The Expanding Universe

IB PHYSICS | ASTROPHYSICS

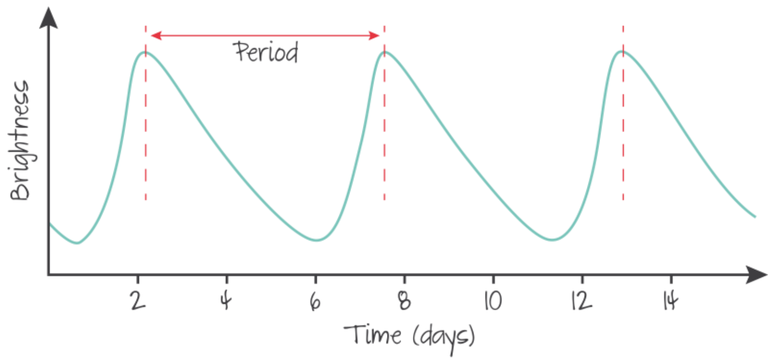
IB Physics Data Booklet

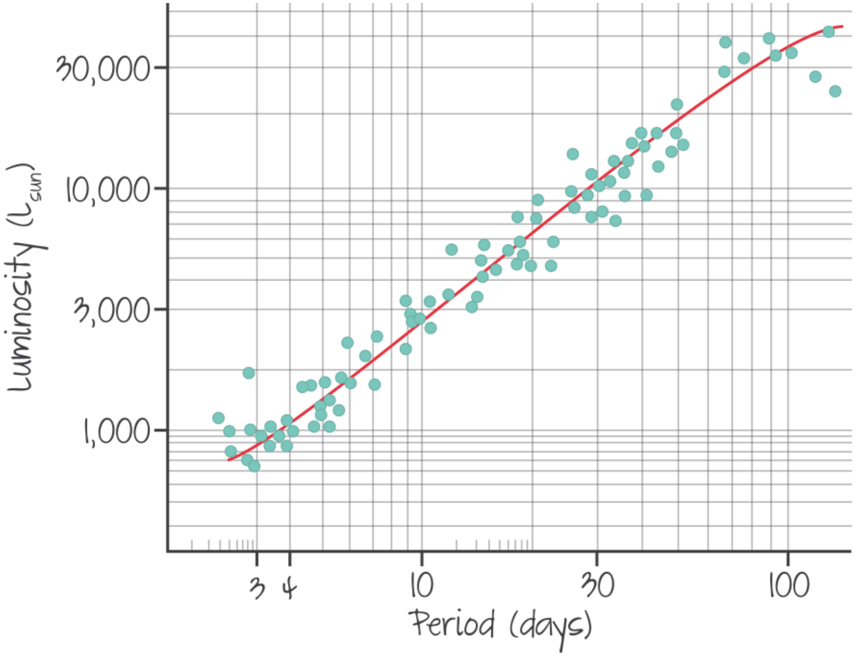
Sub-topic D.1 – Stellar quantities	Sub-topic D.2 – Stellar characteristics and stellar evolution
$d\ (\text{parsec}) = \dfrac{1}{p\ (\text{arc–second})}$ $L = \sigma A T^4$ $b = \dfrac{L}{4\pi d^2}$	$\lambda_{\text{max}} T = 2.9 \times 10^{-3}\ \text{m K}$ $L \propto M^{3.5}$
Sub-topic D.3 – Cosmology	**Sub-topic D.5 – Further cosmology (HL only)**
$z = \dfrac{\Delta\lambda}{\lambda_0} \approx \dfrac{v}{c}$ $z = \dfrac{R}{R_0} - 1$ $v = H_0 d$ $T \approx \dfrac{1}{H_0}$	$v = \sqrt{\dfrac{4\pi G\rho}{3}} r$ $\rho_c = \dfrac{3H^2}{8\pi G}$

Henrietta Swan Leavitt

Cephid Variables

“Standard Candle”



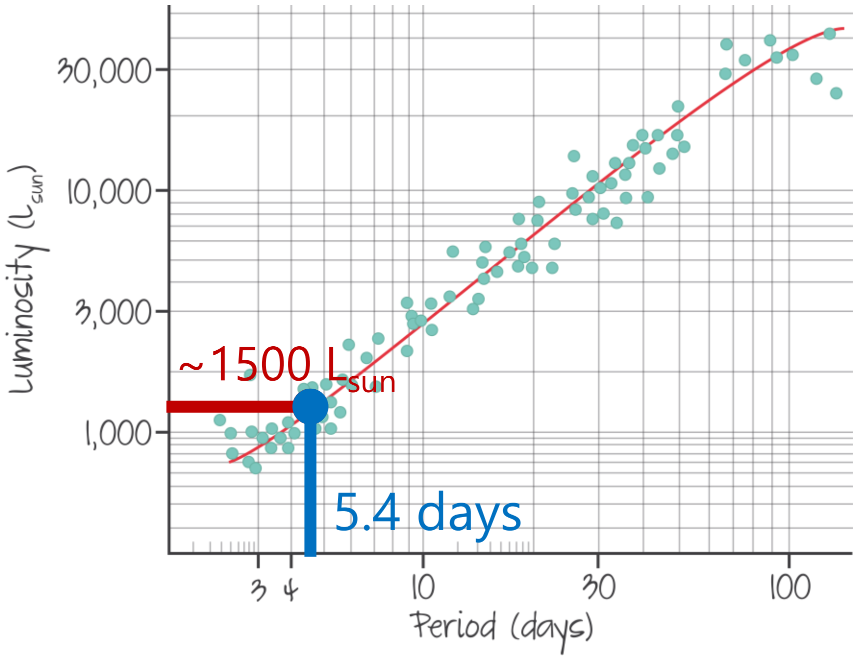


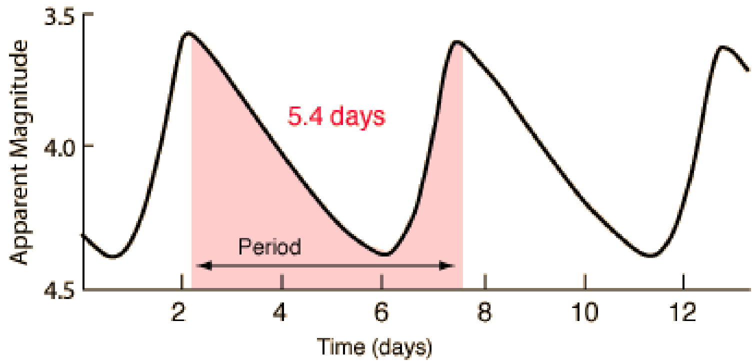
Cephid Variables with longer brightness periods are more luminous

With this table, the luminosity of this “standard candle” can be determined as long as the period is known

Cephid Variables

$1\ L_{sun} = 3.84 \times 10^{24}$ W





What is the distance of the Cephid Variable with the period shown in the graph above? The brightness of this star is 8×10^{-10} W m^{-2}.

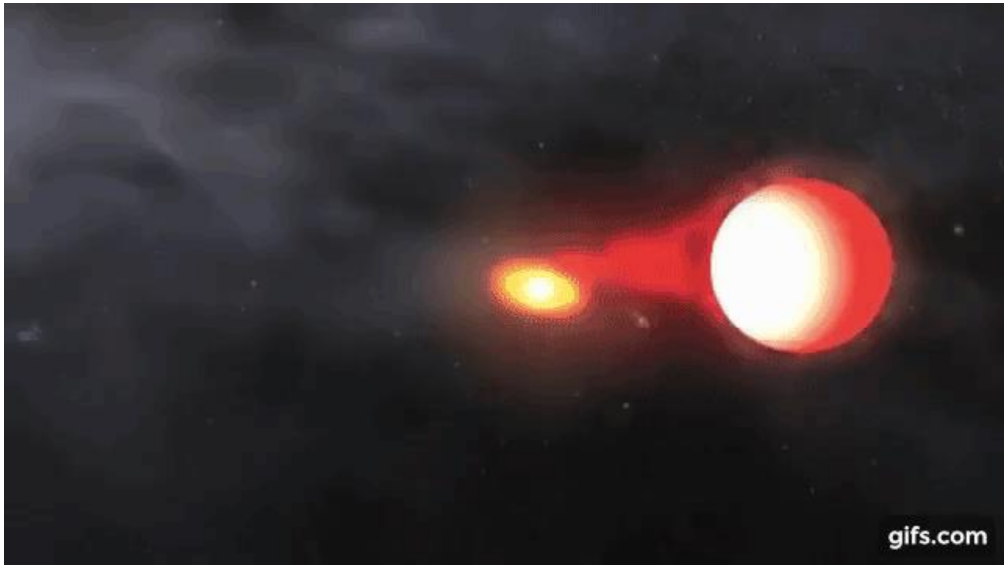
$$L_{star} = 1500 \times (3.84 \times 10^{24})$$
$$= 5.76 \times 10^{27}\ \mathrm{W}$$

$$b = \frac{L}{4\pi d^2} \rightarrow d = \sqrt{\frac{L}{4\pi b}} \rightarrow d = \sqrt{\frac{5.76 \times 10^{27}}{4\pi(8 \times 10^{-10})}} = \boxed{7.57 \times 10^{17}\ \mathrm{m}}$$

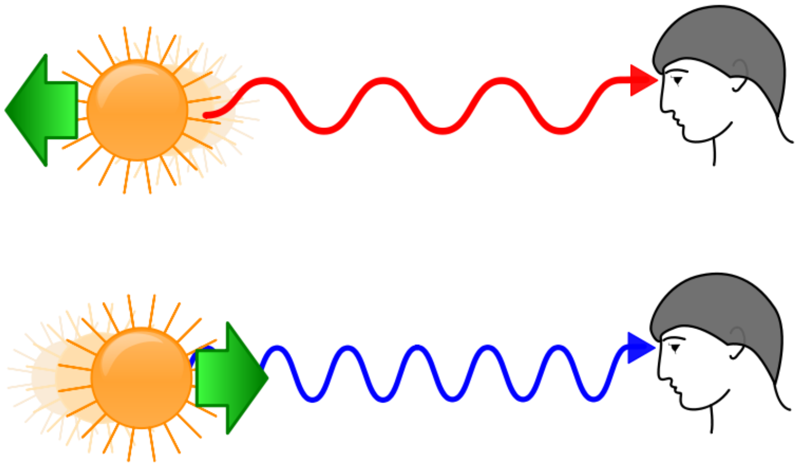
Type Ia Supernova

A type Ia Supernova forms when a white dwarf accretes matter from a companion star until it exceeds the Chandrasekhar limit and explodes

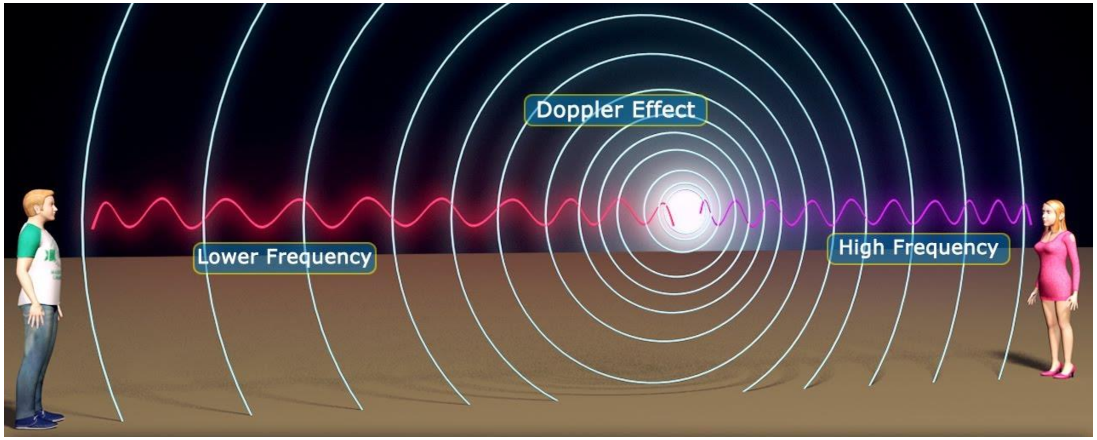
These supernovae have a constant luminosity so their brightness can be analyzed as a standard candle much like the Cephid Variables



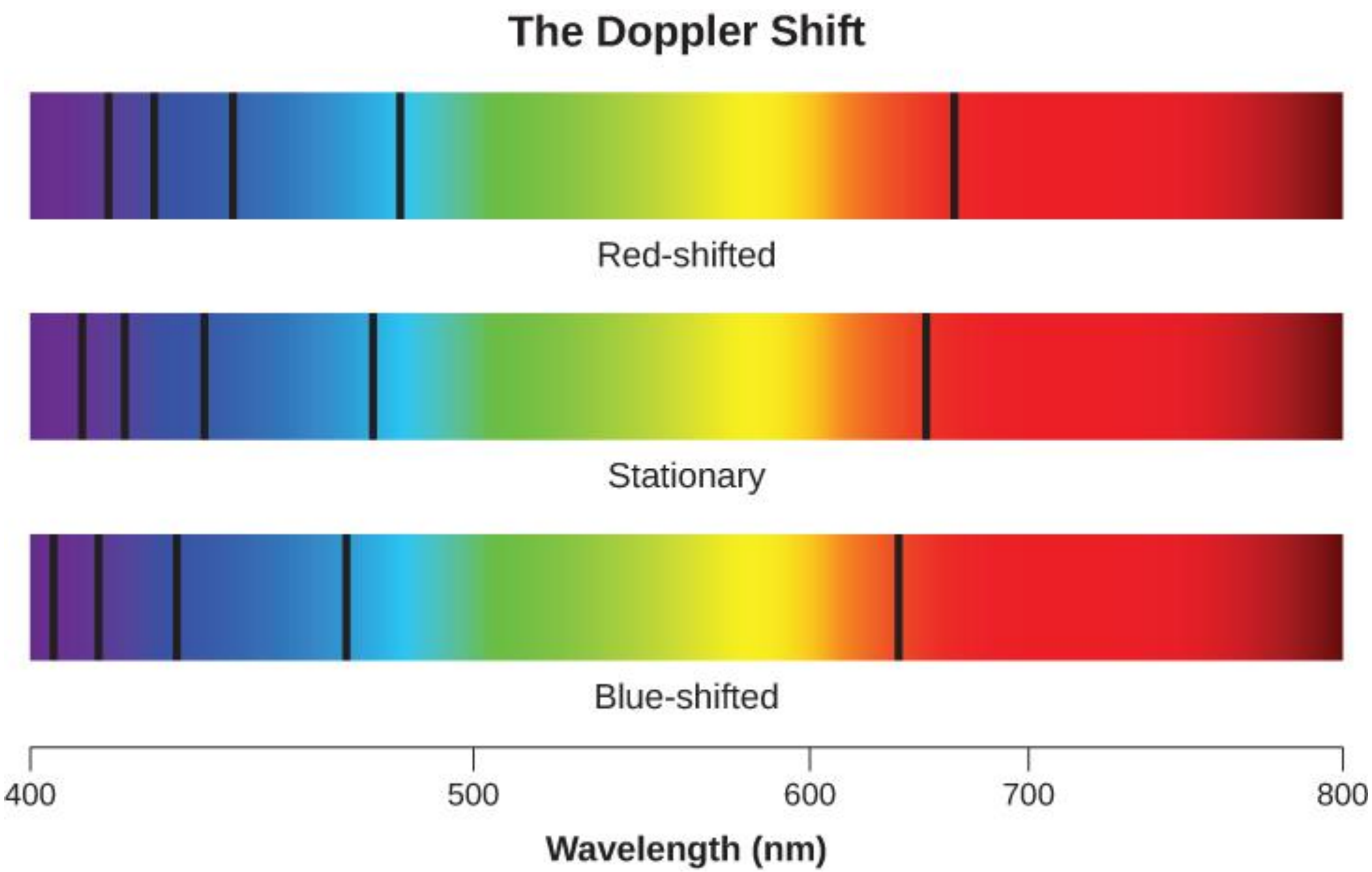
Doppler Effect



Red-shifted



Red Shift, Blue Shift



Calculating Redshift

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

Redshift (z)

Change in Wavelength ($\Delta\lambda$)

Velocity of the Source (v)

Wavelength Emitted (λ_o)

Speed of Light (c)

(3.00×10^8 m s^{-1})

IB Physics Data Booklet

Sub-topic D.1 – Stellar quantities	Sub-topic D.2 – Stellar characteristics and stellar evolution
$d\ (\text{parsec}) = \dfrac{1}{p\ (\text{arc–second})}$ $L = \sigma A T^4$ $b = \dfrac{L}{4\pi d^2}$	$\lambda_{\max} T = 2.9 \times 10^{-3}\ \text{m K}$ $L \propto M^{3.5}$
Sub-topic D.3 – Cosmology	**Sub-topic D.5 – Further cosmology (HL only)**
$z = \dfrac{\Delta\lambda}{\lambda_0} \approx \dfrac{v}{c}$ $z = \dfrac{R}{R_0} - 1$ $v = H_0 d$ $T \approx \dfrac{1}{H_0}$	$v = \sqrt{\dfrac{4\pi G\rho}{3}}r$ $\rho_c = \dfrac{3H^2}{8\pi G}$

Calculating Redshift

A characteristic absorption line often seen in stars is due to ionized helium. It occurs at 468.6 nm. If the spectrum of a star has this line at a measured wavelength of 499.3 nm what is the recession speed of the star?

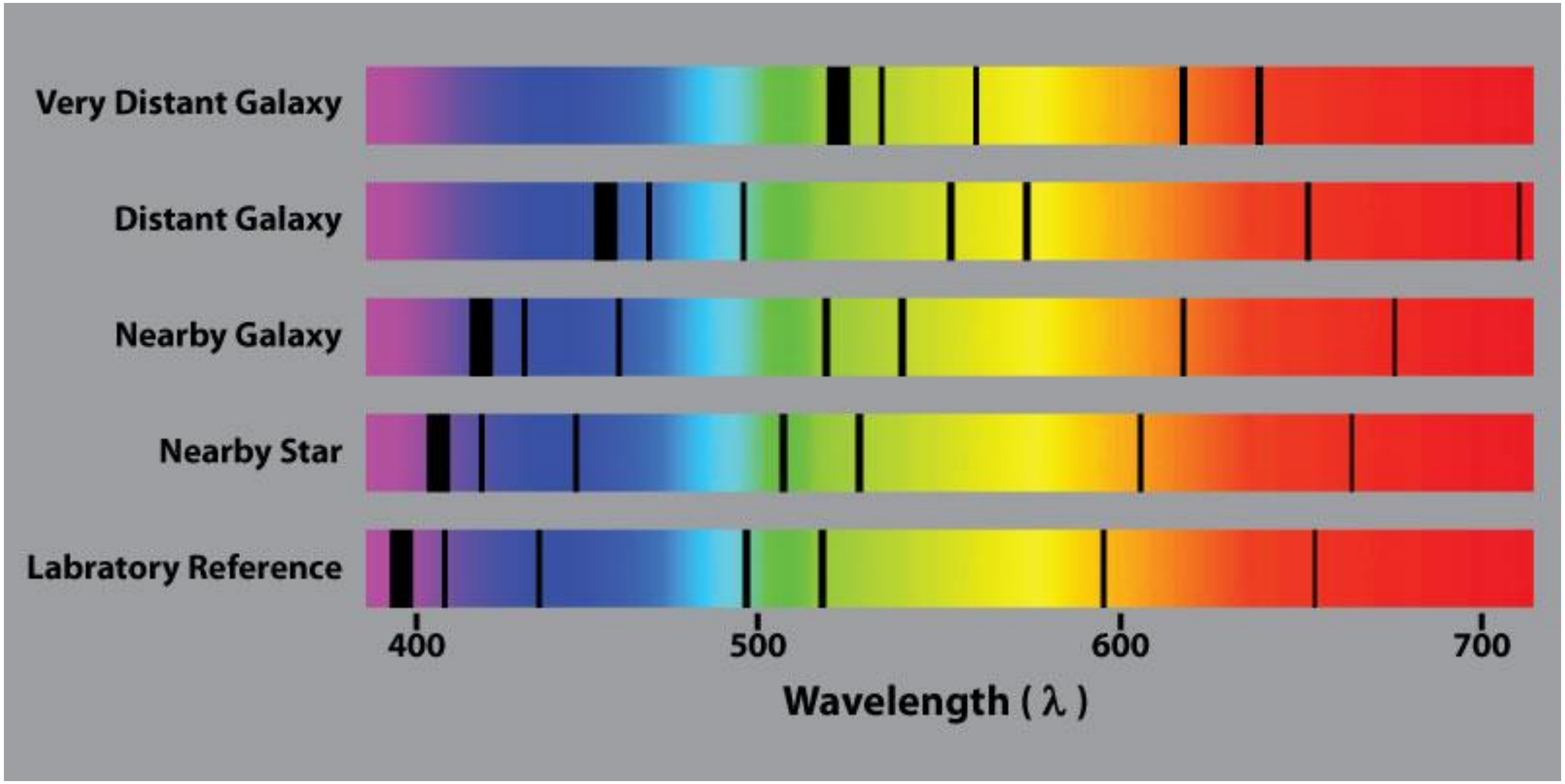
$$\frac{\Delta\lambda}{\lambda_o} \approx \frac{v}{c}$$

$$\frac{499.3 - 468.6}{468.6} \approx \frac{v}{3.00 \times 10^8}$$

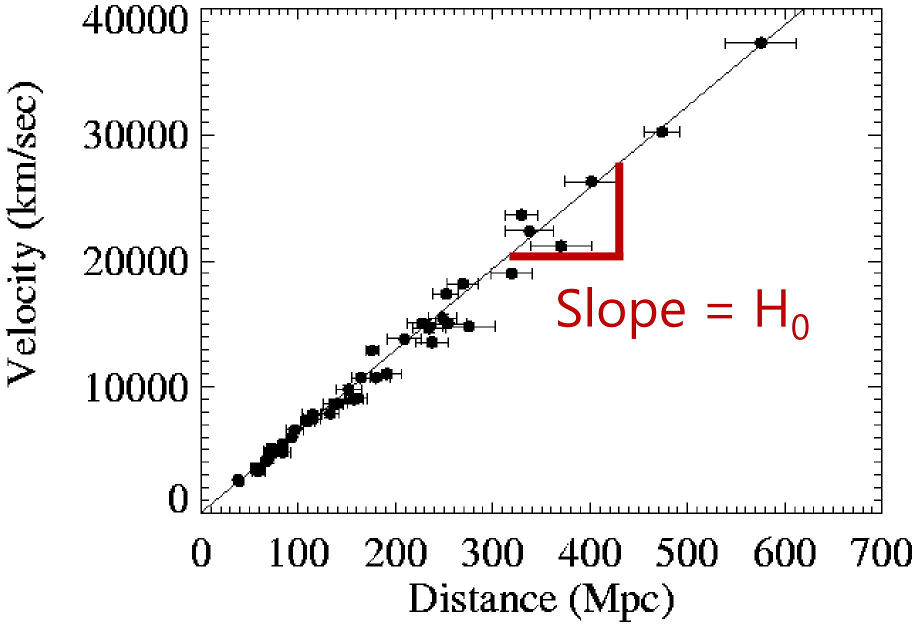
$$v = 1.97 \times 10^7 \text{ m s}^{-1}$$

Hubble's Big Discovery

Edwin Hubble discovered that the amount of redshift changed by the distance



The Universe is Expanding



$$v = H_0 d$$

$H_0 \approx 70$ km s^{-1} Mpc^{-1}

**current value is not necessarily constant*

IB Physics Data Booklet

Sub-topic D.1 – Stellar quantities	Sub-topic D.2 – Stellar characteristics and stellar evolution
$d\ (\text{parsec}) = \frac{1}{p\ (\text{arc–second})}$ $L = \sigma A T^4$ $b = \frac{L}{4\pi d^2}$	$\lambda_{\max} T = 2.9 \times 10^{-3}\ \text{m K}$ $L \propto M^{3.5}$
Sub-topic D.3 – Cosmology	**Sub-topic D.5 – Further cosmology (HL only)**
$z = \frac{\Delta\lambda}{\lambda_0} \approx \frac{v}{c}$ $z = \frac{R}{R_0} - 1$ $v = H_0 d$ $T \approx \frac{1}{H_0}$	$v = \sqrt{\frac{4\pi G\rho}{3}} r$ $\rho_c = \frac{3H^2}{8\pi G}$

Using the Hubble "Constant"

Estimate the distance from the Earth to a galaxy with a recessional velocity of 150 km s^{-1}

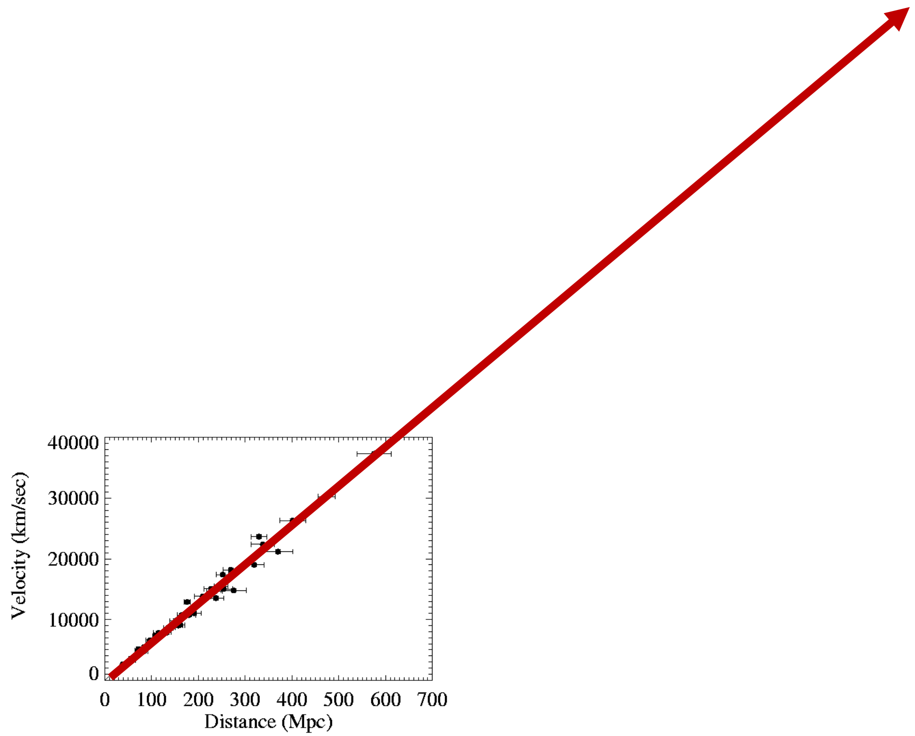
$$v = H_0 d \rightarrow d = \frac{v}{H_0} = \frac{150\ \mathrm{km\ s^{-1}}}{70\ \mathrm{km\ s^{-1}\ Mpc^{-1}}} = 2.14\ \mathrm{Mpc}$$

If a galaxy is 20 Mpc from Earth, how fast will it be receding?

$$v = H_0 d = (70\ \mathrm{km\ s^{-1}\ Mpc^{-1}})(20\ \mathrm{Mpc}) = 1400\ \mathrm{km\ s^{-1}}$$

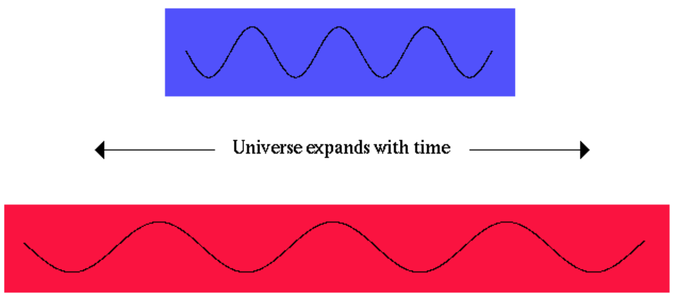
Calculating Redshift

Nothing can go faster than the speed of light so the Doppler effect can't really hold up…



Calculating Redshift

Think of the wavelength change due to the stretching of space-time



Current Universe Size $[R = 1]$

$$z = \frac{R}{R_o} - 1$$

Cosmological Redshift

Cosmic Scale Factor

Size of the universe at the time the light was emitted (relative to the current size)

Calculating Redshift

If the redshift z = 3, what was the scale factor at the time that the light was emitted?

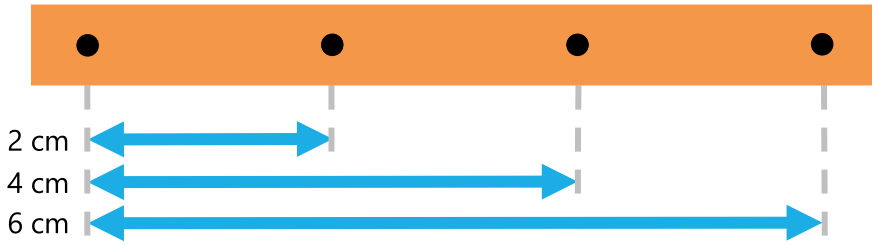
$$z = \frac{R}{R_o} - 1$$

$$3 = \frac{1}{R_o} - 1$$

$$R_o = \frac{1}{4} = 0.25$$

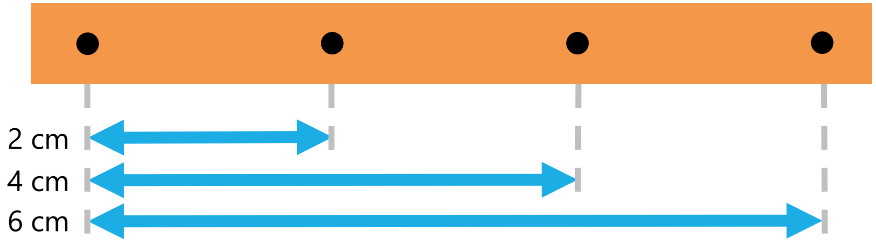
Note: This means that to result in this cosmological redshift, the light had to have been emitted when the universe was a quarter of the size it is now

The Universe is Expanding



Think of a rubber band with marks when it is stretched out… Relative to the first dot, which dot moves the fastest?

The Universe is Expanding



Think of a rubber band with marks when it is stretched out… Relative to the first dot, which dot moves the fastest?

The farthest dot moves away the fastest

The Universe is Expanding