

Chapter 26 Cosmology

The Universe on the Largest Scales

As we have seen, the universe shows structure on every level that we have looked at, from subatomic particles to galaxies, clusters of galaxies, and clusters of clusters. Astronomers asked if there is some scale on which the universe is smooth and featureless. The answer is yes.

The End of Structure

We have seen how astronomers use the redshift surveys to explore the distribution of galaxies in the universe. Figure 26.1 shows us galaxies from one of the most ambitious sky surveys. It shows some 67,000 galaxies lying in a 120° wide slice of the sky within a few degrees of the celestial equator. This is from the Sloan Digital Sky Survey. The distances shown assume H_0 at 70 km/sec/Mpc. The picture goes out to about 1000 Mpc. You can see a structure called the Sloan Great Wall which is about 250 Mpc long and 50 Mpc thick. That makes it the largest structure known. There are huge amounts of information in surveys like this. But remember that this is only about 10 % of the distance to the farthest quasars (about 8000 Mpc). The toughest part in making larger surveys is the sheer effort involved in trying to measure all of these redshifts. One idea is to look at distant galaxies but only in a thin patch. They call this a pencil beam. Figure 26.2 shows us how we use the pencil beam to look out into space. The graph shows how the numbers of things fall off as we move out. This goes out to about 2000 Mpc. So far all of the surveys seem to agree that the largest structures are only 200 – 300 Mpc across. The largest structures can be explained by smaller structures that overlap as seen from our position. There is no evidence for structures larger than 300 Mpc.

The Cosmological Principle

Large scale studies suggest that the universe is *homogenous* (the same everywhere) on scales larger than a few hundred megaparsecs. In other words, no matter where in the universe you look on a large scale, the universe would look pretty much the same. The universe also appears to be *isotropic* (the same in all directions) on large scales. We count about the same number of galaxies no matter what direction we look. All of this will lead to what we call *cosmology*. This is the study of the structure and evolution of the entire universe. Now we have no idea whether our assumptions are correct, but they are consistent with current observations. These 2 assumptions (that we will assume are true) are called the *cosmological principle*. Everything that has been stated throughout this book also assumes one other thing: the laws of physics hold true throughout the universe. If these are true, then it says that there is no edge to the universe because that would violate the idea of homogeneity. It also implies that there is no center because that would mean that the universe would not look the same from everywhere.

Olber's Paradox

We will make an assumption that the universe is homogeneous and isotropic. We will also assume that the universe is infinite and unchanging in time. If that is true, then as we look out into space we should see a galaxy and the stars in the galaxy. Figure 26.3 The farther out you look, the fainter the stars become, but they also become more numerous

so you would see them. That would mean that everywhere you would look in the sky you would see stars and the sky would be bright as the Sun. But we know that it isn't. This is called *Olber's Paradox*. Well the universe appears that it is homogeneous and isotropic so that means that either one or both of the other assumptions are false. Actually it is a little of both.

The Birth of the Universe

How old is the universe? That is a question that has been asked a lot. Well we know that $\text{time} = \text{distance}/\text{velocity}$ so we can modify it to read $\text{time} = 1/H_0$. We assume 70 km/sec/Mpc for H_0 and this gives us an age of about 14 billion years. That means that 14 billion years ago everything was on top of everything else. The locations and velocities are a consequence of some primordial blast. The blast is known as the *Big Bang*. Now the age of 14 billion years has quite a bit of possible error because the value of 70 km/sec/Mpc is not definite. Regardless of that, astronomers do agree that the age of the universe is finite. The Big Bang explains why Olber's paradox occurs. We can only see out to 14 billion light years and the light from anything beyond that hasn't reached us yet. This appears to place us in the center, but it is an illusion. Figure 26.4 This shows 5 galaxies and what is seen if you were on a different galaxy. Everything appears to be moving away from everything else. Each observer would see a H_0 of about 70 km/sec/Mpc as they looked at every other galaxy.

Where Was the Big Bang?

We have an idea of when the Big Bang occurred but do we know where it occurred? We say that the universe is the same everywhere, but what we have described says that the galaxies expanded outward from somewhere. If we assume an explosion, like a bomb, then you are correct in saying that they spread out from a central point. But it is not so with the universe. The Big Bang involved the entire universe, not just matter and the radiation, but the entire universe itself. The universe itself is expanding. This idea is very much like a loaf of raisin bread. As the bread rises, each raisin would see the other raisins moving away from it by the same rate depending on the distance. As space itself is expanding, the galaxies caught up in space are being carried along with the expansion. The motions of the galaxies that make up the Hubble flow are really the expansion of space. The galaxies did not reside at a single point, but rather the entire universe was a point. Basically that means that the Big Bang happened everywhere at once. It involved the entire universe. Let's tape some coins onto a balloon that represent galaxies in the universe. Figure 26.5 As you blow up the balloon (the universe is expanding), the coins move apart from each other. No matter which coin you pick, all the other coins are moving away from you. The fabric of space is expanding, but due to local gravity, the galaxies aren't expanding.

The Cosmological Redshift

We discussed the cosmological redshift as though it was due to the motion of the galaxies. As you can see the galaxies aren't really moving so that idea isn't quite right. The cosmological redshift actually occurs because as the photon of light travels through space the space itself is expanding and the redshift measures how much the universe has

expanded since the photon was released. Figure 26.6 The greater the redshift, the younger the universe was when it was released.

Relativity and the Universe

The idea of the universe expanding from a point into nothing is hard to take. Regardless, this is at the heart of modern cosmology. The evolving universe is beyond what Newtonian mechanics can explain. We must use general relativity. Basically, matter causes space to warp and the warped space tells matter how to move. The amount of curvature is due to the amount of mass present. We know that the overall geometry is described by relativity, much of the dynamics of the universe is explained by Newtonian mechanics.

The Fate of the Cosmos

Will we continue to expand forever or will we come crashing back together? That is a big question asked today. In the 1990's it was thought that the answer would be found by determining the extent to which gravity would slow down the expansion. But now it seems that the answer is more subtle.

Critical Density

Let's assume that gravity is the only force affecting large scale motion in the universe. This idea was the backbone of our ideas about what was happening in the universe. We now know that new observations have forced a change in astronomer's view of the universe. Let's look at a space ship that is being launched. Only 2 things can happen. You can reach escape velocity and get off the planet or you don't reach escape velocity and land back on the planet. Figure 26.8 shows those two possibilities. Now let's look at 2 galaxies in space. They may have the same results as the space ship. They can move apart forever or slow down and come together. The cosmological principle says that that is true for any 2 galaxies. As figure 26.9 shows, the universe has 2 fates. If gravity alone were the deciding factor, then we need to know the density of the universe. The magic density is called the *critical density*. If H_0 is 70 km/sec/Mpc, then the critical density is 9×10^{-27} kg.m³. That is about 5 hydrogen atoms per cubic meter. (house hold closet) That would be about .1 Milky Way per cubic megaparsec.

Two Futures

The 2 possibilities for the universe are so different from each other. If the density is high enough, the galaxies will come to a halt and begin to move towards each other. Eventually they will reach a position where the galaxies and stars in them will collide. This is often referred to as the *Big Crunch*. Figure 26.10a The other option is that the density of the universe is slow enough that gravity never gets a grip on the expansion and it expands forever. Eventually we will all move far enough away from each other that we won't be able to see the light from the other galaxies and we will be all alone. We will suffer a cold death. Astronomers estimate that there is enough gas in the universe to keep forming stars for tens of billions of years. The low mass stars can shine for hundreds of billions of years so the universe probably has another trillion years or so.

The Geometry of Space

We have used the familiar Newtonian mechanics and gravity to explain what is happening. The theory of general relativity makes some predictions that can't be simply explained in Newtonian mechanics. For one thing space is curved and the degree of curvature is determined by the total density of the cosmos. Density is determined by mass (as we know it to be), but relativity says mass and energy are equivalent: $E = mc^2$. According to relativity, the warping of space is due to both mass and energy. So the density of the universe is calculated by not only what we can see, but also dark matter and everything that carries energy. In a homogeneous universe space is curved the same everywhere. That gives us 3 possibilities for the universe. Cosmologists call the ratio of the universe's actual density to the critical value the *cosmic density parameter*. (Ω_0) In a high density universe where Ω_0 is > 1 , then space curves back around on itself and closes off. This is called a *closed universe*. A closed universe has no boundary just like a sphere. Figure 26.11 Just like the sphere if you go in a straight line and keep moving in that direction, you will get back to where you started. This is said to be a *positive curve*. If you think of a saddle shape, you get a *negative curve*. This would be a low density universe. ($\Omega_0 < 1$) This is called an *open universe*. It is infinite in extent. If $\Omega_0 = 1$, then the density is equal to the critical density. This is called the *critical universe*. Basically we think of the geometry as being flat and it is infinite in extent. Flat is what we understand because it is what we experience every day. We don't notice the curvature. The geometry of flat space is called *Euclidian geometry*. It works well for us because the curvature of space is negligible on scales smaller than about 1000 Mpc.

Will the Universe Expand Forever?

The big question today is whether the universe will keep expanding forever or will it slow down and come back together. We live at a time when we can make observations of the universe to see what is happening. Let's begin looking at the cosmic density parameter.

The Density of the Universe

How should we measure the density of the universe? Well we could take the total mass of the universe (we'd estimate it) and divide it by the volume of the universe. When you do that you get about 10^{-28} kg/m^3 in the form of luminous material. Regardless of where you look, the answer is always within a factor of 2 or 3. The value for Ω_0 would be only a few %. If the galaxies were all that existed, we would live in a low density open universe that would expand forever. But we know that there is dark matter in the universe, lots of it. We still don't know what it is, but we know it's there. Galaxies may contain as much as 10 times more dark matter than luminous matter. For galaxy clusters, the total mass of dark matter may be as high as 95%. That means that Ω_0 would be .2 or .3. Unfortunately the amount of dark matter in the universe is unknown because we don't know how much is in between the galaxy clusters. Gravitational lensing by galaxy clusters shows us that there is considerably more dark matter than is shown by the motions of galaxies in the cluster. Optical and infrared studies has shown us that the overall motions of galaxies in the Local Supercluster indicates that there is a unseen mass that is much larger than a supercluster out there. The object is called the Local Attractor

and has a mass of 10^{17} Msun and a size of 100 – 150 Mpc. The density may be close to the critical density.

Cosmic Acceleration

Determining the density of the universe is an example of a local measurement that provides an estimate of Ω_0 . But the problem is that it is only a local measurement. We need to be able to do a global measurement. To do this astronomers use Type I supernovae. By measuring their distances and their redshifts, we can determine the rate of cosmic expansion. According to the measurements, the universe is accelerating, not slowing down nor keeping constant. Figure 26.12 This deviation is small, but it is very significant. This doesn't seem to be consistent with the Big Bang and it has sparked a major controversy. The problem is that the measurements are very difficult because just how standard are the standard candles. Are they exactly the same luminosity? That puts in error. So far nothing has shown that the technique using Type I supernovae is flawed. Sooo... what could cause the expansion to be accelerating? There might be some kind of repulsive force. It has come to be called *dark energy*. This may very well be the biggest puzzle in the universe right now. One possibility is the vacuum pressure cause by the empty space. It is called the *cosmological constant*. It was first proposed by Einstein. The cosmological constant is proportional to the size of the universe. In other words, as the universe gets bigger so does the force. So, as the universe gets bigger, gravity becomes weaker between the galaxies and the cosmological constant gets stronger. At some point gravity won't be able to catch up and the universe will accelerate at an ever increasing pace.

Dark Energy and Cosmology

We know that the Big Bang is simply a theory that explains the universe. When working with a theory we may develop better methods and gather more information and the theory must be able to change or be replaced altogether. The idea of an accelerating universe has gained widespread acceptance due to other pieces of evidence.

Cosmic Competition

Theories have predicted that the universe is flat. This has been widely accepted since the 1980's. But the data showed that the density was only about 30 % of critical including the dark matter and that was a problem. Dark energy seems to help explain that but many astronomers aren't happy with that because it introduces another unknown into the mix. Detailed measurements of the radiation field known to fill the cosmos supports the prediction that $\Omega_0 = 1$. Other studies support this. Now we think that matter makes up 27 % of the universe and dark energy makes up 73 % of it.

The Age of the Universe

The currently accepted age of the universe is about 14 billion years. For 14 billion years gravity and dark energy have been at war with each other. If we didn't have a cosmological constant, the universe would have expanded faster in the past than it does now and the universe would be younger than we think it is today. The effect of dark energy makes it increases the age of the universe. Figure 26.14 shows the possibilities. The constant expansion would be for an empty universe. The age of a critical density

universe with no cosmological constant is about 9 billion years. Most globular clusters are between 10 and 12 billion years old, so the universe couldn't be 9 billion years old.

The Cosmic Microwave Background

How close can we come to predicting the age of the universe? Actually pretty close. In 1964 a team from Bell labs, Arno Penzias and Robert Wilson, were working on a communications problem. They were studying the Milky Way's emission in the infrared. Figure 26.15 As they did their work, they noticed this hiss no matter where they pointed their antenna. They tried several things to get rid of the hiss, but they couldn't. After conversing with colleagues and others at Princeton they came to realize that they had discovered the remnants of the fiery beginning of our universe. It is called the *cosmic microwave background*. They won the Nobel Prize in 1978 for their work. The temperature estimates for the background was around 3 K. It was 25 years before we could accurately measure the temperature since this part of the spectrum is absorbed by the atmosphere. Figure 26.17 shows the plotted microwave background and shows the blackbody curve that fits the data. This shows that the temperature is almost exactly 2.7 K. This fits with the idea of a universe that is 14 billion years old since the temperature is about what it should be if it has been cooling for 14 billion years.