- With the Hubble equation:

$$v = Hd \quad \Rightarrow \quad H = \frac{v}{d}$$

- It can be seen that:

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

- If we consider that all matter was at the same point at the very start of the Big Bang (t = 0), then the time taken for the galaxy to expand to its current state must be equal to the **age of the Universe**
- Using current estimations of the Hubble constant, astronomers believe that the universe has been expanding for around **13.7 billion years**

Worked Example

In 2020, the best estimate for the Hubble constant was 67.4 km s^{-1} Mpc^{-1}.

Use this value to calculate the age of the Universe.

Answer:

Step 1: List the known quantities

- Hubble constant, H = 67.4 km s^{-1} Mpc^{-1}
- 1 parsec ≈ 3.1×10^{16} m
- 1 year = 3.16×10^{7} s

Step 2: Convert 67.4 km s^{-1} Mpc^{-1} to m s^{-1} Mpc^{-1}

- H = 67.4 km s^{-1} Mpc^{-1} = 67.4 × 1000 = 6.74×10^{4} m s^{-1} Mpc^{-1}

Step 3: Convert 1 Mpc to m

- 1 Mpc = $(3.1 \times 10^{16}) \times (1 \times 10^{6}) = 3.1 \times 10^{22}$ m

Step 4: Convert m s^{-1} Mpc^{-1} to s^{-1}

- $H = 6.74 \times 10^{4}$ m s^{-1} Mpc^{-1} = $\frac{6.74 \times 10^{4}}{3.1 \times 10^{22}} = 2.17 \times 10^{-18}$ s^{-1}
- Hence, $H = 2.17 \times 10^{-18}$ s^{-1}

Step 5: Calculate the age of the Universe

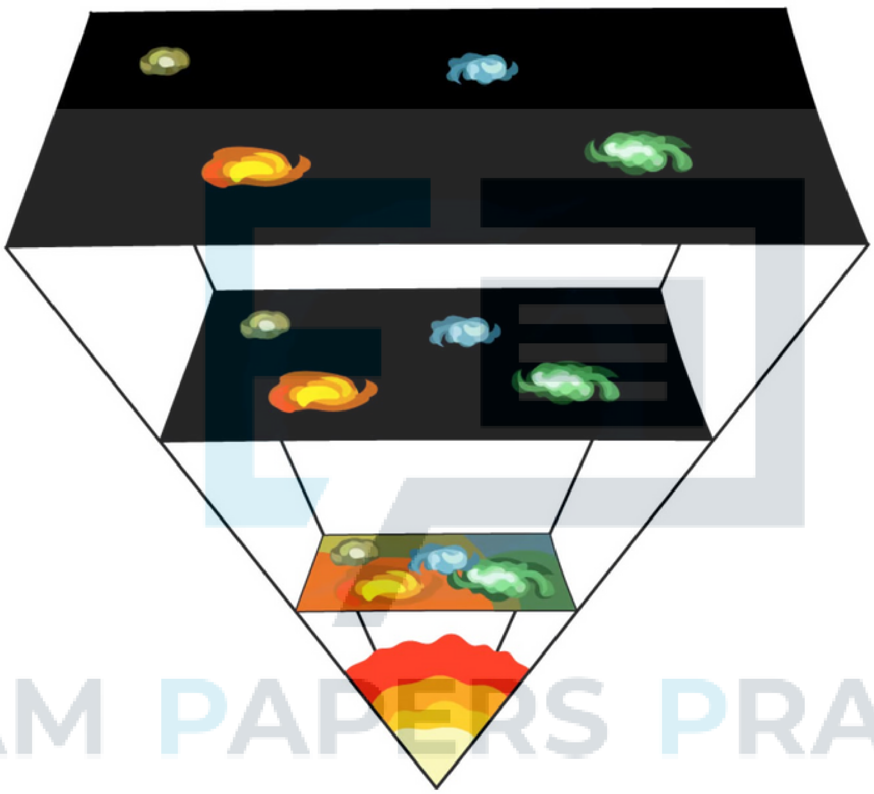
- Age of the Universe: $t = \frac{1}{H} = \frac{1}{2.17 \times 10^{-18}} = 4.60 \times 10^{17}$ s
- Age of the Universe: $t = \frac{4.60 \times 10^{17}}{3.16 \times 10^{7}} = 1.46 \times 10^{10}$ years = 14.6 billion years

9.3.5 Evidence for the Big Bang

Evidence for the Big Bang

- Around **13.7 billion years** ago, all the matter in the Universe exploded from a hot, dense singularity
- Since then, the matter has been **expanding** and **cooling** from this single point to form the Universe that exists today
  - 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've began with a "big bang"

- There are three key pieces of evidence to support the Big Bang theory:

1. Galactic redshift & Hubble's law

  - This provides strong evidence for the expansion of the Universe

2. Cosmic Microwave Background Radiation (CMBR)

  - This provides evidence that the Universe had a hot beginning

3. The relative abundance of hydrogen and helium

  - This provides evidence the Universe was once far hotter and denser than it is now

Evidence from Galactic Redshift

- Redshift provides evidence that the Universe is expanding because:

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

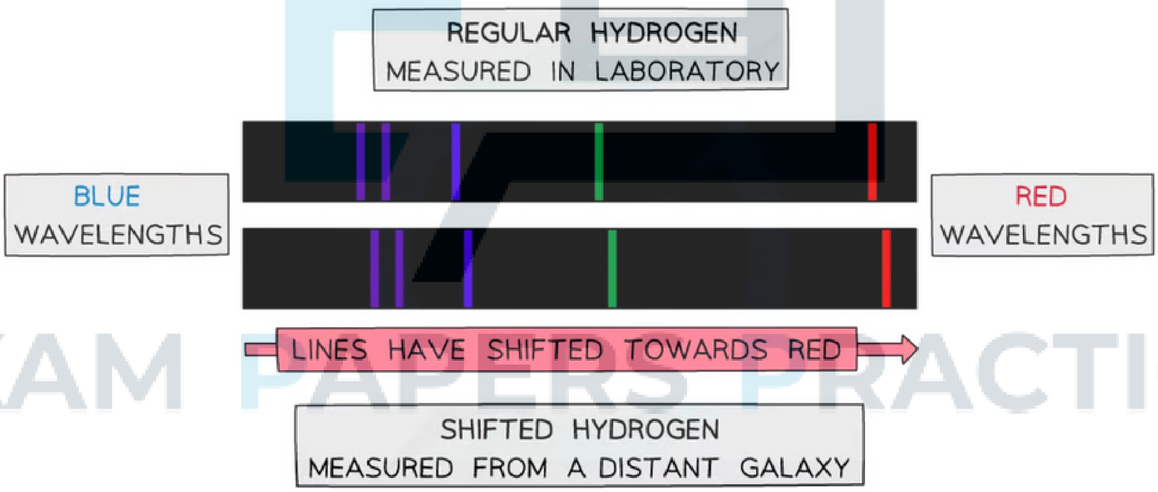
- Light spectra from distant galaxies show redshift
- The light waves stretch (i.e. wavelength increases) due to the expansion of the universe

2. Hubble's law shows that the further away the galaxy, the faster it is moving away from us

- Observations show that the further away a galaxy is, the greater the redshift
- From Hubble's law $(v \propto d)$ the further away a galaxy is, the faster its recession speed

3. This suggests that at some point in the past, all galaxies must have been at the same point

- Extrapolating Hubble's law back to time t = 0 suggests that matter must have been closer together in the past

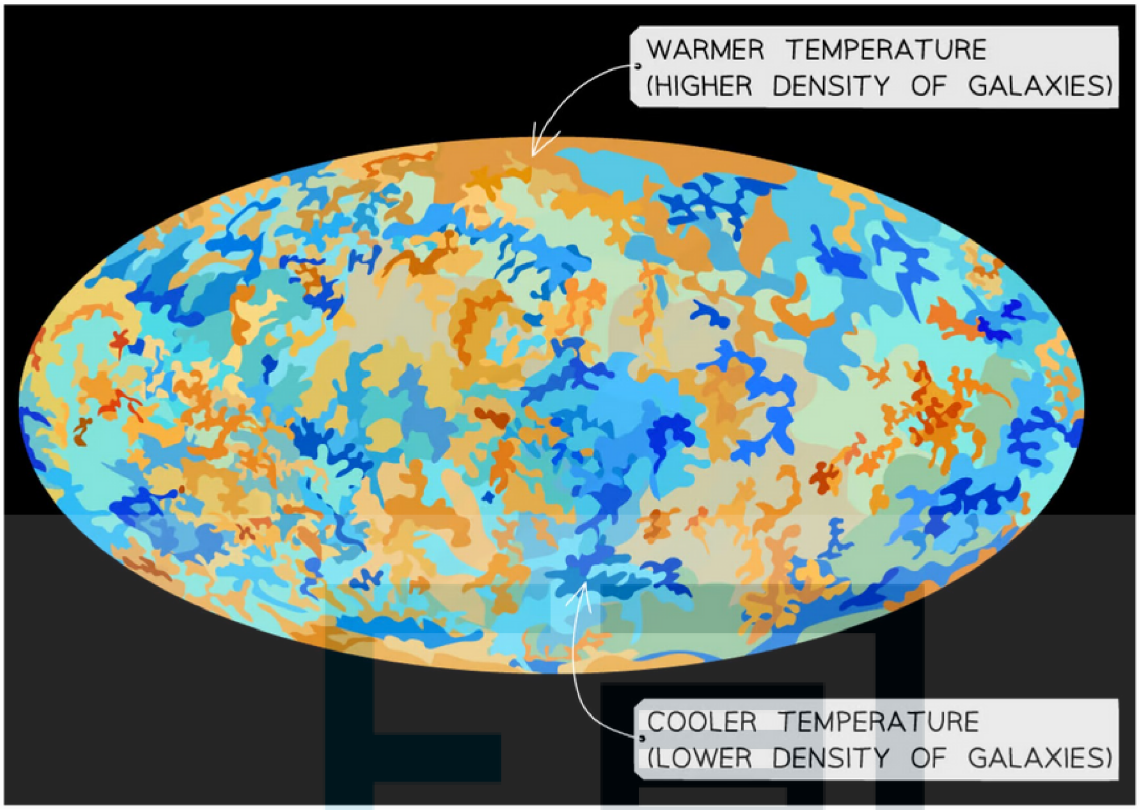


Comparing the light spectrum produced from the Sun and a distant galaxy

Cosmic Microwave Background Radiation

- Cosmic microwave background radiation (CMBR) is the radiation detected in **all** parts of the Universe
- The spectrum of CMBR shows a peak in the **microwave** region that corresponds to a temperature of **2.7 K**
- The CMBR is found to be extremely **uniform** throughout the Universe

CMBR Map of the Universe



The CMBR map with areas of higher and lower temperature

- The CMBR map is the closest image that exists to a map of the Universe
- The different colours represent extremely small fluctuations in temperature
  - The redder regions represent slightly **warmer** temperatures indicating a **higher density** of galaxies
  - The bluer regions represent slightly **cooler** temperatures indicating a **lower density** of galaxies

Evidence from Cosmic Microwave Background Radiation

- Cosmic microwave background radiation provides evidence that the Universe had a hot beginning because:

1. Theory predicts the existence of uniform black body radiation that peaks in the microwave region

- CMBR is isotropic, meaning it can be detected coming from all directions equally
- Measurements show it perfectly fits a black-body profile with a peak wavelength in the microwave region
- It is extremely uniform which indicates the Universe was initially much smaller than it is now

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

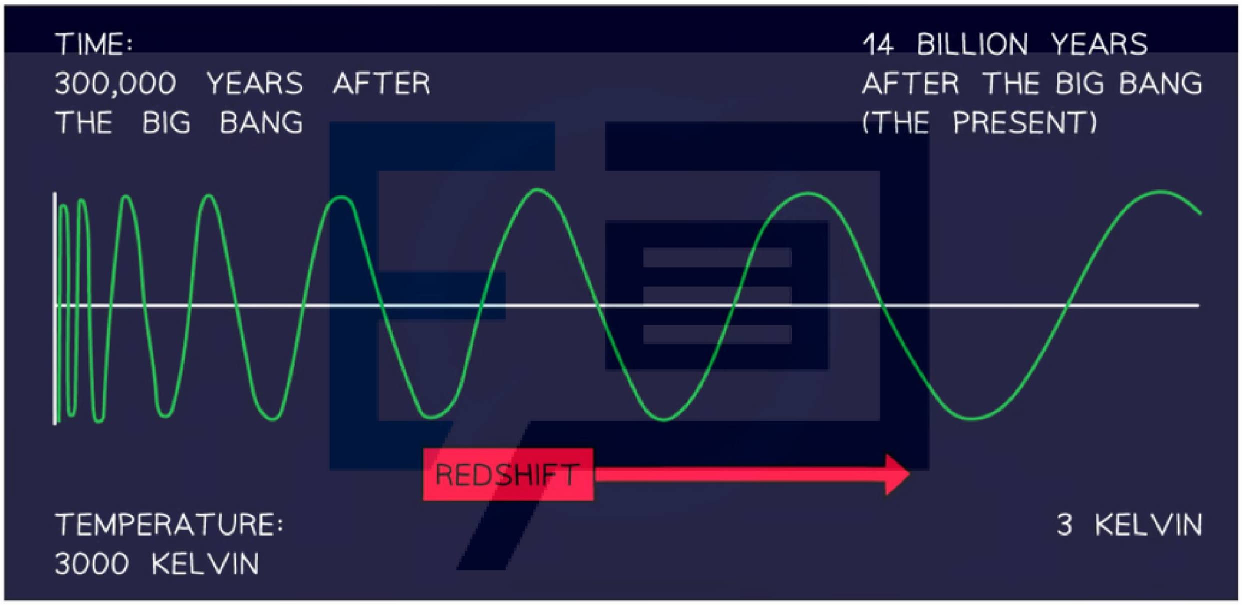
- The wavelength of the CMBR has been redshifted by an expanding and cooling Universe

- The shorter wavelength in the past indicates the Universe must have been very hot in the beginning

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

- CMBR was emitted when the Universe cooled sufficiently for matter and radiation to 'decouple' i.e. when protons and electrons combined into neutral atoms and photons were released
- The emitted radiation would have been extremely high-energy gamma which has been redshifted into the microwave region as the Universe has expanded

Redshift of CMBR



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

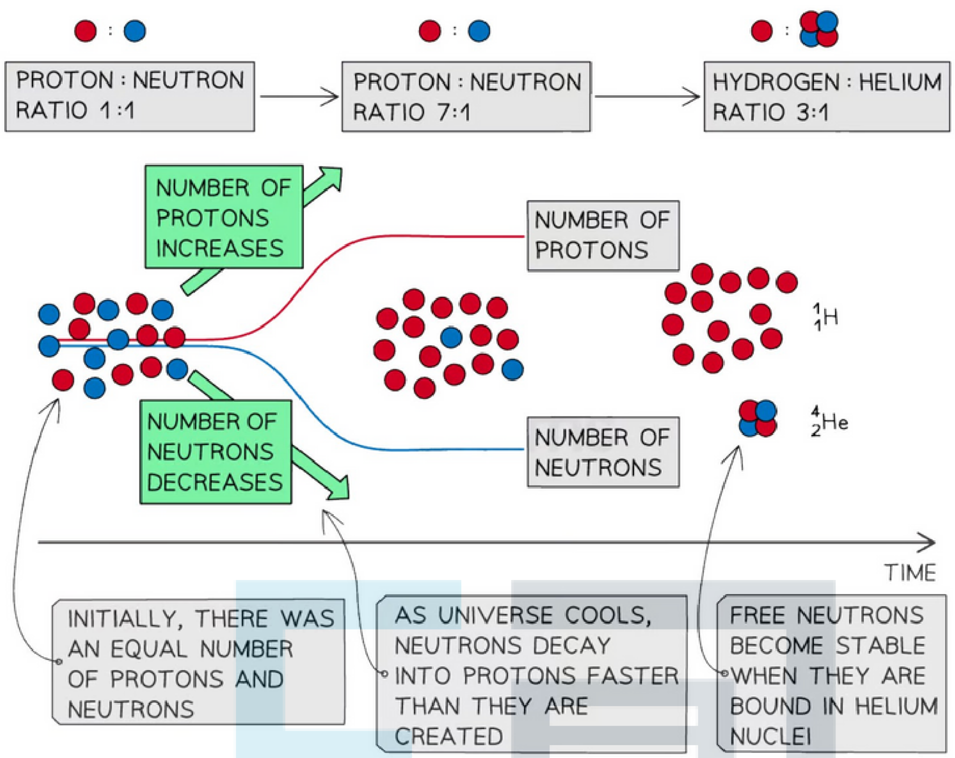
Relative Abundance of Hydrogen & Helium

- At the time of the Big Bang, the Universe would have been extremely hot
- Initially, it would have been **too hot** for even protons and neutrons to exist

- The Universe would have quickly cooled to the point where protons and neutrons could exist freely
- However, at this point, free neutrons would start to **decay** into protons
- As a result, the ratio of protons to neutrons would **increase** rapidly

- For a **short time**, it would have been hot enough for hydrogen nuclei to **fuse** into helium nuclei
- The neutrons bound in helium nuclei would then become **stable**

Nucleosynthesis of Hydrogen & Helium



- Initially, the ratio of protons to neutrons is 1:1
  - In a sample of 16 nucleons, there would be 8 protons and 8 neutrons
  - If 6 neutrons decay into protons, then there would be 14 protons and 2 neutrons
- The ratio of protons to neutrons becomes 7:1
  - During fusion, 2 neutrons combine with 2 protons to form a helium nucleus, i.e. 4 nucleons in total
  - Out of 16 nucleons in total, **25%** of the total mass (4 nucleons) makes up a **helium** nucleus and **75%** of the total mass (12 protons) makes up **hydrogen** nuclei
  - Therefore, the relative abundance of hydrogen to helium in the early Universe is **3:1**

Evidence from the Relative Abundance of Hydrogen & Helium

- The relative abundance of hydrogen and helium provides evidence for the Universe being hotter and denser in the past because:

  1. Theory predicts hydrogen fused into helium nuclei in the early Universe

  - The Big Bang theory suggests that a very brief period of hydrogen fusion occurred when the Universe was very young and hot, resulting in the production of helium

  2. Fusion would have stopped before heavier nuclei were created

  - As the Universe expanded and cooled, fusion reactions would have stopped before the creation of larger nuclei could have taken place

  3. The predicted relative abundances of hydrogen and helium are consistent with observation

- Calculations predict the early Universe would've consisted of hydrogen and helium nuclei in the ratio of 3:1
- This is consistent with observations of some of the Universe's oldest objects (73% hydrogen, 25% helium and 2% everything else)

Exam Tip

Take some time to practice writing succinct answers to the following:

Explain how .... supports the Big Bang theory.

- Galactic redshift and Hubble's law
- The existence of cosmological microwave background radiation
- The relative abundance of hydrogen and helium

As one, or all of these could come up in the exam!

9.3.6 Dark Matter & Dark Energy

Dark Energy & Dark Matter

- Over several decades, astronomers have gathered a wealth of evidence that has furthered our understanding of the Universe
  - Ascertaining a precise value for the Hubble constant was one of the most **important goals of cosmology** then, and still is today

- In the past, huge **discrepancies** between measured values of the Hubble constant and predictions from Hubble's law were ascribed to random and systematic errors
- However, as our telescopes and imaging techniques become more sophisticated, it's becoming increasingly clear that different sources at different distances seem to produce **fundamentally different values** of H
  - For example, CMB observations give a value of $H = 68$ km s^{-1} Mpc^{-1} but measurements from type 1a supernovae give a value of $H = 73$ km s^{-1} Mpc^{-1}
  - This discrepancy is known as the **Hubble Tension** problem, and it's one of the deepest mysteries of cosmology at the moment

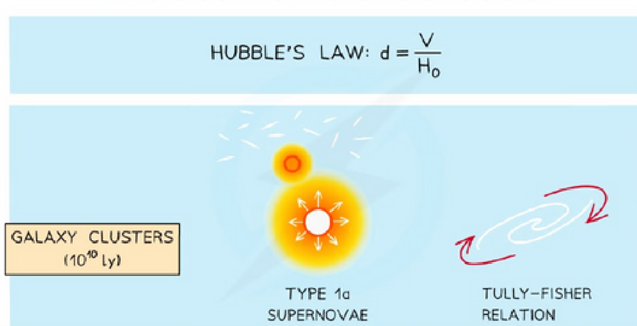
- Measurements of type 1a supernovae, which tend to be very distant, suggest that the Universe is expanding at an **increasing rate**
- This means that the Universe is not only expanding, but the rate of expansion is **accelerating**, and astronomers have no idea why

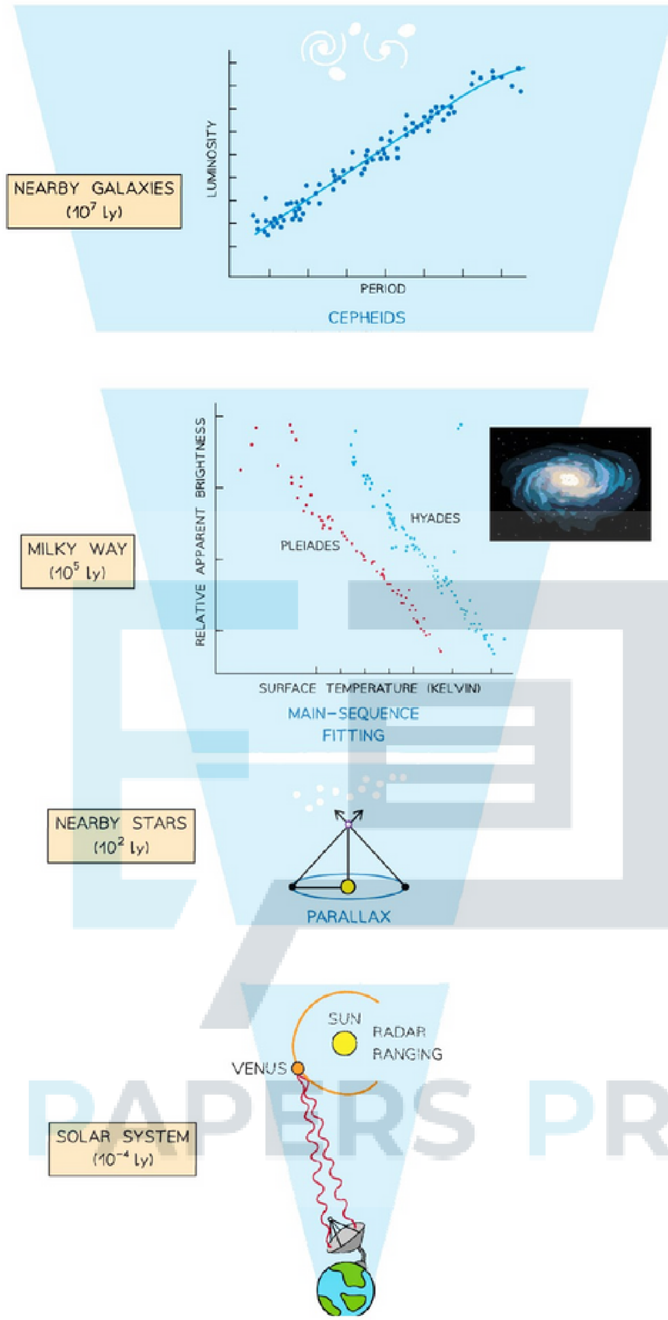
Dark Energy: A Controversial Solution

- It has been suggested that the acceleration of expansion could be caused by a mysterious energy source called **dark energy**
- However, dark energy is **controversial** because:
  - It cannot be detected directly, but there is evidence for its existence
  - Nothing is known about its nature or its origins
  - No mechanisms can currently explain how it drives the accelerated expansion

- If dark energy isn't the solution, then cosmologists may need to re-think some of our fundamental models, such as the cosmic distance ladder, or even Einstein's Theory of General Relativity

The Cosmic Distance Ladder





Could everything we know about the cosmic distance ladder be wrong? Or are we on the verge of a huge cosmological breakthrough?

Exam Tip

Don't get dark energy confused with dark matter!

Dark matter is also one of the great mysteries of modern astronomy, however, it has more to do with rotational motion in galaxies or the gravitational lensing of starlight

9.3.7 Quasars

Quasars

- Quasars, or quasi-stellar objects, are

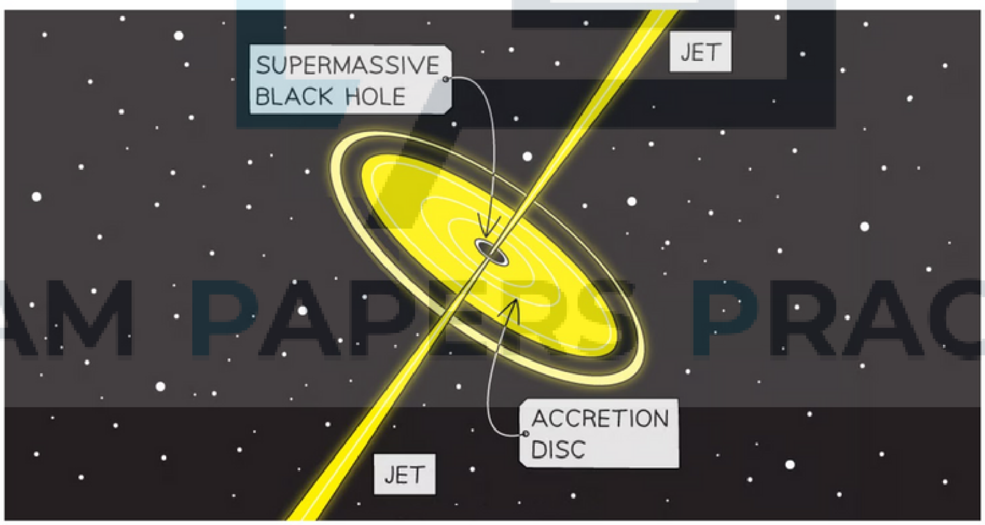
Extremely luminous star-like sources of radiation with very high redshifts

- Quasars were first discovered in the 1960s due to their **strong radio emissions** but were also notable for their
  - High luminosities
  - Extremely large redshifts
  - Small size

Formation of Quasars

- After the discovery of supermassive black holes at the centres of galaxies, astronomers were able to determine that quasars are a type of active galactic nucleus, meaning
  - They are supermassive black holes surrounded by an **accretion disc** of matter
  - They are found at the centre of **extremely distant** galaxies
  - When they become **active**, i.e. when matter falls into it, they become quasars

Structure of a Quasar



The quasar features a black hole surrounded by an accretion disk and emits jets of radiation

- As matter falls into the black hole, **jets** of radiation are emitted from the poles
  - The equivalent of 100 solar masses of matter can fall into a quasar each year
  - The gravitational potential energy of infalling matter is transferred to electromagnetic radiation
  - Now it is known that quasars are strong emitters of **all** wavelengths, not just radio waves

Redshift of Quasars

- Quasars are thought to be some of the **most distant** measurable objects in the known universe

- This is evidenced by the extremely large redshifts they show
- This allows astronomers to see very far back to an early Universe as it was not long after the Big Bang

9.3.8 Exoplanets

Exoplanets

- An exoplanet is:

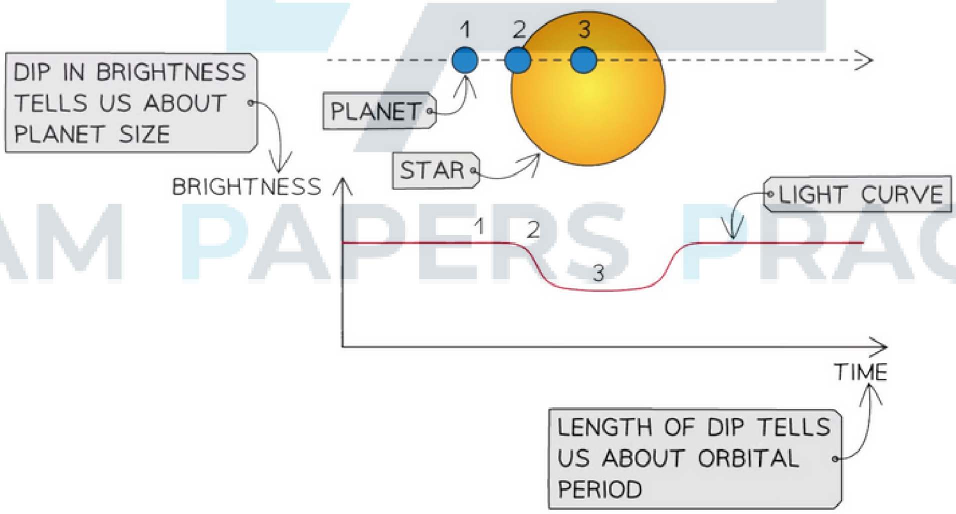
A planet found outside our Solar System, in orbit around another star

- Exoplanets are difficult to detect directly because:
  - Light from the host star is much **brighter** than the reflected light from the planet
  - They subtend extremely **small angles** compared to the resolution of telescopes
- Astronomers must use indirect detection techniques to observe exoplanets, such as:
  - Transit method
  - Radial velocity method

The Transit Method

- When a planet passes in front of a star (as seen from Earth), some of the light from the star is obscured
- Therefore, the total amount of light reaching the Earth is reduced
- By measuring the apparent magnitude, or intensity of light received from the star over time, a **light curve** can be obtained

Light Curve using the Transit Method



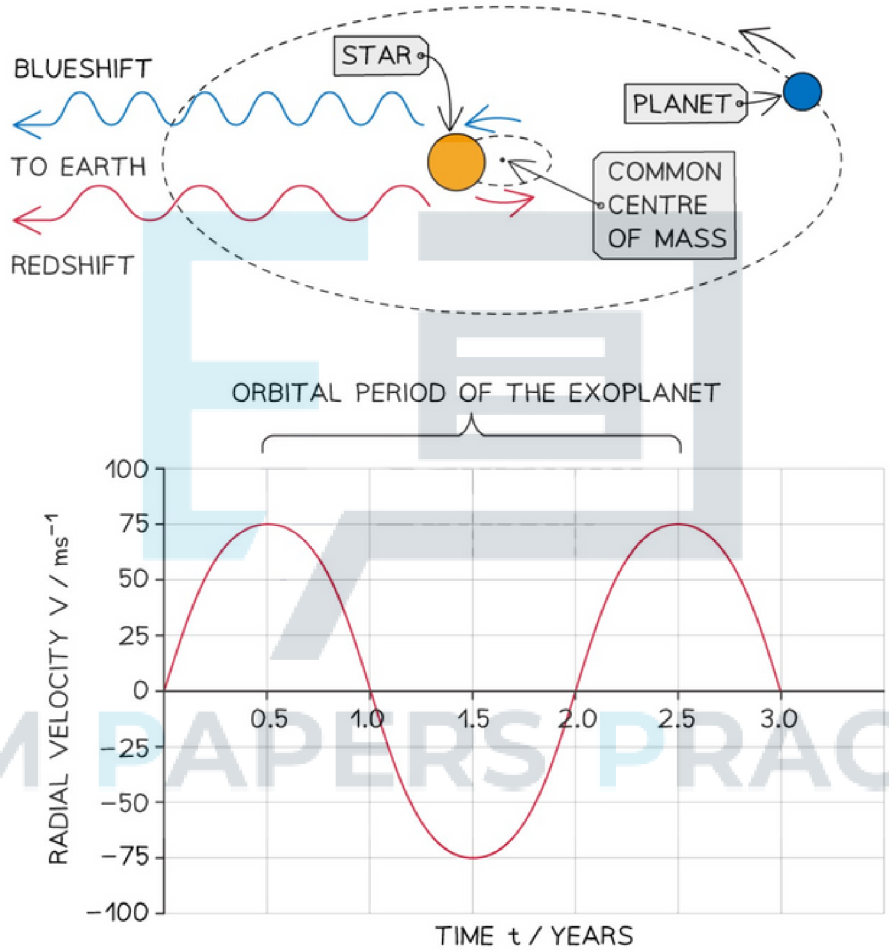
The transit method can tell us about both the size of the exoplanet and its orbital period

- The dip in brightness can be used to determine the **size** of the planet
- The duration of the dip can be used to determine the **orbital period** of the planet
- Some of the limitations of this technique are:
  - The accuracy can be reduced if the Earth, planet and star are not aligned in the same plane
  - Only planets with a short orbital period can be detected

The Radial Velocity Method

- As a planet orbits its host star, they both orbit around a common centre of mass
- During the orbit, the star will move slightly towards, or away from the Earth as the planet moves to different positions in the orbit
    - The line spectrum of the star will show **blueshift** when it moves towards the Earth, then **redshift** when it moves away

Doppler Shift of an Exoplanet



How to determine the orbital period of an exoplanet using the radial velocity method

- This causes very small, but measurable, periodic shifts in the wavelength of the light received from the star
    - The time period of the planet's orbit is equal to the time period of the Doppler shift
- The main limitation of this technique is that
    - Low-mass, or Earth-like, planets do not cause as much 'wobble' as high-mass planets since they have a greater gravitational pull on the star