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The Structure of the Universe

During the past few decades of research a plausible picture of the universe's most distant past has begun to emerge. The current view is that the universe came into existence some ten billion years ago in the form of a huge, exploding 'fireball'. This was the *big bang*.

We are going to discuss some key features of the big bang in this book. In particular, we will look at the central question of just how 'big' it really was. But before we can begin our journey back towards the origin of the universe, we must work out our present location within it. Let us therefore embark on a brief sight-seeing tour of the universe.

The Earth belongs to a collection of objects known as the *solar system*. The central and largest object in this system is the sun. Nine planets, including the Earth, orbit the sun. Pluto is the planet most distant from the sun, and Pluto's orbit may be viewed as the edge of the solar system.

The nearest significant object to the Earth, its moon, is some four hundred thousand kilometres away. For comparison, the distance between the Earth and the sun is roughly one hundred and fifty million kilometres, whereas the average distance between the sun and Pluto is approximately six billion kilometres.

What lies beyond the solar system? As we travel past Pluto, the vastness of empty space soon becomes apparent. For example, the nearest star to the sun – Proxima Centauri – is some forty trillion kilometres away from it.

We thus encounter a major problem even during this early stage of our journey: When thinking about the universe, how are we to deal with the huge distances involved? We were already talking of billions of kilometres before we left the confines of the solar system. This distance is in itself difficult to imagine. Yet we must increase this scale to trillions of kilometres before we arrive at the nearest star.

Astronomers make sense of such large scales by measuring distance in terms of a *light year*. This is the distance light travels in one year when moving at its speed of three hundred thousand kilometres per second. Numerically, one light year is equivalent to nine and one-half trillion kilometres. The distance from the Earth to the sun is about eight light minutes. This is the time it takes light to travel from the surface of the sun to us here on Earth. The distance from the sun to Proxima Centauri is over four light years.

Scale models also prove useful when comparing distances between various objects in the universe. Let us consider what would happen if we were to reduce all distance scales so that the radius of the Earth was comparable to the radius of a typical wristwatch. In this case, the radius of the sun would be equivalent to the height of an average man. The distance between the Earth and the sun would then be four hundred metres. Pluto would be some fifteen kilometres away, but we would still have to travel about one hundred thousand kilometres before we reached Proxima Centauri. Such a trip would be equivalent to travelling two and one-half times around the world.

Our sun and Proxima Centauri are just two of the many stars that belong to the Milky Way Galaxy. If we were to move outside our galaxy and view it from above, we would find that it looks rather like a giant Catherine-wheel, as shown in Figure 1.1a. The Milky Way contains a number of spiral arms that are attached to a central region. These arms consist of numerous stars. When viewed from its side, the galaxy resembles a disc with a bulge in its centre, as shown in Figure 1.1b. The radius of the bulge is about ten thousand light years, and the disc itself is at least one hundred thousand light years across. The disc can be seen on a clear, moonless night and resembles a thin cloud that stretches across the sky. It has a diffuse appearance, and, indeed, the word ‘galaxy’ can be traced to the Greek word *galacticos*, which means milky.

There is also a halo of very old stars around the centre of the galaxy. This halo extends out in all directions for about fifty thousand light

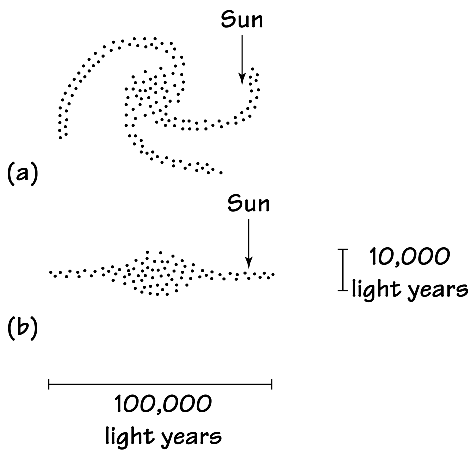

Figure 1.1. (*a*) The Milky Way Galaxy when viewed from above. It contains a spherical, central region and a number of spiral arms. These consist of stars. The location of the sun near one of these arms is shown. The sun lies about 28,000 light years from the centre of the galaxy. (*b*) The galaxy when viewed from its side. At its widest point, the galaxy's width is about 100,000 light years.

years. In total, the Milky Way contains over one hundred billion stars. Our sun is located about 28,000 light years from the centre of the galaxy.

We need a further reduction of scale to make comparisons on the galactic scale. Let us shrink the entire solar system so that it has a size comparable to that of a typical grain of sand. (Recall that the solar system's actual size is about six billion kilometres.) The nearest star, Proxima Centauri, would now be just over one metre away from the edge of the solar system. The distance from the solar system to the centre of the galaxy would correspond to the height of Mount Everest. When comparing the solar system to the rest of the galaxy, we can think of a mountaineer who has reached the summit of Everest and in whose pocket is a grain of sand.

The overall picture we have thus far is that the sun and other stars in our galaxy are separated by many thousands of light years. Yet despite these great distances, the stars are still attracted to one another by the force of gravity. It is this attraction that keeps the stars confined to the galaxy.

What do we find when we move beyond the neighbourhood of the Milky Way? As far as our journey through the universe is concerned, we have only just begun. Once more we are confronted with the vastness of empty space. We do not encounter another significant object until we have travelled outwards for a further 170,000 light years. At this distance, we find a small galaxy known as the Large Magellanic Cloud.

There are numerous other galaxies in the universe besides the Large Magellanic Cloud and the Milky Way. The observable universe probably contains over one hundred billion galaxies. These galaxies come in many shapes and sizes. Many are spiral in shape just like the Milky Way, although the majority are not. Those that are not are referred to as 'elliptical' galaxies due to their shape. These elliptical galaxies are dominated by stars that may be as old as ten billion years.

Although galaxies exist as separate entities throughout the universe, they do not behave as isolated objects. They attract each other by the force of gravity and so group together into clusters. The number of galaxies in a particular cluster may be quite low, but can be as high as a few thousand. Typically, a cluster of galaxies extends for millions of light years. For example, our own Milky Way belongs to a cluster known as the *local group*. The largest galaxy in this group is the Andromeda Galaxy, a spiral galaxy that is over two million light years away from the Milky Way. The local group extends for about six million light years, about sixty times the size of our own galaxy.

Clusters of galaxies are grouped into superclusters. Superclusters extend for hundreds of millions of light years. Our local group of galaxies belongs to what is known as the *local supercluster*. At the centre of this supercluster is the cluster of galaxies known as the Virgo cluster. The Virgo cluster, which contains thousands of galaxies, is located about fifty million light years away from our own local group. In a broad sense, the universe may be viewed as a hierarchical structure of galaxies, clusters of galaxies and superclusters of galaxies.

Finally, the most distant visible objects that have been observed to date are known as *quasars*. Quasars emit an enormous amount of energy, but the source of this energy has not yet been identified. These objects are thought to be at least ten billion light years away from us, and this distance represents the size of the observable universe.

Some typical distance scales are summarized in Table 1.1. What have we discovered from this tour around the universe? We see that our planet orbits an average star that is located in the outer regions of the Milky Way Galaxy. Our galaxy contains at least one hundred billion stars and is just one example of the hundred billion galaxies that constitute the observable universe. Although we tend to think of the other planets in our solar system as being a great distance from us,

Table 1.1. *Some typical distance scales in the universe. The symbol 'ly' stands for light year and corresponds to 9.5 trillion kilometres*

Objects	Distance
Earth–Moon	4×10^5 km
Earth–Sun	1.5×10^8 km
Solar system diameter	6×10^9 km
Sun–Nearest star	$4.3ly$ (4×10^{13} km)
Milky Way diameter	$10^5 ly$ (10^{18} km)
Cluster of galaxies	$\geq 10^6 ly$ (10^{19} km)
Size of the universe	$\geq 10^{10} ly$ (10^{23} km)

the entire solar system is *tiny* when compared to our own galaxy, let alone to the rest of the universe.

Given this broad picture, we can proceed to investigate the structure and history of the universe in more detail. The study of the universe as a whole is known as *cosmology*. The primary aim of the cosmologist is to understand how the universe developed over time into its present state and then to predict how it might behave in the future. One question that has occupied many cosmologists in recent years is how the current structure of the universe was influenced by physical processes that operated during the big bang.

Cosmologists are able to look progressively further back in time by probing the depths of the universe. Light that originates from a very distant galaxy has to travel farther to reach us here on Earth than does light emitted from a relatively nearby galaxy. This means that it takes longer for light from a distant galaxy to complete its journey. Many of the galaxies that we observe are so far away that it has taken their light billions of years to reach our solar system. Thus the photographs that we take of these galaxies are not pictures of what they look like today, but rather are images of what they looked like in the past.

The light emitted from distant galaxies has certain characteristic features, as we shall see in Chapter 3. These features indicate that the galaxies are moving away from each other. This finding is very significant, because it implies that the universe as a whole is *expanding*. Indeed, our observations indicate that the universe has been expanding for at least ten billion years.

Let us study the implications of this expansion further. We can view physical distances in the universe in terms of a given distance between two fictitious particles. Suppose we were to consider a particle in our own Milky Way Galaxy and a second particle in the neighbouring Andromeda Galaxy. An expansion of the universe can then be interpreted as an increase in the distance separating these two particles. This is what we shall have in mind when we talk about an increase in the volume of the universe.

As we go back in time, the distance between our two particles must have been somewhat smaller than it is today. This provides us with our first insight into what the universe may have looked like at earlier times. It is reasonable to suppose that the universe must have been *smaller* at some stage in its history than it is at present. Consequently, the galaxies must have been closer together than they are today, and the density and temperature of matter must have been correspondingly higher. If we are prepared to go sufficiently far into the past, the distance separating our two particles would have been much smaller than the size of a typical galaxy. At these very early times, galaxies as we know them today could not have existed. All the matter in the universe would have behaved as though it were a superhot and superdense fluid.

The big bang model describes the universe when it went through this early phase, after it was just a few seconds old, and we summarize the key features of this model in Chapter 7. We will also consider what may have happened in the universe before the first second had elapsed. In Chapters 8 and 9 we will see that there are strong arguments to suggest that the universe underwent a period of very rapid expansion when it was no more than 10^{-35} seconds old. At that time the matter currently contained within the observable universe (around one hundred billion galaxies) would have been squashed into a region of space considerably smaller than that occupied by a typical atom. Furthermore, the temperature of the universe would have been exceptionally high, many times higher than the temperature at the centre of the sun.

This period of expansion is referred to as *inflation*, because the universe increased in size by a huge factor. It did this very quickly indeed. The duration of this rapid expansion was extremely brief, at least in the simplest versions of the theory, and may have taken less than 10^{-33} seconds to complete.

If inflation is to provide us with a plausible picture of the universe at these very early times, we need to understand what caused the universe to expand so rapidly. In the next five chapters we will develop the background necessary for discussing the very first moments of the universe's history. We will then proceed in the remainder of the book to discuss what we think may have happened during the first 10^{-35} seconds of the universe's existence. This will lead us to some of the more speculative ideas that have been developed recently regarding the origin of the universe.

Where is a suitable place to begin? It seems reasonable that we start from somewhere relatively close to home – that is, from somewhere within the solar system. Since the sun is the largest object in this system, we could begin by discussing its properties. The most obvious feature of the sun is that it shines. Let us begin then by asking what it is that causes the sun to shine.

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Why Does the Sun Shine?

Visible light is an example of *electromagnetic radiation*. This radiation may be pictured as a wave travelling through space. Although light always travels at a fixed speed, its wavelength – defined as the distance between two successive peaks or troughs – is not uniquely specified. Different types of light can have different wavelengths. These differences manifest themselves as different colours in the visible spectrum. For example, red light has a slightly longer wavelength than blue light. The light that we receive from the sun is a mixture of all the different colours.

Electromagnetic radiation with wavelengths significantly longer or shorter than those associated with visible light also exists. Two examples are gamma rays and radio waves. All types of electromagnetic radiation carry a certain amount of energy. A gamma ray has a lot of energy whereas a radio wave carries a relatively small amount of energy. In a sense, we can imagine the energy as localized around the peaks and troughs of the wave. Thus the energy of a given type of electromagnetic radiation is specified by its wavelength; a shorter wavelength corresponds to a higher energy and vice versa. This follows since a shorter wavelength means that more crests and troughs will arrive in a given interval of time, so more energy will be received.

Light has a very important property in that it changes its direction of motion as it travels between regions of different density. Much of what we know today about the internal composition of stars is deduced directly from this property. In effect, as it passes from one medium to another, light becomes deflected from its original path. What makes this phenomenon so interesting to us is that the precise amount of deflection is determined by the wavelength of the light. For example, the deviation of red light differs from that of the shorter-wavelength blue light. As a result, red light and blue light follow *different* paths. A beam of light that is made up of radiation of different wavelengths will separate into its individual colours because of the change in density.

Sunlight is just such a mixture of different colours and can be separated in this fashion. In fact, this is precisely what happens when a rainbow appears in the sky during a shower. We see the rainbow as the sunlight passes from the atmosphere, through the denser water droplets, and back out again into the atmosphere.

An identical effect arises when sunlight is passed through a prism onto a piece of photographic film. Once the film has been developed, the resulting photograph resembles a picture of a rainbow. However, a closer look at the picture reveals dark bands. These regions are so thin that they look as if someone has drawn a vertical line on the photograph with a black pen. Lines that are much brighter in intensity can also be seen. What is causing these dark and bright lines to appear in the picture?

Let us concentrate on the dark lines. Because each colour in the picture corresponds to light of a certain wavelength, the existence of dark lines at specific colours implies that the light with that particular wavelength is missing from the sunlight directed through the prism. It is important to ask what might have happened to this radiation. That we do not see it in the photograph tells us that it failed to reach the Earth's surface for some reason. One possibility is that this particular light was absorbed by something during its journey from the sun to the Earth. But this is unlikely, because the region between our planet and the sun is basically empty. It is also unlikely that this light could have been absorbed by the Earth's atmosphere. A more plausible possibility is that the light was never emitted in the first place. The light could have been absorbed by the material in the sun before it had time to escape from the sun's surface.

Can we determine the nature of the stellar material that is responsible for this absorption? The answer is yes, we can, but before doing so we need to study the internal structure of atoms.

The atom is the fundamental building block of all matter including that contained within our own bodies. The typical size of an atom is about 10^{-10} metres. Every atom has a nucleus that is made up of tiny particles called 'protons' and 'neutrons'. These particles are packed together very tightly inside the nucleus. For the purposes of this discussion, we may think of them as minute billiard balls. They have a diameter that is roughly 10^{-15} metres. Protons and neutrons are similar to each other, but they are not identical. They have roughly the same mass, although the neutron is slightly heavier than the proton. The proton also carries a positive electric charge, whereas the neutron is electrically neutral. This means that the nucleus as a whole is positively charged.

Surrounding this nucleus are particles known as electrons. The electrons are smaller and lighter than the protons and neutrons, so most of the mass of an atom is concentrated inside the nucleus. Electrons have negative electric charge, and an atom has just enough electrons to ensure that the positive charge of the nucleus is precisely cancelled. The atom is therefore electrically neutral.

The electrons around the nucleus of an atom are not free to assume just any orbit. Electrons have a tendency to remain as near to the nucleus as possible (without actually falling into it), and some are able to get relatively close. If there are many electrons inside the atom, the region closest to the nucleus becomes occupied and inaccessible to the remaining electrons, and these particles are then forced to occupy larger and larger orbits. This means that the orbits of the electrons are *restricted*.

This is important because the energy of each electron in the atom is determined by its distance from the nucleus. Those electrons that are farther away have a higher energy. To see why this is, let us consider the simplest atom in existence. This is the hydrogen atom. In the hydrogen atom the nucleus contains a single proton and has one electron orbiting around it. If we want to separate these two particles, we have to overcome the attractive force that operates between them due to their opposite electric charge.

A certain amount of energy must be expended in overcoming this resistance to separation. Since energy must always be conserved in any physical process, the energy it costs us to separate the proton and electron must go somewhere. It cannot simply disappear. It becomes stored as 'potential' energy in the electron. The electron *gains* energy as it becomes separated from the proton and assumes a larger orbit. It