

Astronomy Summary Knowledge Organiser – Ch. 16 (Topic 16) Cosmology (i) Redshift & Hubble's Law

In the 1920s, EDWIN HUBBLE studied the **spectra of almost 50 galaxies** using the **100-inch Hooker Telescope** at the **Mt. Wilson observatory in California**. He discovered that the **observed wavelengths** (λ) of well-known **absorption lines** in the galaxies' spectra were all **longer** than the same **wavelengths** when measured in the **laboratory** (λ_0). This phenomenon, called **redshift**, is due to the **Doppler Effect**. The fact that **all of the galaxies studied showed redshift in their spectra** tells us that they are all **moving away from us** and so **therefore the Universe (space) must be expanding** and as it does it 'drags' the galaxies with it. The redshift is evidence that all galaxies are moving away from us but it is **not direct evidence for the Big Bang** - there could be other explanations of **why** they are moving away!) The **change in wavelength** ($\lambda - \lambda_0$) calculated is directly linked to the **radial velocity** (v) of the galaxy (**how fast it is moving away from us**). If galaxies are **moving away fast (higher radial velocity)** we will calculate a **larger change in wavelength**. **16% longer wavelength = galaxy moving at 16% the speed of light**
You need to be able to 'use' this formula to calculate either wavelengths or v ;

$$\frac{(\lambda - \lambda_0)}{\lambda_0} = \frac{v}{c}$$

It does not matter what units we use for wavelength, speed and velocity as long as we are **consistent**.
We can therefore use the **nanometer (nm)** for our unit of **wavelength**, without needing to convert it into meters.
Similarly, we can use **m/s** or **km/s** for our unit of **radial velocity** and the **speed of light** – **BUT DON'T MIX THEM!**

Where;
 λ is the **wavelength** measured when **observing** the galaxy from Earth,
 λ_0 is the **true wavelength** when measured in a **laboratory** when there is **zero radial velocity**,
 c is the **speed of light** (300,000 km/s, 3.0×10^6 km/s or 3.0×10^8 m/s).

Diagram X shows the spectral lines of helium observed in a distant galaxy.

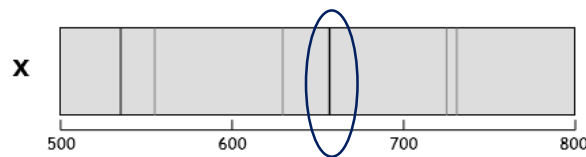
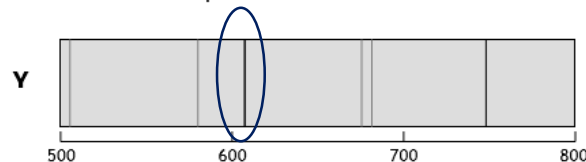


Diagram Y shows the same spectral lines for helium obtained in the lab.



Use the prominent spectral line of helium to estimate the recession velocity of the galaxy. ($c = 3.0 \times 10^5$ km/s)

We choose one of the **spectral lines** shown in the diagram and solve the left hand side of the formula first, so;

$$(660-610) / 610 = 0.081967$$

So $0.081967 = v / c$
since we know the value of c , next we rearrange the formula to make v the subject, so;
 $v = 0.081967 \times c$
and so;

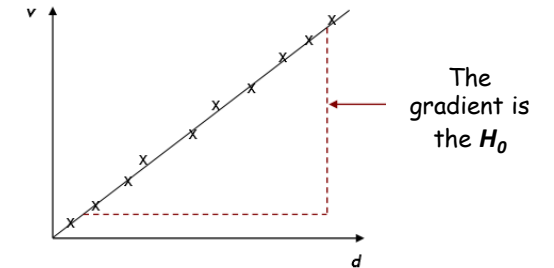
$$v = 0.081967 \times 3.0 \times 10^5 \text{ km/s}$$

$$\text{Velocity} = 2.5 \times 10^4 \text{ km/s}$$

Although measuring redshift allowed us to calculate the speed at which galaxies were moving away from us, calculating **how far away** the galaxy was still very difficult! A breakthrough came when Hubble discovered there was a **LINEAR RELATIONSHIP** between a galaxies **recessional (radial) velocity** (v) and its **distance** (d) from us. Hubble published this relationship in 1929 and it is now known as **HUBBLES LAW** and can be **expressed graphically** or as an **equation** (as shown below);

$$v = H_0 \times d$$

v = the recessional velocity (km/sec)
 H_0 = the Hubble constant (km/sec/Mpc)
 d = distance (Mpc)



The **true accurate value** of the **Hubble constant** is important for astronomers to know because if it is known we can easily calculate the distance to galaxies once we have worked out their radial velocity (v) from their redshift! We simply rearrange the formula and $d = v / H_0$
The value of the Hubble constant can be found **graphically** by calculating the **GRADIENT** of a v - d graph (change in v / change in d).

The currently-accepted value of the Hubble constant is **68 km/sec/Mpc**

HOW TO use the Hubble constant to calculate the AGE of the Universe

The unit for the **Hubble constant** contains **two units of length** (kilometer and Megaparsec). If we **convert km into Mpc** we get a very small number with the unit '**per second**', this value is called **HUBBLE TIME** (T).

If this **number and unit** are **INVERTED** we get the **length of time the universe has been expanding for** and so the **AGE of the Universe in seconds**.

HOW TO use the Hubble constant to calculate the SIZE of the Universe

The H_0 can also be used to calculate **HUBBLE LENGTH**. This is the **DISTANCE light has travelled during the Hubble Time** -ie. the **SIZE of the Universe**.

If we apply the well known formula **Distance = Speed x Time**
to cosmology we get;

$$\text{Hubble Length} = \text{speed of light} \times \text{Hubble Time}$$

and so it becomes **easy** to calculate the size of the Universe!

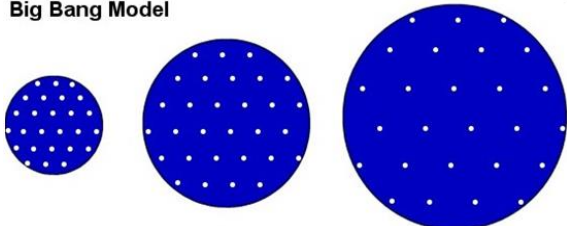
Astronomy Summary Knowledge Organiser – Ch. 16 (Topic 16) Cosmology (ii) The Big Bang!

Most astronomers agree that our **UNIVERSE** began with a **SMALL, HOT, DENSE EVENT** called the **BIG BANG**. It was an **EXPANSION EVENT** not an explosion and when it happened **SPACE was created & TIME began**.

The British astronomer **Fred Hoyle** came up with the name 'Big Bang' as a derogatory term to describe a new theory that the Universe '**once had a beginning**' and had expanded ever since. He **rejected the idea that the Universe had a beginning** on philosophical grounds but he did accept that the **evidence 'it was expanding' was irrefutable** (could not be denied). Hoyle and his colleagues put forward a **counter theory** called the **STEADY STATE MODEL (SSM)** which agreed that the Universe was expanding but argued it had '**always been expanding**' and that '**as it expanded new matter was being created**' and so '**the density of the Universe was constant**'. The **BIG BANG THEORY (BBT)** clearly suggested the **Universe was becoming less dense** over time as it expanded (all **matter was created at the time of the Big Bang event**). A 3rd model of a **CYCLIC UNIVERSE** in which there are a continuous series of **BIG BANG / BIG CRUNCH events** has also been proposed.

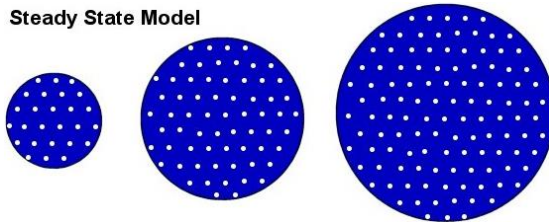
All 3 models are supported by the observed expansion of the Universe.

Big Bang Model



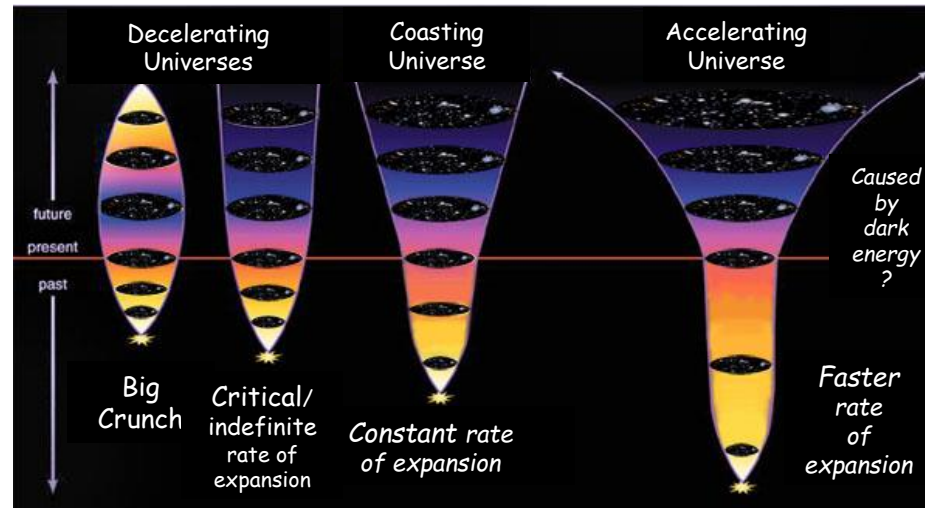
The **density of galaxies GETS LESS** as the Universe expands because **no new matter is created!**

Steady State Model



Density of galaxies **REMAINS CONSTANT** because **new space** is filled by **new galaxies!**

What happens to the Universe next?
Scientists cannot agree! The **4 models** shown below predict very different fates.

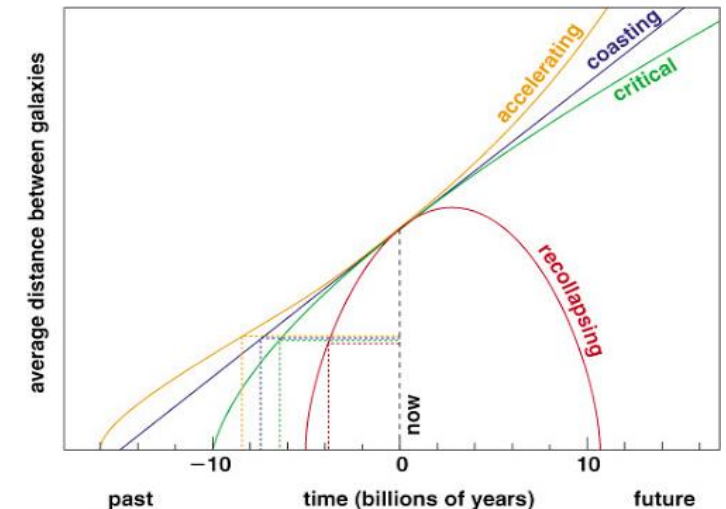


The **EVIDENCE** to support the **BIG BANG THEORY**:

QUASARS - the radiation from every quasar we've ever found is **highly redshifted**, telling us that they are **huge distances away from us** and therefore every one of them must have formed when the universe was young.
**If the SSM was correct quasars would be seen at many different distances!*

COSMIC MICROWAVE BACKGROUND RADIATION (CMBR)- in 1948 the Russian cosmologist **George Gamow** **predicted** that if the BBT was correct (the early Universe was hot & dense) it **would have cooled** (as it expanded) to a temperature just '**a few degrees above absolute zero**' (OK). **17 years later**, in 1965, **Penzias & Wilson** **accidentally discovered** the **CMBR** that comes from **all parts of the sky** (the '**thermal relic**' of the BB) and found its temperature matched to a **temperature of 2.7 Kelvin**, so proving both Gamow and the BBT correct!

HUBBLE DEEP FIELD IMAGE (HDF)- this was the first of a series of **long exposure** images taken by the **Hubble Space Telescope (HST)** of '**empty space**'. The image taken had a **tiny field of view** of only **2.6 arcmin** (same as a tennis ball at 100m away) but seen within it are **1000's of old, distant galaxies** yet again proving the early Universe to be very different from the one we see today!
Again, this supports the **EVOLUTIONARY NATURE of the **BBM**.*



Astronomy Summary Knowledge Organiser – Ch. 16 (Topic 16) Cosmology (iii) Dark matter & dark energy!

Cosmological research is ongoing as you read this text our astronomers and scientists are still trying to find out what **95% of the known universe** is made of!

Of the Universe we exist within;

5% is ORDINARY MATTER & ENERGY (that we can interact with),

25% is DARK MATTER, (27%)

70% is DARK ENERGY. (68%)

Research in the last few decades has produced evidence to suggest that the Universe is slightly older than we previously thought – approx. **13.8 billion years old**.

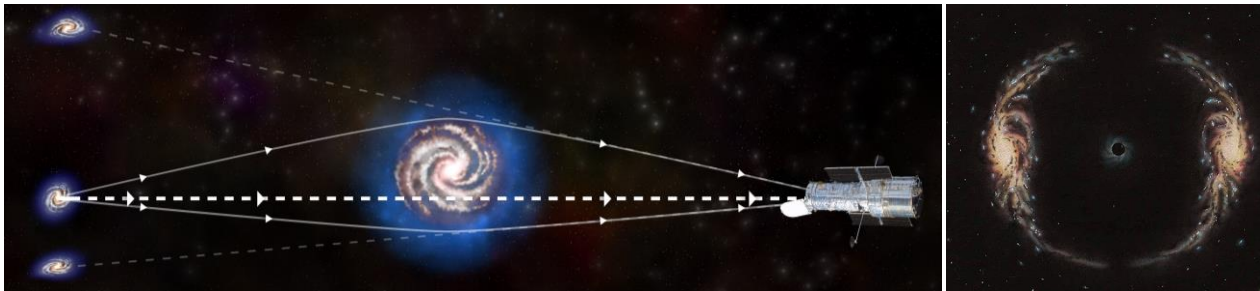
No evidence has been found to cast doubt on the theory of COSMIC INFLATION (the idea that after the Big Bang the expansion of the Universe was **VERY RAPID** and **UNIFORM**).

DARK MATTER

Dark matter is called 'dark' because it **does not appear to interact with observable electromagnetic radiation**, such as light, so it is **undetectable** by our existing scientific instruments. It is composed of particles that do not absorb, reflect, or emit light, so they cannot be detected by observing electromagnetic radiation. Dark matter is material that cannot be seen directly. We know that dark matter exists because of the effect it has on objects that we can observe directly. Many believe that dark matter may exist in the form of **Weakly Interacting Massive Particles (WIMPs)**, possibly an as yet undiscovered type of **NEUTRINO**.

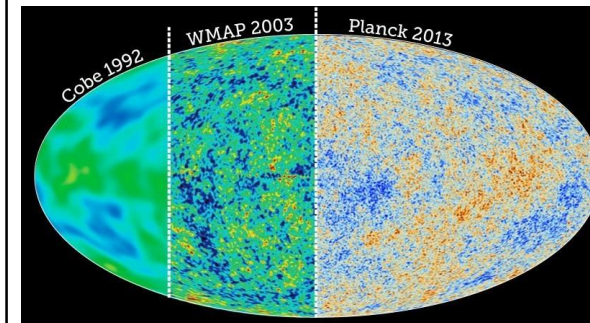
We believe dark matter (DM) is present in our Universe because:

it would explain the **GRAVITATIONAL LENSING** of the light from distant galaxies (DM 'bends light' like a glass lens and so we see **multiple images** of the same single galaxy when we photograph the sky)



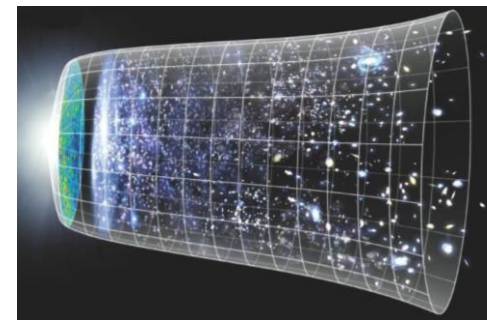
and

from measuring the speeds of the objects in the spiral arms of our Milky Way galaxy we've calculated that **stars in the outer Galaxy are orbiting faster than they should be!** With the gravity of the mass that is visible to us, the outer arms should fly out into space! A huge hidden mass (DM) must be present in the galaxy in order to keep everything gravitationally bound together.



3 missions have mapped the **tiny fluctuations in the radiation** coming from all around us (the background) and helped us to create an all sky CMB map (shown left). First NASA's Cosmic Background Explorer (**COBE**) satellite mapped the CMB, but with limited resolution.

Later, from 2001-2010, NASA's Wilkinson Microwave Anisotropy Probe (**WMAP**) studied the minute fluctuations in the CMB in even more detail. Most recently, from 2009-2015, the European Space Agencies (ESA) **Planck observatory** mapped the tiny differences found in the CMB in even finer detail. **Differences in colour** shown in the map above **show tiny temperature fluctuations** that match to **regions of different densities** in the very early Universe. We believe **denser regions** are where **stars & galaxies were later created**.



The **fate of our Universe** relies on the existence of **both DM & DE**. If the '**accelerating Universe model**' is correct the **REPULSIVE GRAVITATIONAL FORCE** that we call **dark energy** will cause the rate of expansion of our Universe to increase rapidly! The image above illustrates that the Universe began with an incredibly fast expansion then expanded at a slower rate but that now the rate of expansion is increasing.

DARK ENERGY

Dark energy is the name given to the force that is believed to be making the universe larger. It is the name given to an **UNEXPLAINED FORCE** that is **drawing galaxies away from each other**, against the pull of gravity, at an accelerated pace. Dark energy is a bit like anti-gravity. Where gravity pulls things together at the more local level, **dark energy tugs things apart on the grander scale**.