Edexcel International A Level (IAL) Physics

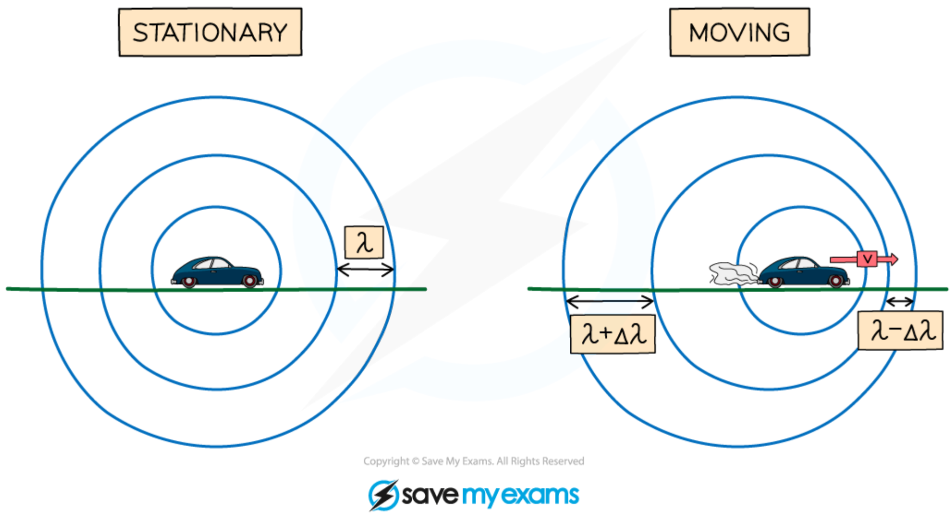
Your notes

Cosmology

Contents

Doppler Shift

- If a wave source is stationary, the wavefronts spread out **symmetrically**
- If the wave source is moving, the waves can become **squashed** together or **stretched** out
  - If the wave source is moving **towards** an observer the wavefronts will appear **squashed**
  - If the wavefront is moving **away** from an observer the wavefronts will appear **stretched** out
- Therefore, when a wave source moves relative to an observer there will be a change in the observed **frequency** and **wavelength**



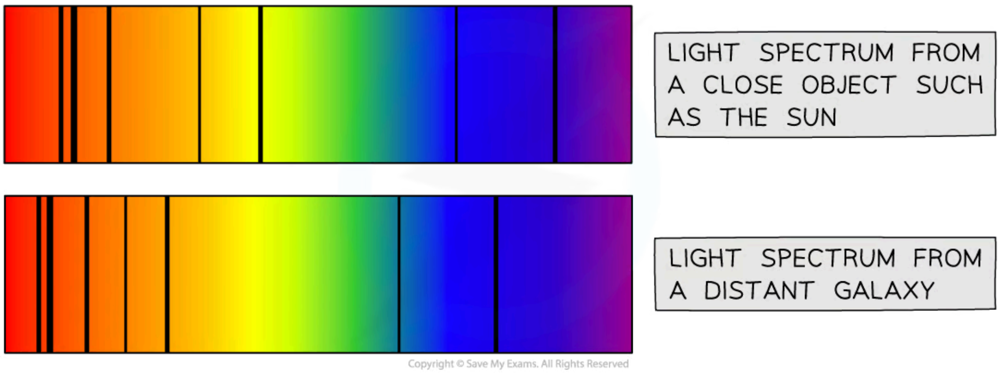
Wavefronts are even in a stationary object but are squashed in the direction of the moving wave source

- A moving object will cause the **wavelength**, λ, (and frequency) of the waves to change:
  - The **wavelength** of the waves **in front** of the source **decreases** ($\lambda - \Delta\lambda$) and the **frequency increases**
  - The wavelength **behind** the source **increases** ($\lambda + \Delta\lambda$) and the **frequency decreases**
- Note: Δλ means '**change in wavelength**'
  - The actual wavelength emitted by the source remains the same
  - It is only the wavelength that is received by the observer that appears to have changed

- This effect is known as the **Doppler effect** or **Doppler shift**
- The Doppler effect is defined as:

  The apparent shift in wavelength occurring when the source of the waves is moving

- The Doppler effect, or Doppler shift, can be observed using any form of **electromagnetic radiation**
- It can be observed by comparing the light spectrum produced from a close object, such as our Sun, with that of a distant galaxy
  - The light from the distant galaxy is shifted towards the red end of the spectrum (There are more spectral lines in the red end)
  - This provides evidence that the universe is expanding



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

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Redshift Equation

- Recall the Doppler effect is defined as:

  The apparent change in wavelength or frequency of the radiation from a source due to its relative motion away from or toward the observer

  - On Earth, the Doppler effect is most easily observed when something which is both fast moving and emitting a loud sound (such as an ambulance or fast car) moves past an observer, producing a characteristic change in the pitch of the sound that is heard
- In space, the Doppler effect of light can be observed when spectra of distant stars and galaxies are observed, this is known as:
  - **Redshift** if the object is moving away from the Earth, or
  - **Blueshift** if the object is moving towards the Earth
- Redshift is defined as:

  The fractional increase in wavelength (or decrease in frequency) due to the source and observer receding from each other

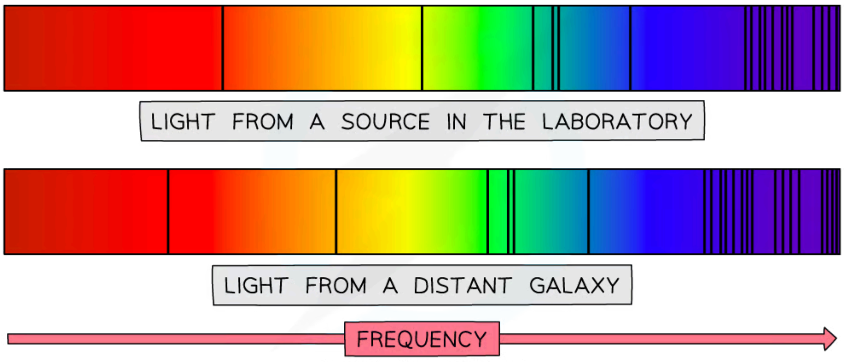
- For non-relativistic galaxies, Doppler redshift can be calculated using:

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

- Where:
  - $\Delta\lambda$ = shift in wavelength (m)
  - λ = wavelength emitted from the source (m)
  - Δf = shift in frequency (Hz)
  - f = frequency emitted from the source (Hz)
  - v = speed of recession (m s^{-1})
  - c = speed of light in a vacuum (m s^{-1})

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 has a frequency of 4.547×10^{14} Hz.

a) What speed is the distance galaxy moving in relation to the Earth?

b) Is it moving towards or away from the Earth?

Answer:

Part (a)

Step 1: Write down the known quantities

- Emitted frequency, $f = 4.570 \times 10^{14}$ Hz
- Shift 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

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

Part (b)

Step 1: Compare the frequencies and answer the question

- The observed frequency is **less** than the emitted frequency (the light from a laboratory source),
- The source is **receding** (moving away from) from the Earth

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Examiner Tips and Tricks

In your exam, be sure to emphasise that redshift means the wavelength of spectral lines increases towards the red end of the spectrum, **do not** say that the spectral lines become red, as this is incorrect.

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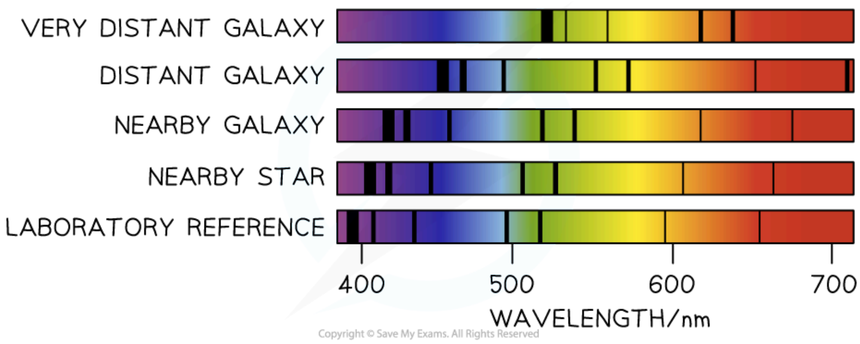
The Hubble Equation

- In 1929, the astronomer Edwin Hubble showed that the universe was **expanding**
  - He did this by observing that the absorption line spectra produced from the light of distant galaxies was shifted towards the **red** end of the spectrum
  - This **doppler shift** in the wavelength of the light is evidence that distant galaxies are moving away from the Earth
- Hubble also observed that light from more distant galaxies was **shifted further** towards the red end of the spectrum compared to closer galaxies
  - From this observation he concluded that galaxies or stars which are **further away** from the Earth are **moving faster** than galaxies which are closer



- Hubble's law states:

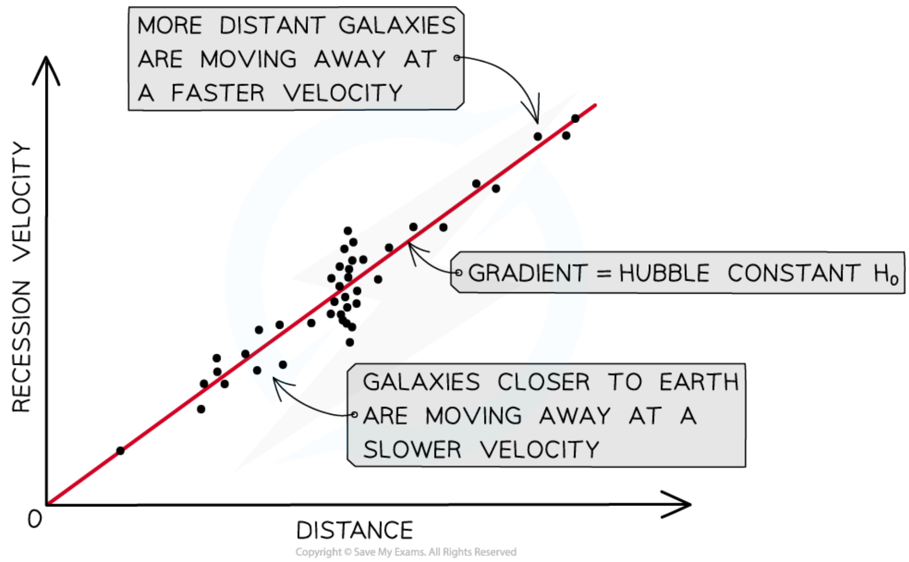
The recessional velocity, v, of a galaxy is proportional to its distance from Earth

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

$$v \approx H_0 d$$

- Where:
  - v = recessional velocity of an object, the velocity of an object moving **away** from an observer (km s^{-1})
  - H_0 = Hubble constant, this will be provided in your examination along with the correct units (km s^{-1} Mpc^{-1})
  - d = distance between the object and the Earth (Mpc)

- Alternatively, if the velocity of the receding object was measured in km s^{-1} and the distance from the earth to the object was measured in km, then then unit for the Hubble constant would be s^{-1}
- Hubble's law shows:
  - The further away a star is from the Earth, the faster it is moving away from us



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

Worked Example

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

Use Hubble's Law to determine the velocity of the galaxy as it moves away from Earth.

The Hubble constant is currently agreed to be 2.2×10^{-18} s^{-1}.

Answer:

Step 1: List the known quantities:

- d = 20 light years
- $H_0 = 2.2 \times 10^{-18}$ s^{-1}

Step 2: Convert 20 light-years to m:

- From the data booklet: 1 ly ≈ 9.5×10^{15} m
- So, 20 ly = $20 \times (9.5 \times 10^{15}) = 1.9 \times 10^{17}$ m

Step 3: Substitute values into Hubble's Law:

- From the data booklet: $\mathbf{v \approx H_0 d}$
- So, $v \approx (2.2 \times 10^{-18}) \times (1.9 \times 10^{17}) = 0.418$ m s^{-1}

Step 4: Confirm your answer:

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- The velocity of the galaxy as it moves away from Earth 0.42 m s^{-1}

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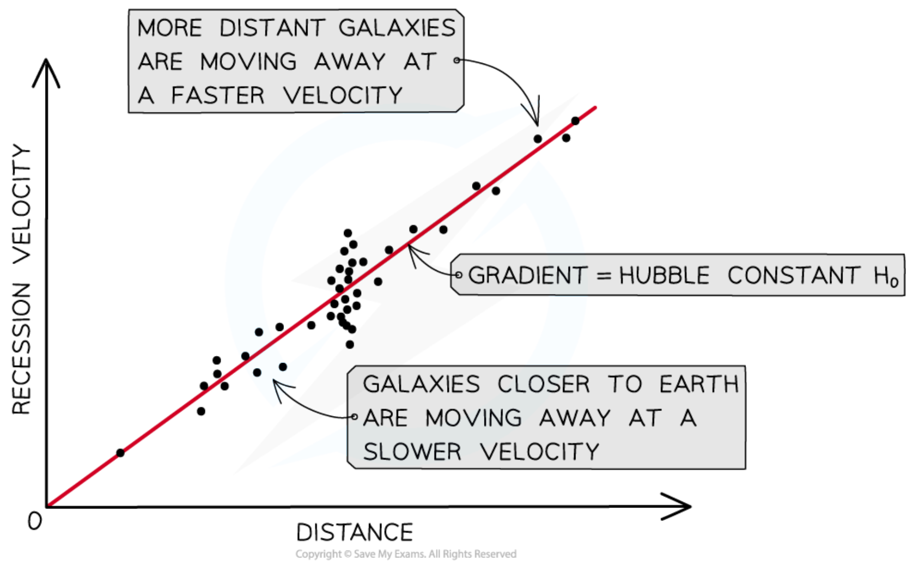
The Hubble Constant

- By rearranging the equation for Hubble's law, we can determine that the Hubble constant, H_0, is:

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

- Where:
  - v = recessional velocity of an object (km s^{-1})
  - d = distance between the object and the Earth (Mpc)
  - H_0 = Hubble constant (km s^{-1} Mpc^{-1})



- The value for the Hubble constant has been estimated using data for thousands of galaxies
  - The latest estimate of the Hubble constant based on CMB observations by the Planck satellite is:

H_0 **= 67.4 ± 0.5 km** $\mathbf{s^{-1}}$ **Mpc**$\mathbf{^{-1}}$ (Planck Collaboration VI 2020)

- It is difficult to be certain about just how accurate the values for the Hubble constant are
  - This is due to the random and systematic errors involved when calculating the distance to a galaxy or star

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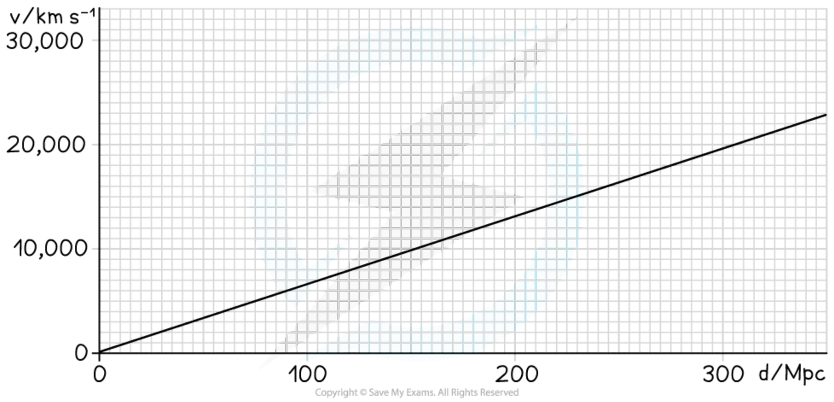
Worked Example

The graph shows how the recessional velocity, v, of galaxies varies with their distance, d, measured from the Earth.



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

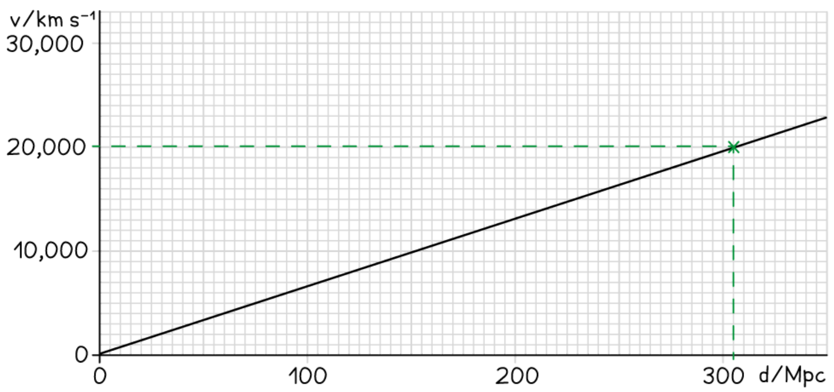
Answer:

Step 1: From the data booklet:

Hubble's Law: $\boldsymbol{v \approx H_0 d}$

Step 2: Determine the Hubble constant, H_0, from the graph:

- y-axis = v = 20, 000
- x-axis = d = 305
- gradient = H_0



Step 3: Calculate the gradient of the graph:

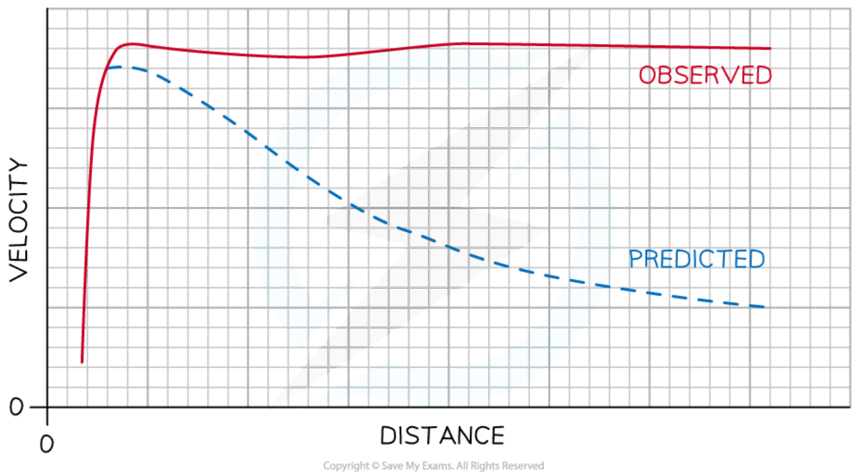
- $H_0 = \frac{y_2 - y_1}{x_2 - x_1} = \frac{20\,000 - 0}{305 - 0} = 66 \text{ km s}^{-1} \text{ Mpc}^{-1}$

Step 4: Confirm your answer:

- The Hubble Constant = 66 km s^{-1} Mpc^{-1}

Dark Matter

- We would expect the **velocity** of an object within a galaxy to **decrease** as it moves away from the galaxy's centre because of weakening gravitational field strength
  - This is observed in smaller mass systems, like the solar system where planets orbiting **furthest** from the Sun have the **slowest orbital velocity**
  - This is not the case in bigger mass systems like entire galaxies



- Mass is not actually concentrated in the centre of galaxies; it is **spread out**
  - All the observable mass of a galaxy is, however, concentrated in its centre, so there must be another type of matter we can't see, called **Dark Matter**
- Dark matter is defined as:

  Matter which cannot be seen and that does not emit or absorb electromagnetic radiation

- Dark matter cannot be detected directly through telescopes
  - It should make up 27% of the mass in the universe
  - It is detected based on its gravitational effects relating to either the rotation of galaxies or by the gravitational lensing of starlight

Your notes