Exercise walk-through

Hubble's law and the Big Bang theory ▪ 25.3

eXercise

You must be able to

- use the **redshift** $\frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}$
- use **Hubble's law** $v \approx H_0 d$
- explain how redshift and Hubble's law support the **Big Bang**

Method — Redshift

The spectral lines of distant galaxies are at **longer** wavelengths than in the lab — a **redshift**, showing the galaxy is moving **away**. For $v \ll c$:

$$\frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}, \qquad \Delta\lambda = \lambda_{\text{observed}} - \lambda_{\text{emitted}}.$$

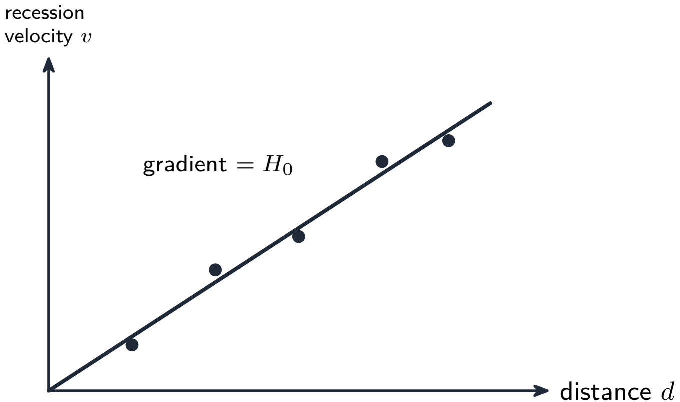
Method — Hubble's law

The recession speed is **proportional to distance**:

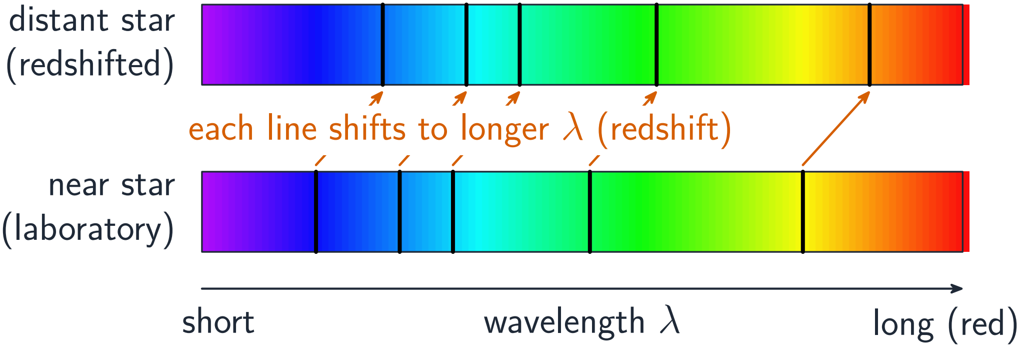
$$v \approx H_0 d.$$

Every galaxy moving away (faster if further) means the Universe is **expanding** — so in the past it was smaller and denser, leading to the idea that it began from a single point: the **Big Bang**.

Method — Hubble's law



Method — Hubble's law



Redshift in a galaxy spectrum

Practice 2.1 ▪ 1 mark

State what is meant by **redshift**.

Solution 2.1

Method: Redshift

Worked steps

The **increase in wavelength** of light from a source moving **away** from the observer **B1**.

Practice 2.2 ▪ 1 mark

Write the **redshift** equation linking $\Delta\lambda$, λ and v.

Solution 2.2

Method: Redshift

Worked steps

$$\frac{\Delta\lambda}{\lambda} \approx \frac{v}{c} \quad \boxed{\textbf{B1}}.$$

Practice 2.3 ▪ 1 mark

Write **Hubble's law**.

Solution 2.3

Worked steps

$v \approx H_0 d$ **B1**.

Practice 2.4 ▪ 1 mark

State what the redshift of distant galaxies tells us about the Universe.

Solution 2.4

Method: Redshift

Worked steps

It is **expanding** (galaxies are moving apart) **B1**.

Exam-style 3.1 ▪ 1 mark

The redshift of distant galaxies is evidence that:

A the Universe is static

B the Universe is expanding

C galaxies are approaching us

D light slows down over distance

Solution 3.1

Method: Redshift

A the Universe is static

B the Universe is expanding ✓

C galaxies are approaching us

D light slows down over distance

Worked steps

B — the Universe is expanding.

Exam-style 3.2 ▪ 3 marks

A spectral line emitted at 4.62×10^{-7} m is observed at 4.91×10^{-7} m. Calculate the **recession velocity** of the source.

Solution 3.2

Method: Redshift

Worked steps

$\Delta\lambda = 4.91 \times 10^{-7} - 4.62 \times 10^{-7} = 0.29 \times 10^{-7}$ m **M1**; $v = \frac{\Delta\lambda}{\lambda} c = \frac{0.29 \times 10^{-7}}{4.62 \times 10^{-7}}(3.0 \times 10^{8})$ **M1** $= 1.9 \times 10^{7}$ m s^{-1} **A1**.

Exam-style 3.3 ▪ 2 marks

A galaxy recedes at 2.0×10^7 m s^{-1}. Taking $H_0 = 2.2 \times 10^{-18}$ s^{-1}, calculate its **distance**.

Solution 3.3

Worked steps

$$d = \frac{v}{H_0} = \frac{2.0 \times 10^{7}}{2.2 \times 10^{-18}} = 9.1 \times 10^{24}\ \text{m}\quad \textbf{M1}\ \textbf{A1}.$$

Exam-style 3.4 ▪ 3 marks

Explain how **Hubble's law** leads to the **Big Bang** theory.

Solution 3.4

Method: Hubble's law

Worked steps

All galaxies are moving **away**, faster the further they are B1, so the Universe is **expanding** — in the past it was smaller and denser B1; extrapolating back, everything began from a single point/event — the **Big Bang** B1.

Exam-style 3.5 ▪ 2 marks

A spectral line emitted at 486.1 nm in the laboratory is observed at 492.6 nm in the light from a distant galaxy. Take $c = 3.00 \times 10^{8}$ m s^{-1} and the Hubble constant as 2.3×10^{-18} s^{-1}.

(a) **State** Hubble's law.

(b) **Explain** why the observed and emitted wavelengths differ.

(c) **Determine** the speed of the galaxy relative to the Earth, and state whether it is approaching or receding.

(d) **Determine** the distance of the galaxy from the Earth.

(e) **Suggest** why an estimate of the age of the Universe can be made from the Hubble constant, and **state** one assumption that estimate depends on.

Solution 3.5

Method: Redshift

Worked steps

(a) The **recession speed** of a galaxy is **directly proportional to its distance** from us B1, $v = H_0 d$, for galaxies far enough away B1.

(b) The galaxy is **moving away** from us, so each wave takes slightly longer to reach us than the one before B1; the waves are stretched, the observed wavelength is longer, and the light is **redshifted** B1.

(c) $\dfrac{\Delta\lambda}{\lambda} = \dfrac{492.6 - 486.1}{486.1} = 0.01337$ M1; $v = \dfrac{\Delta\lambda}{\lambda}c = 0.01337 \times 3.00 \times 10^8$ M1 $= 4.0 \times 10^6$ m s^{-1}, **receding** — the wavelength has increased A1.

Solution 3.5

(d) $d = \dfrac{v}{H_0} = \dfrac{4.01 \times 10^6}{2.3 \times 10^{-18}}$ **M1** $= 1.7 \times 10^{24}$ m **A1**.

(e) If every galaxy has been moving apart at a constant speed since the beginning, the time since they were all together is $\dfrac{d}{v} = \dfrac{1}{H_0}$ **B1**, which gives about 4.3×10^{17} s, roughly 14 billion years **B1**. It assumes the expansion rate has **not changed** over that time **B1**.