1 Observational Overview of the Universe

The Earth's atmosphere admits only a small portion of the electromagnetic spectrum. The visible light band lies between 400–800 nm. Historically, our picture of the Universe was built up from visible light observations. Now, we have access to the whole of the electromagnetic spectrum using satellites (γ-ray, X-ray, ultraviolet, far-infrared) and radio dishes.

1.1 The Universe in Visible Light

1.1.1 Stars

The main source of visible light in the Universe comes from stars like the Sun. Energy is produced through nuclear fusion in the core – 4 protons fuse to form a helium nucleus – and the difference in the mass is released as γ-rays (E = Δmc^2). These are degraded to visible light photons as they undergo many collisions on their journey from the core to the surface of the Sun. (Takes 2 $\times 10^5$ yr.)

Our Sun is a fairly typical star and has a mass of 2 $\times 10^{30}$kg – known as a solar mass, $1M_\odot$ – astronomical measure of mass.

The nearest stars to us are a few light years away (= 10^{16}m). The unit of distance used in astronomy is the parsec: 1 pc = 3.26 light yr = 3.086 $\times 10^{16}$ m.

This unit originates from measuring the distances of stars using the phenomenon of parallax or the apparent change in direction of a star as the Earth moves round the Sun. A star that apparently moves by one second of arc has a distance of 1 parallax–second (1pc). In practice, no stars are close enough to give a parallax of $1''$ – the closest star Alpha Centauri is 1.32 pc away.

Although Copernicus is acknowledged as the first person to put forward the heliocentric view, Aristarchus (c. 310-230 BC) put forward the same idea but this was not accepted by Aristotle. Aristophanes realised that he could prove that the Earth moves by measuring parallaxes of stars. He failed. Tycho also tried to do this and failed. This lack of success was one of the main problems in adopting Copernican ideas.

The first parallaxes were not measured until 1838 – the stars were further away than anyone realised, and a high precision was required to measure such a tiny effect. The first star measured was 61 Cygni with a parallax of $0''.3$.

Parallaxes can be reliably measured up to 30 pc away ($\sim$ about four thousand stars). The precise measurement of distance is a huge problem in astronomy. A satellite named Hipparcos was launched in 1989 and has measured parallaxes for tens of thousands of stars out to a few hundred pc. The results from Hipparcos have provided fundamental revisions to the distance scale and the age of the Universe.

If the distance of a star is known, then we can determine its intrinsic brightness or luminosity (= total energy output in Watts). The luminosity depends on the surface area of the star and its temperature.

Stars come in a wide range of masses. Minimum mass = $0.08M_\odot$ (= lowest mass for nuclear fusion) up to perhaps $120M_\odot$. Our sun at $1M_\odot$ is a very typical star – most stars have about this mass.

The more massive a star is, the faster it fuses hydrogen into helium, and therefore it uses up its energy supply more quickly and thus has a shorter lifetime.

A star with a mass of $50\,M_\odot$ lives for a few million years whereas the Sun will live for 10^{10} years and is currently halfway through converting its hydrogen into helium in the core.

When a star has converted all the hydrogen into helium in its core the rest of its short remaining lifetime ($\approx 1/10$ of time spent converting H $\longrightarrow$ He) depends on the mass of the star, M_*, or more precisely, the mass of the core, M_c.

If $M_* \simeq 1 M_\odot$, the stellar core will contract, heat up, and start burning $^4He \longrightarrow^{16} C$. The core has contracted so much that the electrons in the core become degenerate (Pauli's exclusion principle). This implies there must be an upper limit to the mass of the core otherwise Pauli's exclusion principle would be violated. This upper mass limit $= 1.4\,M_\odot$ and is called the Chandrasekhar limit.

The eventual fate of the Sun is that it will burn He to C for $\sim 1\times10^9$ years and during that time, it will gently shed its outer layers to leave the degenerate core or *white dwarf* as the remnant.

When $M_* > 8\,M_\odot$, the core mass $> 1.4\,M_\odot$ and the fate of the star will be different. Because the core is more massive, it can easily heat up on contraction (i.e. it will not become degenerate) to fuse He $\longrightarrow$ C, and then C $\longrightarrow$ O and successive elements until its core is composed of iron.

It is impossible to fuse iron and liberate energy so the star undergoes a spectacular death – a supernova explosion. The Fe core contracts, and the density becomes so high ($\approx$ nuclear) that because of P.E.P., the electrons and protons form neutrons and a neutron star is born (made of degenerate neutrons and held up by degenerate neutron pressure). The outer layers of the star are thrown off in a gigantic explosion or "supernova" (SN). Takes ~ 1 second.

NB: Tycho and Kepler both discovered supernovae – this challenged the idea that the stars are fixed/unchanging. (Made them famous – awarded money to continue their work.) Tycho – 1572; Kepler – 1604; next 1987.

If the mass of the core $\geq 3\,M_\odot$ ($M_* \sim 20\,M_\odot$), nothing can stop the collapse of the core and a black hole is formed.

Supernovae are important because the explosion produces many "rare" elements.

A star like the Sun has a composition of 75% H, 23% He and 2% of everything else. As we shall see later, only H and He were produced in the Big Bang, and so every other element has been synthesised in stars, and is released in SN explosions. Elements up to Fe are made by fusion in the core of a star, and most elements beyond Fe (U, Ag, Au) are made in SN explosions. Thus the 2% of heavy elements in the Sun all come from previous generations of stars.

Stars – produce visible light in the Universe and are factories for making elements from H and He.

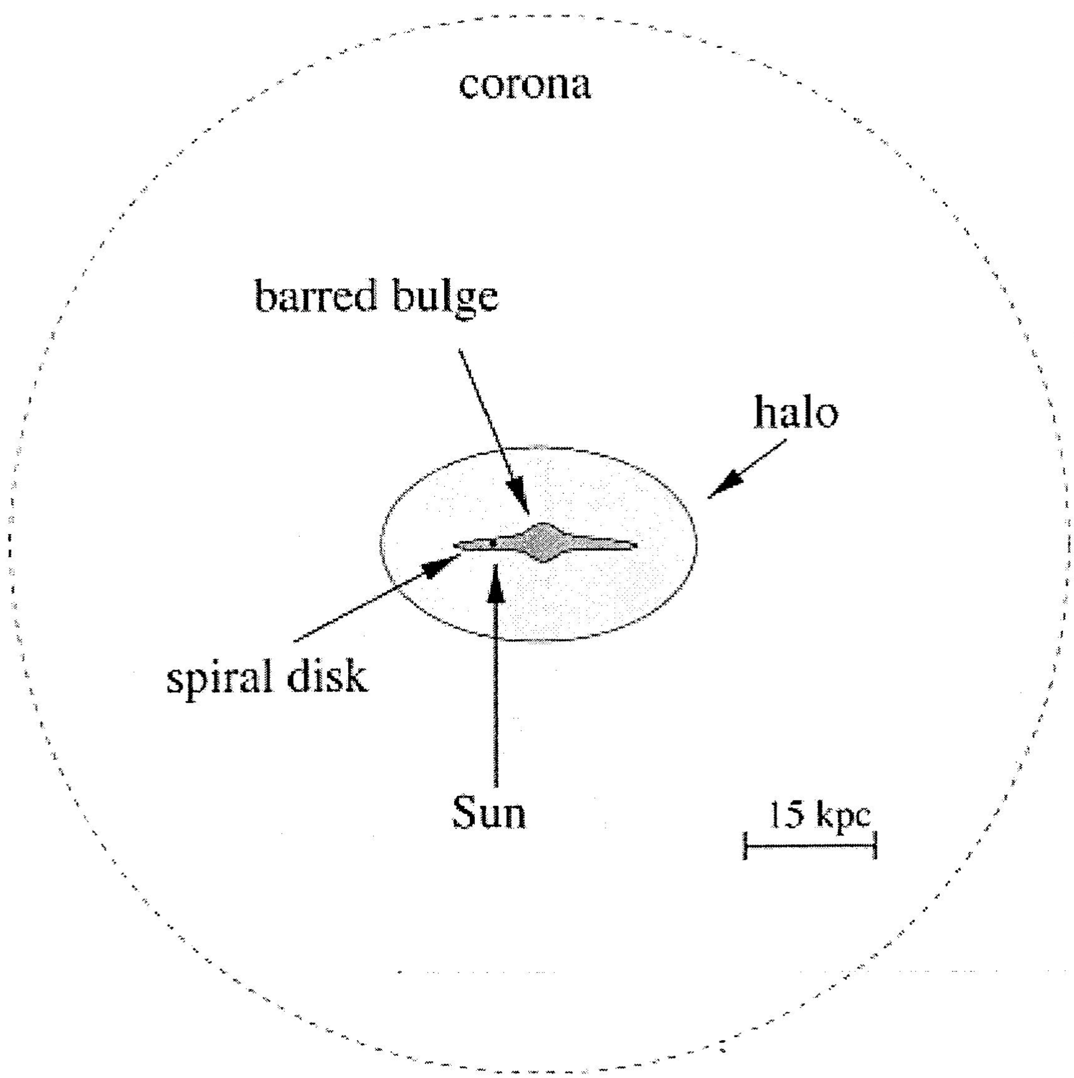
Stars are made from huge clouds of molecular hydrogen which collapse. In between the stars – interstellar medium – very low density (1 atom per cm^3) gas.

1.1.2 The Milky Way Galaxy

All the stars that we see belong to a large grouping of stars held together by mutual gravitation – called a galaxy.

With the advent of the telescope, Galileo first looked at the misty band of light "the Milky Way" that stretches across the sky and found that the "clouds" were composed of thousands of faint stars.

Today, through much careful observation, we know that we live in a disk-shaped galaxy (Milky Way = disk) with spiral arms. It took a long time to work out the size and shape because we live inside, and there is a lot of obscuration.



DISK – thin compared to the diameter, thickness = 0.3 kpc and diameter = 25 kpc. Contains all raw material for making stars (huge clouds of molecular hydrogen and dust (tiny particles made of carbon and silicate)) and all the young stars, including Sun which is 8 kpc from centre.

BULGE – contains old, low mass stars.

NUCLEUS – centre of our Galaxy, and contains a $2 \times 10^6 M_\odot$ black hole. The centre is totally obscured from direct view at visible λ's because the dust scatters the starlight. We use infra-red/radio observations to probe its nature.

HALO – surrounds disk and has a radius of at least 50 kpc. It contains globular clusters – gravitationally bound systems of stars. They are typically 3 pc in diameter and contain $\sim 10^5$–10^6 stars. These stars are the oldest stars in our Galaxy $\Longrightarrow$ fundamental to setting a minimum age for the Universe. They have a composition of 0.1% elements heavier than He.

In total, our Galaxy contains $\sim 10^{11}$ stars. The disk rotates slowly and differentially (outer edges much more slowly). At the distance of the Sun, the rotational period = 200 Myr.

When we measure the orbital velocity of the Galaxy as a function of radius, the orbital velocity falls off more slowly than we would expect if all the mass is concentrated at the centre $\Longrightarrow$ mass is more uniformly spread out in a form that cannot be seen i.e. not stars $\Longrightarrow$ halo of dark matter whose form is unknown (failed very low mass stars called brown dwarfs?) $\Longrightarrow$ first example of missing matter.

The rotation curve of our Galaxy implies a total mass of $\sim 10^{12} M_\odot$ but we see only $\sim 10^{11} M_\odot$ (10^{11} stars $\sim 10^{11}$M$\odot$) or 10%.

1.1.3 Galaxies

Since the invention of the telescope, observers recognised a considerable number of celestial objects which were not stars but looked like small fuzzy clouds. They were called nebulae and were catalogued by Charles Messier in 1781. Most nebulae are still known by their Messier numbers e.g. Orion nebula = M42.

In the early part of 20th century, the nebulae were divided into two distinct groups – those concentrated towards the MW with cloud shapes, and those of spiral or elliptical shape occurring at random on the sky. There was then a huge debate: were they collections of stars, just like the MW, at great distances, or hazy nebulae within our own Galaxy? The debate was finally settled in 1924 when Edwin Hubble employed a technique of using variable stars (period $\propto$ intrinsic brightness) to measure their distances $\Longrightarrow$ galaxies.

Hubble classified galaxies according to their appearance: spirals, ellipticals and irregular.

Today, we know our Galaxy is part of a small group of ~ 30 galaxies (called the Local Group). It is dominated by two spiral galaxies: the Milky Way and the Andromeda galaxy or M31 which is 770 kpc away. The nearest galaxy to us is the small irregular galaxy – The Large Magellanic Cloud which is 50 kpc away.

Studies of spiral, elliptical, and irregular galaxies show that they are all about the same age i.e. not an evolutionary sequence. One active research area today is the study of why we have different shaped galaxies. One popular idea is that large galaxies are made by the merging of smaller galaxies.

In cosmology, galaxies are treated as point-like objects – the details of their shapes are mainly irrelevant.

$1\,\mathrm{Mpc} = 10^6$ pc $= 3.086 \times 10^{22}$m – cosmologists' unit. 1 Mpc $\approx$ distance between galaxies (eg M31 d = 770pc).

1.1.4 Clusters of Galaxies, Superclusters and Voids

When larger regions of the Universe are surveyed (on a scale $\approx$ 100 Mpc), large-scale structures are revealed i.e. galaxies are not randomly distributed. In some places we see *clusters of galaxies* – largest gravitationally bound objects in the Universe e.g. Virgo cluster – 16 Mpc away, size of 3 Mpc.

Coma cluster – 100 Mpc away, 7 Mpc in size, contains $\sim 10^4$ galaxies. Total mass $\sim 10^{15}$ $M_\odot$. Spacing of galaxies $\approx 100 \times$ diameter of a galaxy (spacing of stars $\sim 10^6$ typical stellar diameter). The Local Group is being pulled towards the Virgo cluster at a velocity of 630 $\mathrm{km\,s^{-1}}$.

On still larger scales, clusters of galaxies themselves are grouped into *superclusters* – chains of clusters/walls or filaments. In between these structures there are *voids* up to 50 Mpc across.

One of the most important areas of study in cosmology is to understand how such large structures can be formed. We will look at the formation of structure later. Observations – huge surveys currently being carried out to map the distribution of galaxies in the local Universe.

1.1.5 Quasars

We can see galaxies through the integrated light of their constituent stars. Galaxies that shine through starlight are called normal galaxies and can be observed to distances of a few thousand Mpc.

In the 1940's, it was realised by astronomer Carl Seyfert that the light output from some galaxies was quite different. These galaxies have much brighter nuclei than normal – called Seyfert galaxies and form part of large collection of *active* galaxies. These are galaxies that produce more radiation than can be produced by their stars.

In 1963, objects that looked like stars – called Quasars – were discovered to be the most distant objects in the Universe and thus incredibly luminous. The first object discovered 3C 273 was at a distance of 900 Mpc (= 3 billion l yr). The only possible explanation for the huge luminosities of such distant objects was the existence of a supermassive black hole ($\sim 10^8$ $M_\odot$) at the centre of each galaxy. Stars are destroyed near the black hole and the energy released is enormous.

Today, thousands of quasars are known – we use them to observe the distant Universe. They represent a time when the Universe was young ($\approx$ 10% of its present age) and galaxies were very energetic ie. producing lots of energy, powered by supermassive black holes.

1.2 Other Wavebands

1.2.1 Microwaves

This is the most important waveband for cosmology (cm wavelengths). In 1965, Penzias and Wilson accidentally discovered that the Earth is bathed in microwave radiation, obeying a blackbody spectrum with $T \sim 3\,\mathrm{K}$. It represents the radiation left over from the origin of the Universe. This is one of the most powerful pieces of evidence in support of the hot Big Bang theory. The cosmic microwave background (CMB) was formed about 300,000 yrs after the Big Bang.

The Cosmic Background Explorer satellite (COBE) was launched in 1989 to measure the uniformity and temperature of the CMB. It has a perfect BB spectrum with $T = 2.725 \pm 0.001\,\mathrm{K}$. COBE found that there are tiny deviations in the temperature – 1 part in 10^5 – this level is extremely important because it is related to the origin of structure in the Universe.

1.2.2 Sub-mm and Radio

Many active galaxies emit very powerfully at radio wavelengths.

Recently, surveys at sub-mm wavelengths on the James Clark Maxwell Telescope have revealed a new population of very distant galaxies. The nature of these galaxies is still being investigated.

1.2.3 Infra-red

This is an exciting "new" waveband. The youngest galaxies, producing their first generation of stars, will be brightest in the far-IR (light is red-shifted into this region). The successor to the Hubble Space Telescope will focus on the IR part of the spectrum and study the time "when galaxies were young".

1.2.4 X-rays

These are a vital probe of clusters of galaxies because they contain very hot gas (10^6–$10^7\,\mathrm{K}$) which emits at X-ray wavelengths. Distant clusters can be detected only at X-ray wavelengths. The two current X-ray satellites *Chandra* and *XMM-Einstein* are producing lots of new exciting results.