UNIT G485	Module 5	5.5.1	Structure of the Universe

- **Candidates should be able to :**
  - Describe the principal contents of the universe, including **stars**, **galaxies** and **radiation**.
  - Describe the solar system in terms of the **Sun**, **planets**, **planetary satellites** and **comets**.
  - Describe the **formation of a star**, such as our Sun, from interstellar dust and gas.
  - Describe the Sun's probable evolution into a **red giant** and **white dwarf**.
  - Describe how **a star much more massive than our Sun** will evolve into a **super red giant** and then either a **neutron star** or **black hole**.
  - Define distances measured in **astronomical units (AU)**, **parsecs (pc)** and **light-years (ly)**.
  - State the **approximate magnitudes in metres**, of the parsec and light-year.
  - State **Olber's paradox**.
  - Interpret Olber's paradox to explain why it suggests that **the model of an infinite, static universe is incorrect**.
  - Select and use the equation : $\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$
  - Describe and interpret **Hubble's red shift observations**.
  - Convert the Hubble constant (H_0) from its **conventional units (km s^{-1}, Mpc^{-1})** to **SI (s^{-1})**.
  - State the **cosmological principle**.
  - Describe and explain the significance of the **3K microwave background radiation**.

CONTENTS OF THE UNIVERSE

- The universe contains about 10^{11} **galaxies**, each of which contains about 10^{12} **stars**. It also contains vast amounts of **interstellar dust** and **dark matter** (neutrinos and black holes) and it is saturated with **electromagnetic radiation**, mainly in the **microwave** region.

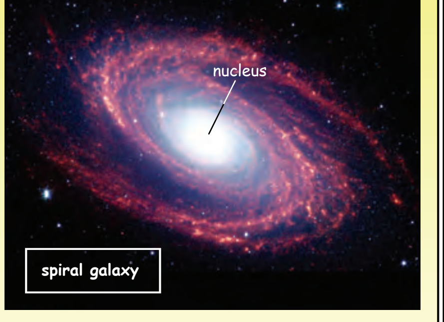
GALAXIES

A **GALAXY** is a cluster of many billions of stars rotating slowly around its centre of gravity.

- Galaxies usually have a region where the concentration of stars is greatest and this is called the **nucleus**.

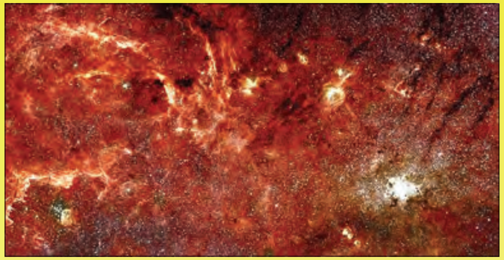
  All the stars in the galaxy rotate around this central bulge.

  The rotational period of each star depends on its distance from the nucleus. The further out a star is, the longer it takes to complete one rotation.



Our own galaxy, known as the **Milky Way**, is a **spiral** galaxy having a mean diameter of about **100 000 light-years (ly)**.

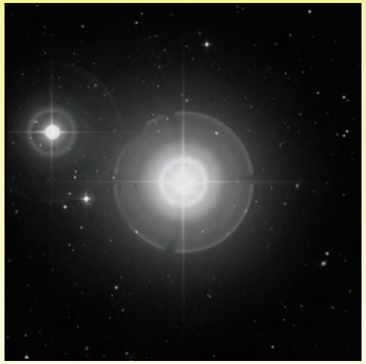
The **Sun**, one of the **billions** of stars in the Milky Way, is located at a point about **28 000 ly** from the galactic centre and it takes about **230 million years** to complete one revolution.



- Shown on the right is an infra-red image of the centre of the Milky Way, revealing a new population of massive stars.

- Astronomers have recently announced that there is a **massive black hole** at the very centre of the Milky Way. This black hole is relatively small in size, having a radius of only **6.25 light-hours,** but it is massive because of the extraordinary amount of matter it contains, estimated at about **3.7 million solar masses!**

STARS



- Stars are really gigantic **nuclear fusion reactors** which continuously emit vast amounts of **electromagnetic radiation.**

  There are many different types of star and they are categorised by their colour and brightness.

  On a clear, moonless night away from our own artificial lights, a few 1000 are visible to the naked eye and this number rises to billions when telescopes are used.

  The picture opposite shows the concentration and variety of stars in the central parts of the Milky Way.

PLANETS

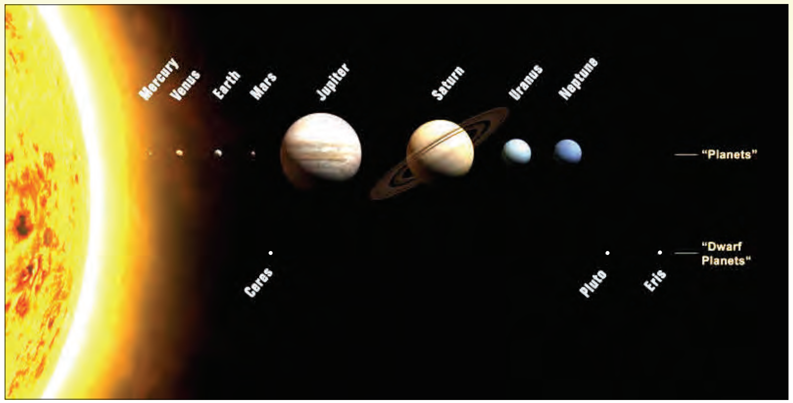
- These are relatively cold objects moving in **slightly elliptical orbits** around a star.

- Apart from those in our own solar system, no other planets can be detected by direct visual observation. This is because of their relatively small size and the tremendous distances from one star to another. **Proxima Centauri,** the closest star to the Sun, is **4.5 light-years** away, so if it has planets in orbit around it, they would not be visible even using the most powerful telescopes.

- Modern telescopes are capable of detecting the slight wobble of some stars resulting from the orbit of planets around them and the infra-red emitted by a few planets around distant stars has also been detected. In this way we have proof of the existence of planets outside our solar system, but given the immense number of stars in the universe, there should be little doubt about this anyway.

- The **solar system** is made up of :

  - The **Sun** which contains **99.8%** of the total matter in the system.
  - **Eight planets** and their various **moons** in orbit around the Sun (Pluto has now been deemed too small to be seen as a planet).
  - A region between **Mars and Jupiter**, called the **asteroid belt,** which contains rocks of varying sizes also in orbit around the Sun.



MOONS

- These are the **natural satellites of planets.**

- They do not emit any visible radiation and can only be seen as a result of reflected radiation from a star. In the case of our own **Moon** (shown opposite) it is reflected sunlight.

STAR FORMATION

- Most of the universe is **'empty space'** - Atoms are much further apart than in ordinary matter (i.e. atomic separation in solids ≈ $\mathbf{10^{-10}}$ **m,** whereas in 'empty space' ≈ $\mathbf{10^{2}}$ **m**). So the density of most of the universe is extremely low.

- **Nebulae** are immense, interstellar gas clouds. They are regions in space where the density is much larger and it is in these regions that stars are formed. Regions of higher density contain more matter than those of lower density and so exert strong gravitational attraction forces which pulls in more and more matter at an ever increasing rate.

*The photograph shown opposite is That Of the **Crab Nebula** located in the constellation of **Taurus**. It is the shattered remains of an exploded star, a **supernova** that occurred more than 6000 light-years from Earth and was first recorded by Chinese and Arab astronomers in 1054.*

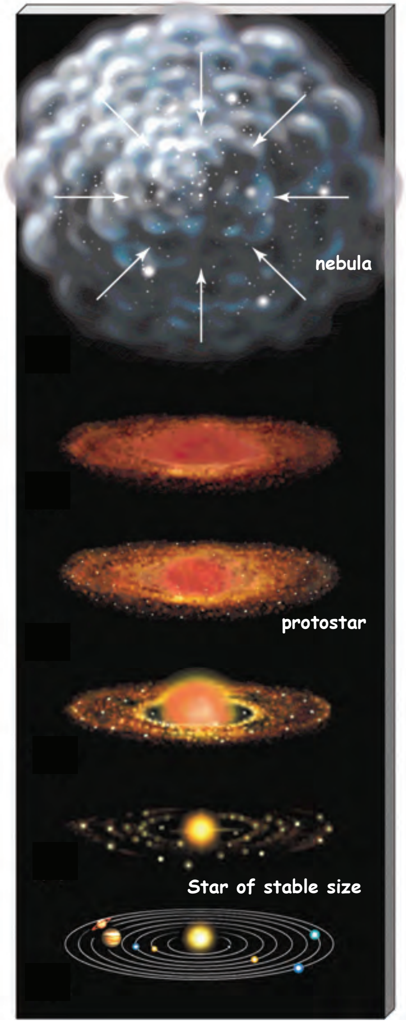
- As the density of gases in a nebula increases, the atoms in them are attracted towards each other, losing potential energy and gaining kinetic energy. This results in an **increase in temperature.**

- The process produces a large core of material, called a **protostar,** which continues to attract material and hence increase its **mass, density and temperature.**

- The enormous increase in density and temperature (up to about $\mathbf{10^{7}}$ **K**), also means an **increase in pressure** and under these conditions the **hydrogen nuclei fuse together to form helium nuclei,** releasing vast amounts of energy and causing the temperature to increase even more.

- A star of a stable size forms when the **gravitational pressure balances the radiation pressure** produced by photons released in the fusion reactions. The initial size of the star depends on the mass of the nebula from which it forms.

- The time taken for a star to form depends on size and varies from as little as $\mathbf{10^{4}}$ **years to** $\mathbf{10^{6}}$ **years.** During the process, some of the material that does not form into the protostar continues to orbit the star. These are the **planets.**



- Our Sun is a relatively small, stable **main sequence star** of mass **2 x 10^{30} Kg**. It was formed from a dust cloud about **5000 million years** ago and it will continue as a main sequence star for at least the same amount of time.

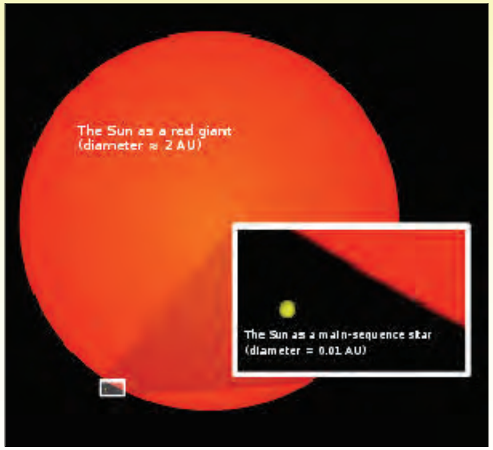
- By **stable** we mean that the Sun has achieved thermal equilibrium. The rate at which it emits electromagnetic energy into space = the rate at which it produces energy from nuclear fusion.

THE SUN'S FATE

- In about 5000 million years the rate of hydrogen fusion in the Sun's core will decrease because much of the core will consist of fusion products (mostly helium). Some hydrogen fusion continues in the shell around the core, but **the core itself starts to collapse** as a result of decreased radiation pressure.

- The loss of potential energy on contraction causes an increase in kinetic energy and this means an increase in temperature and pressure of the core.

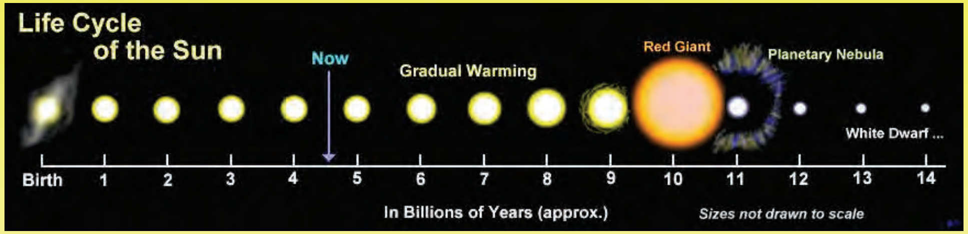
- This increased pressure in the core **causes the Sun to expand,** engulfing Mercury, Venus and Earth. The Sun becomes a **red giant** whose surface temperature is much lower than that of the Sun.



- The core continues to collapse and when the temperature reaches about 10^8 K, helium nuclei start to fuse at a phenomenal rate. Once the fusion of helium ends, the Sun becomes **unstable** and much of its mass is radiated outwards in huge ion sprays.

- The rest of the Sun shrinks to become a **white dwarf** whose diameter is about 1/100th of the Sun's present diameter. This increases the density from its present value of **1400 kg m^{-3}** to about **700 million kg m^{-3}**.

- As a result of the loss of potential energy there is a subsequent increase in kinetic energy and the surface temperature rises again to about 20 000K. After this the Sun gradually cools to become a lump of cold, extremely dense matter. It is then a **black dwarf**.



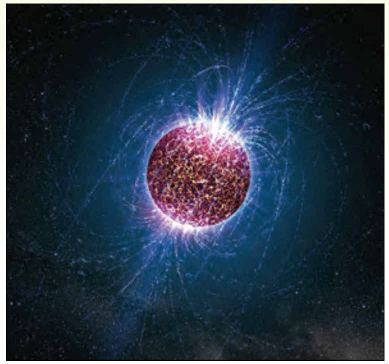
FATE OF STARS BIGGER THAN THE SUN

- When a star of mass > **3 solar masses** reaches the end of its red giant phase, it continues to increase its surface area and eventually becomes a red super giant. Further nuclear fusion reactions occur in its collapsing core, raising the temperature to billions of Kelvin. During this stage the immense pressure causes **protons to absorb electrons and become neutrons**.

- The final collapse produces intense heating, followed by an explosive blowing out of the outer shell and compression of the core. The resulting gigantic release of energy is called a **supernova**.

- Under certain conditions the nucleus of a supernova explosion remains intact, forming a **neutron star** of incredibly high density.

  Such a star may have about the **same mass as our sun** and yet be a mere **30 km** in diameter!



- Neutron stars have large magnetic fields and rotate rapidly, emitting Very well defined electromagnetic waves.
  Some, like the one that is known to exist in the **Crab Nebula**, send out a broad spectrum of radiation in pulses and are aptly called **pulsars**.

- A further stage of development is the formation of a **black hole**.

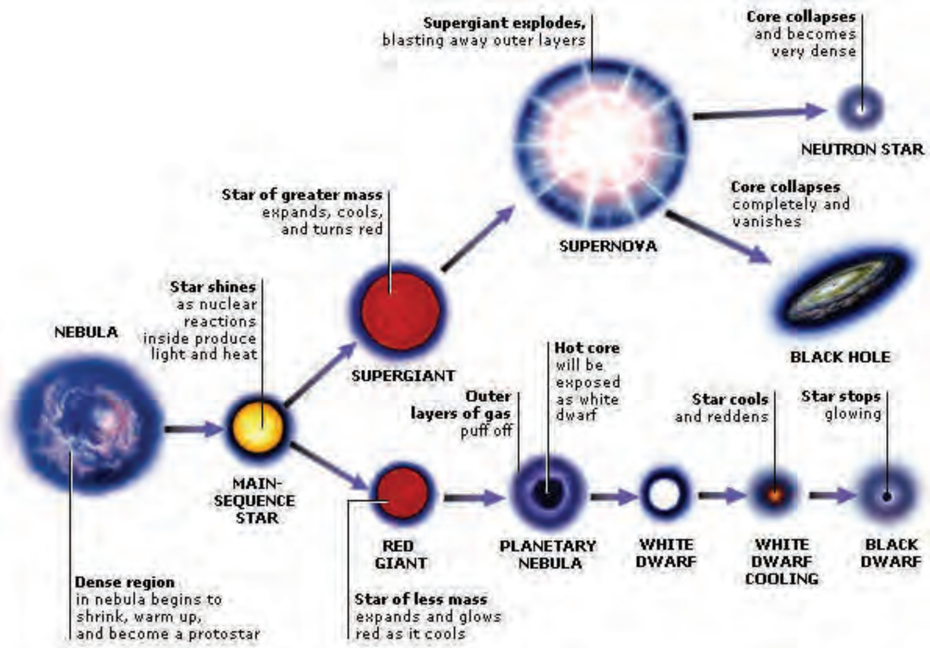
  In theory the pressure on the core could become so large that a neutron star would collapse to a point having infinite density and generating a gravitational field of such incredible strength that nothing, not even light, can escape its grip.

- **Quasars** are phenomenally bright objects with as much power output as 10^{12} **Suns**. They have black holes at their centre and are thought to be **galaxies in the process of formation**.

LIFE HISTORY OF STARS - SUMMARY

The diagram below shows how stars, both large and small, progress through their lifetime after their initial creation from the dust particles in a nebula.

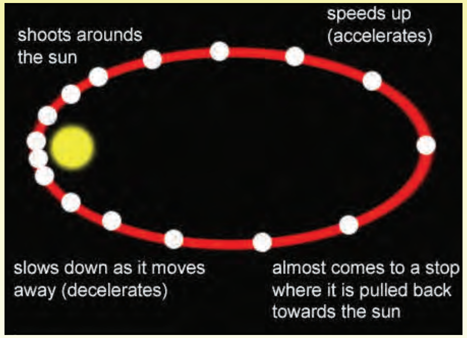
- **Stars of mass < 3 solar masses** become red giants and eventually end their lives as a black dwarf.
- **Stars of mass > 3 solar masses** become super red giants and eventually end their lives as a neutron star.
- **Stars of mass > 10 solar masses** may eventually end up as a black hole.



COMETS

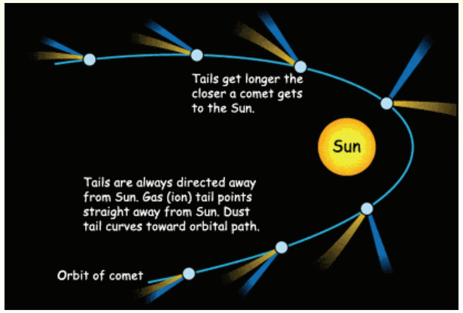
- Comets consist of **ice, rock and a cloud of gas.**
- They originate in a region of rock and ice called the **Kuiper Belt,** situated **outside the orbit of Neptune.**
- Some comets travel around the Sun in very **elongated elliptical orbits** and these **appear at regular intervals. Halley's comet,** shown in the photograph opposite is an example of this type of comet. It returns to the Sun every **76 years** and is then visible from Earth.

- Some comets travel around the Sun along a **hyperbolic path** and these **appear once and are never seen again.**



- The **faint tail** of a comet only appears when it is near the Sun and **it always points directly away from the Sun.**

  The solar wind, an emission of ions from the Sun's surface, causes the comet's gases to spread out, become ionised and therefore glow.



ASTRONOMICAL DISTANCE MEASUREMENT

THE ASTRONOMICAL UNIT (AU)

- This is the unit used for distances within the **solar system.**

The ASTRONOMICAL UNIT (AU) is the mean* distance from the centre of the Earth to the centre of the Sun.

$$1 \text{ AU} = 1.496 \times 10^{11} \text{ m}$$

* Earth's orbit around the Sun is elliptical, so the mean distance **(1.496×10^{11} m)** is calculated from the distance in January **(1.471×10^{11} m)** and that in July **(1.521×10^{11} m).**

THE LIGHT-YEAR (ly)

- This is the unit used for distances to **stars and galaxies.**

One LIGHT-YEAR (ly) is the distance travelled by light in a vacuum in 1 year.

$$1 \text{ ly} = (2.9979 \times 10^8) \times (365.25) \times (24) \times (3600) = 9.461 \times 10^{15} \text{ m.}$$

$$1 \text{ ly} = 9.461 \times 10^{15} \text{ m}$$

THE PARSEC (pc)

- This unit is also used for measuring distances to **stars and galaxies**, but before we can define the parsec (pc), we need to understand **stellar parallax** and the **arc second (arc sec)**.

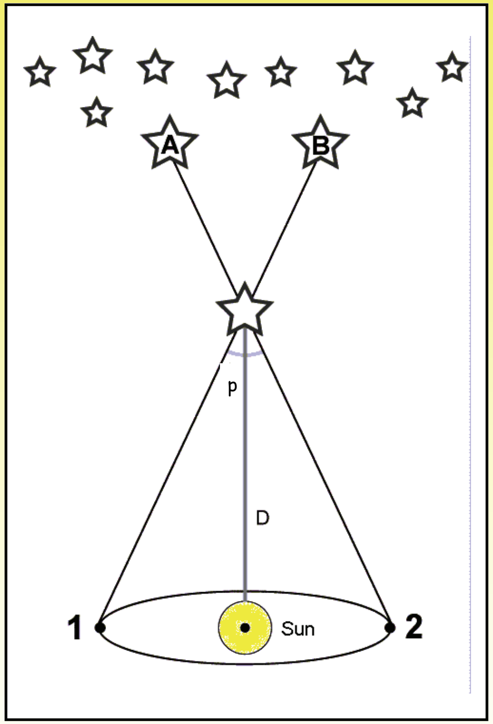
STELLAR PARALLAX

- A nearby star **X** is photographed against the distant background of stars when the Earth is in its orbit at **position 1**.

  Another photograph is taken **exactly 6 months later** when the Earth is at **position 2**.

  The apparent shift in position of star **X** is called **stellar parallax**.

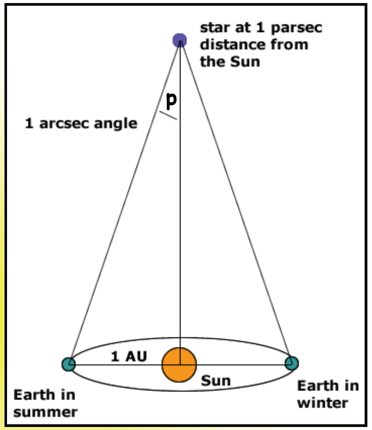
  Half the total angle subtended by the star between Earth positions **1** and **2** is called the **Parallax angle (p)**.



- Since p is much smaller than 1 degree, it is measured in **arc seconds (arc sec)**, which is a much smaller unit of angular measure.

1 arc sec = 1/3600 degrees

1 PARSEC (pc) is the distance from a baseline of length **1 AU** (= **1.496 x 10^{11} m**) when the parallax angle **(p)** is **1 arc sec** (= **4.848 x 10^{-6} rads**).



For very small angles :

$\sin p = p$ (in rads)

$\sin p = p \text{ (rads)} = \dfrac{1 \text{ AU}}{x}$

So $x = \dfrac{1 \text{ AU}}{p}$

$1 \text{ pc} = \dfrac{1.496 \times 10^{11}}{4.848 \times 10^{-6}}$

$= \mathbf{3.086 \times 10^{16}}$ **m.**

1 pc = 3.086 x 10^{16} m

- **PRACTICE QUESTIONS (1)**

1 The mean distance from the Earth's centre to the Sun's centre is **1 AU** (= **1.496 x 10^{11} m**). Express this distance in **light-years (ly)**.

2 **Sirus** is a very bright star in the night sky. It has a parallax angle of **0.38 arc sec**. Calculate its **distance from Earth** :

(a) In **parsecs (pc)**.

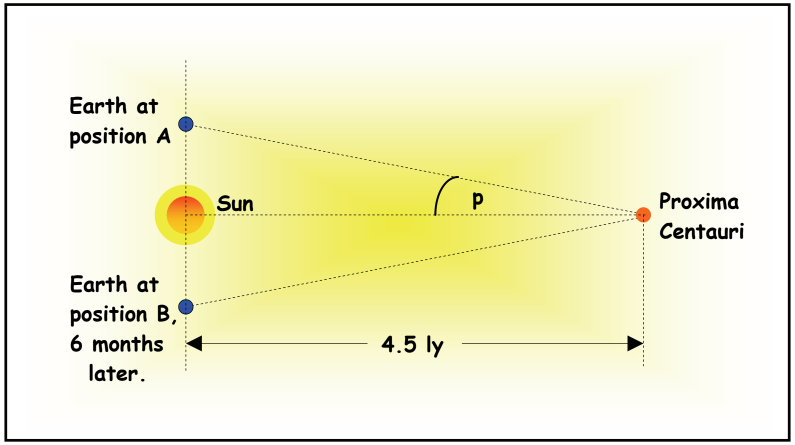
(b) In **light-years (ly)**.

3 **(a)** State the value of **1 AU in metres in standard form.**

(b) Given that light travels at **2.9979×10^8 m s^{-1}** in a vacuum, calculate the **distance in metres of 1 light-year (ly).**

(c) Define the **parsec (pc)** and hence, using the value for 1 AU stated in **(a)**, calculate the **distance in metres of 1 parsec (pc).**

4 Excluding the Sun, the nearest star to Earth is **Proxima Centauri.** It is approximately **4.5 ly** from Earth as shown in the diagram below.



As viewed from the Earth when in **position A** and **6 months later** from **position B,** the parallax angle **(p)** is as shown. Calculate the value of **p.**

(Mean distance from the Earth's centre to the Sun's centre = **1 AU**).

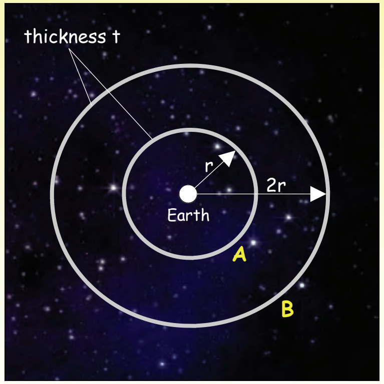
HEINRICH OLBER'S PARADOX

For an infinite, uniform and static universe, the night sky should be bright because of light received from stars in all directions.

Explaining the Paradox

Olber assumed that the universe is **infinite and static.**

Consider the diagram opposite.



- On a large enough scale, stars are spread evenly throughout the universe, with **(n)** stars per unit volume.
- A thin shell **A** of stars at distance **r** has **volume** = **$4\pi r^2 t$** and contains **$4\pi r^2 tn$** stars.
  The thin shell **B** of stars at distance **2r** has **volume** = **$16\pi r^2 t$** and contains **$16\pi r^2 tn$** stars.
- The **brightness of a star is α $1/r^2$.**
  So brightness on Earth due to **shell A** stars = **$4\pi r^2 tn/r^2$** = **$\underline{4\pi tn}$**.
  And brightness on Earth due to **shell B** stars = **$16\pi r^2 tn/(2r)^2$** = **$\underline{4\pi tn}$**.
  So every shell of stars produces the same brightness on Earth.
- Since there are an infinite number of shells in an infinite universe, **the Earth should be infinitely bright as a result of starlight.**

- Since **the night sky is not bright, but dark,** Olber deduced that the **universe is not infinite.**

- The universe is **neither infinite nor static,** since it has been expanding since the big bang some 12 billion years ago.

Reasons For The Dark Night Sky

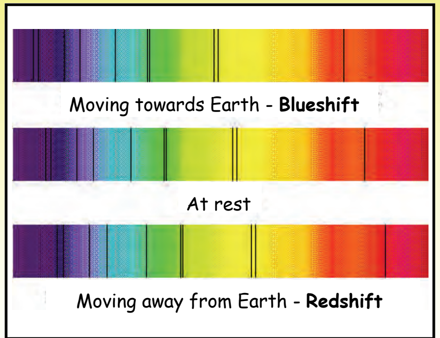
- The universe is of **finite size.**
- The universe is **not static, but expanding.**
- The finite age of the universe means that **light from distant galaxies has not yet reached us.**

THE DOPPLER REDSHIFT

- According to the **Doppler effect,** the wavelength of light from a star or galaxy which is moving away from Earth **(i.e. receding)** is apparently **longer** and that from a star or galaxy which is moving towards Earth **(i.e approaching)** is apparently **shorter.**

- The line spectra of light from **receding** stars and galaxies are found to be slightly shifted towards the **RED** end of the spectrum **(RED-SHIFTED).**

- The line spectra of light from **approaching** stars and galaxies are found to be slightly shifted towards the **BLUE** end of the spectrum **(BLUE-SHIFTED).**



If λ = the **original wavelength** of the light measured in the laboratory.

v = the **speed of the star or galaxy.**

c = the **speed of light in vacuo.**

Then, the **wavelength change ($\Delta\lambda$)** is given by :

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

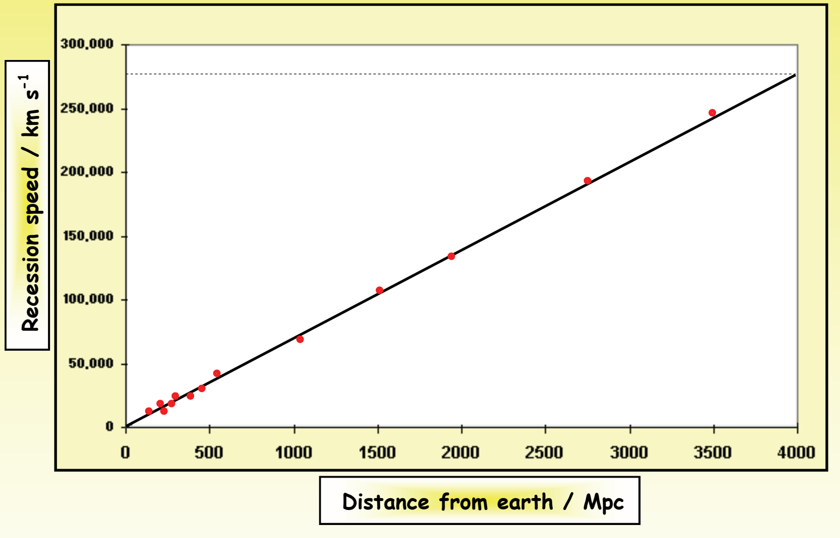
- **Edwin Hubble's** analysis of the line spectra from a particular galaxy showed that the spectrum for one of them did not fit any known element, but the pattern of lines was the same as that for hydrogen but very substantially **shifted towards the red end of the spectrum.** One of the lines was even shifted into the invisible infrared.

Hubble was convinced that the spectral line shift he had observed was due to the **Doppler effect** and using the Doppler shift equation above he concluded that the galaxy's recession speed was much larger than anything found previously. Since then, over 100 000 quasars have been discovered and these have been shown to have even higher recession speeds.

HUBBLE'S LAW

- Hubble analysed the line spectra of light from some relatively near galaxies and determined the **redshift** from his measurements. The distances from Earth to these galaxies were known.

- Using the Doppler shift equation, Hubble calculated the **recession speed** of each of these galaxies. When he plotted **recession speed** against **distance from Earth,** the result was a straight-line graph as shown below.



- His findings are summarised in **Hubble's Law** which states that :

The recession speed of a galaxy is directly proportional to its distance from Earth. Mathematically expressed as :

- v = recession speed.
- D = distance from Earth.
- H_0 = the Hubble constant.

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

- **v/D (= H_0)** is the **gradient** of graph of **recession speed (v)** against **distance from Earth (D).**

$$H_0 = \frac{280\,000 \text{ km s}^{-1}}{4\,000 \text{ Mpc}} = \boxed{70 \text{ km s}^{-1} \text{ Mpc}^{-1}}$$

- The **unit of H_0 can be converted to SI units** as follows :

1 km s^{-1} = **10^3 m s^{-1}**.

1 Mpc = 10^6 pc x 3.086 x 10^{16} m pc^{-1} = **3.086 x 10^{22} m.**

$$H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} = \frac{70 \times 10^3 \text{ m s}^{-1}}{3.086 \times 10^{22} \text{ m}} = \boxed{2.3 \times 10^{-18} \text{ s}^{-1}}$$

- It is difficult to obtain an accurate value of H_0 because :
  - The **most accurate values of distances and recession speeds** are those for **relatively near stars and galaxies.**
  - **Stars and galaxies are rotating** as well as receding and this affects the value of recession speed calculated using Doppler shift.

- The value of H_0 **(= 70 ± 2 km s^{-1} Mpc^{-1})** is the latest value of the Hubble constant. The value has varied between 50 and 100 km s^{-1} Mpc^{-1} over the last 50 years. It is hoped that measurements using the **HST** will yield a more accurate value over the next few years.

- Hubble showed that the whole **universe is expanding** i.e. the distance between all points in the universe is continually increasing. This means that the **speed of recession between any two points must be directly proportional to their separation,** with the constant of proportionality being H_0.
  H_0 is a property of the expansion and it has the same value at all points in the universe.

- **Hubble's law** is now used to calculate the distance to galaxies at the edge of the observable universe.

- v = H_0D, so since **v cannot be > the speed of light, D must be finite.**

- **Age of the universe = 1/H_0.**

- **PRACTICE QUESTIONS (2)**

1 Explain why stars in the Milky Way show **little or no redshift.**

2 A distant galaxy shows a different redshift from one edge of the galaxy to the redshift from its opposite edge. What could be deduced from :

(a) The **mean redshift?**

(b) the **difference between the two values from opposite edges?**

3 The wavelength of a particular calcium absorption line in a spectrum when measured in a laboratory is **3.969×10^{-7} m.** When the same line is viewed in a spectrum of light from the galaxy known as the **Boötes Cluster,** its wavelength is found to be **4.485×10^{-7} m.** Calculate the **speed of recession of the Boötes Cluster.**

4 The wavelength of a particular spectral line in the laboratory is **119.5 nm.** The same spectral line in the light emitted from a star has a wavelength of **121.6 nm.** Calculate the **speed of the star** and state whether it is moving away from us or coming towards us.

5 A galaxy at a distance of **100 Mpc** from Earth has a recessional speed of 8000 km s^{-1}. Use this information to determine the **Hubble constant (H_0) in s^{-1}** and hence **estimate the age of the universe in years.**

THE COSMOLOGICAL PRINCIPLE

- This principle states that :

On a large scale, **the universe is UNIFORM.**

This means that as long as a large enough volume is used, the universe is :

- **HOMOGENEOUS - Of constant density.**
- **ISOTROPIC - The same in all directions.**

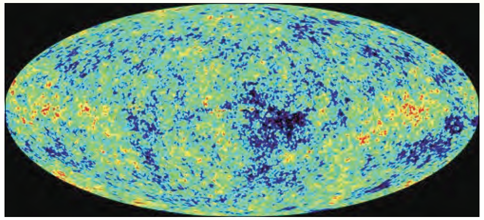
BACKGROUND MICROWAVE RADIATION

- In 1965, **Penzias** and **Wilson** aimed a radio telescope at various different parts of the sky. Their observations were carried out at different times of the day and repeated over many months.

- On each occasion they detected unwanted noise having the same peak frequency and amplitude and this radiation did not vary with time. Their calculations showed that these radio waves had a maximum intensity at a wavelength of 1.1 mm and that the temperature of their source was 2.7 K.

- The discovery of this **cosmic microwave background (CMB)** radiation, at just the correct temperature of **2.7 K,** confirmed the validity of the **big bang theory of the creation of the universe.** This is because astrophysicists supporting the theory had previously calculated that after the big bang, the universe would expand and cool and that a background microwave radiation would exist at a temperature of a few degrees Kelvin.

- *The picture shown opposite reveals the afterglow of the **big bang,** also known as the **cosmic microwave background (CMB).***



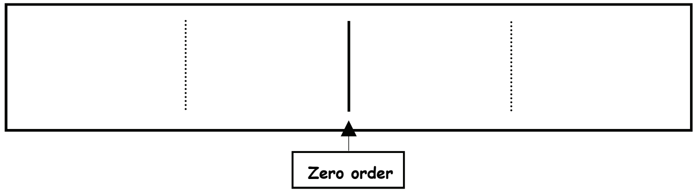
UNIT G485	Module 2	5.5.1	Structure of the Universe

- **HOMEWORK QUESTIONS**

1 Hydrogen gas in a discharge tube in the laboratory can be excited to emit a line spectrum. The strongest wavelength in the visible spectrum is at a wavelength of **660 nm**.

(a) Light from the discharge tube is viewed through a diffraction grating that has **600 lines per mm**. Show that the **660 nm** line will appear at an angle of about **23° from the zero order**.

(b) The **zero** and **first-order** lines at **660 nm** seen through the grating are shown below.



The light from a star, moving away from the Earth, is **redshifted**. Draw the possible positions of the same spectral lines from the star seen through the grating.

(c) The wavelengths of light from the star **Regulus** are found to be redshifted by **0.0020%**. Calculate the **velocity of recession** of Regulus relative to Earth.

2 The nearest star, **Proxima Centauri**, is at a distance of **4.3 ly** from Earth. Calculate the **distance to Proxima Centauri** in :

(a) metres (m).

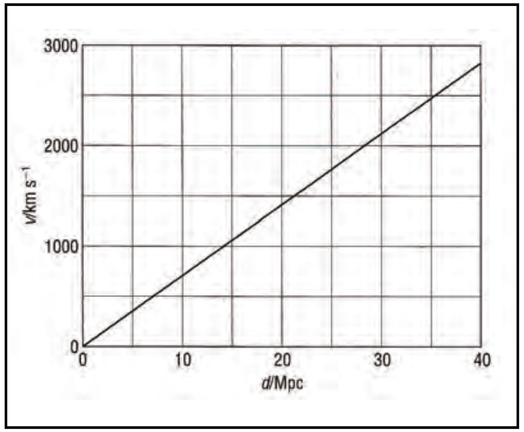
(b) astronomical units (AU).

(c) parsecs (pc).

3 **Hubble's law** states that the velocity of recession of a galaxy is proportional to the distance to the galaxy as measured from Earth. The constant of proportionality is called **Hubble's constant, H_0**.

(a) State the **observational evidence** that supports Hubble's law.

(b) Shown opposite is a graph for the observed speed of recession, **v** of a number of distant galaxies against their distance, **d** from our galaxy.



(i) Explain how the graph illustrates Hubble's law.

(ii) Calculate the value of H_0 given by the graph.

(c) The value of $1/H_0$ gives an estimate of the time passed since all the galaxies were close together, that is, an estimate of the **age of the universe**.

(i) Use your value of H_0 to estimate the **age of the universe in years**.

(ii) Suggest **one reason** that the age of the universe may be **larger** than your answer to **(c) (i)**.

4 The first stars were not formed until some time after the big bang.

(a) Outline **how the first main sequence stars formed from clouds of gas.**

(b) The first stars are believed to have consisted solely of hydrogen and helium.

(i) State the **origin of the helium.**

(ii) State **one major difference in chemical composition** between the 'first' stars and the Sun.

(OCR A2 Physics - Module 2825 - January 2002)

5 **(a)** Outline the **assumptions and arguments** leading to **Olber's paradox.** Explain how it may be resolved in **big bang cosmology.**

(b) A certain galaxy at a distance of **300 Mpc** is observed to be receding from Earth at a velocity of **2.1×10^4 km s^{-1}**.

(i) Calculate a value for the **Hubble constant** in **km s^{-1} Mpc^{-1}**, based on these data.

(ii) Estimate the age in s of the universe using your answer to **(b) (i).**

(iii) Explain why the Hubble constant is not really a constant at all.

(OCR A2 Physics - Module 2825 - January 2003)

6 **(a)** State **three** properties of the **cosmic microwave background** radiation.

(b) Describe how the microwave background radiation is thought to have arisen in standard big bang cosmology.

(c) The **cosmological principle** states that, 'on a sufficiently large scale, the universe is **homogeneous** and **isotropic.**

(i) Explain the meaning of the terms **homogeneous** and **isotropic.**

(ii) State how the **microwave background radiation supports** the **cosmological principle.**

(OCR A2 Physics - Module 2825 - June 2002)