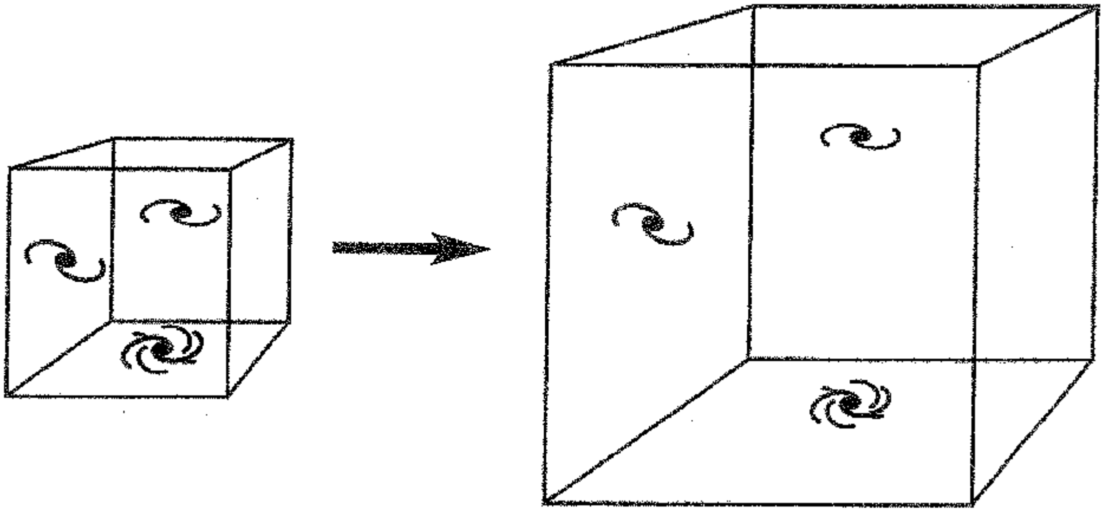
Tony Fairall - AST 1000 PART 8
COSMOLOGY

OLBER'S PARADOX AND THE FINITE AGE OF THE UNIVERSE

Even without the observations of modern technology, a fundamental observation - the night sky is dark - tells us that we cannot be looking into a universe of infinite age. If we attempted to look an infinite distance into space, our line of sight ought to eventually impinge upon a star, and the sky in that direction would be as bright as the disk of that star. The whole sky ought therefore to be as bright as the disk of the Sun, and we would not survive in such a universe. Although this is now known as Olber's paradox, credit should go the to novelist Edgar Lear who first correctly interpreted the situation as meaning that we could see only a finite distance into space.
Other considerations clearly show that the universe as we know it is of finite age: Already star formation is declining, and stars have finite lifetimes. The 'fuel' on which stars run is finite. The Stars cannot shine forever, nor could they have already been shining forever in the past.
Hubble's famous law (see below) is interpreted as the expansion of the universe - and that implies a beginning. If the galaxies are now seen moving apart from one another, then going back in time causes them to get closer, until they seem to 'meet up' with one another a certain time ago.

THE EXPANSION OF THE UNIVERSE



The accompanying diagram suggests how on a large scale (only from Diagram 11 in the overview 'Our Place in the Universe'), the universe is expanding. The galaxies (or more correctly the groups of galaxies) do not get any larger, but the space between them does.

This would seem to fly in the face of common sense, were it not for Einstein's enormous breakthrough in realising that the dimensions of space, time included, have a sort of elasticity. The contents of the Universe are like ants living on the surface of a balloon. As the balloon is inflated, its surface grows larger, and the ants are moved further apart from one another.
In three-dimensional space, a good analogy is that of a fruit cake being baked. The galaxies are the currants; space is like the dough. As the cake bakes, so the dough expands, but the currants do not get any larger. Every currant sees its neighbouring currants (if currants could see) moving away from it.

Seen from any galaxy, surrounding galaxies appear to be moving away. The further the distance, the faster the galaxies move away. Earlier we saw that the relatively nearby Virgo Cluster was moving away from us at 1000 km/s, and the more distant Coma Cluster at over 6000 km/s. This is what Hubble had discovered and expressed in his famous law:

$$V = H.d$$

where V = velocity of recession (measured in km/s), d = distance (measured in Mpc), and H, commonly known as Hubble's constant = 72 km/s per Mpc. However, Hubble, like many of us, had difficulty in accepting that it was space expanding. Conceptually, it is much easier to imagine all the galaxies expanding from a point in space, but this is incorrect.

WHERE DID THE BEGINNING TAKE PLACE?

The galaxies did not all shoot out from a point in space, like a bomb exploding inside an empty hall. Rather, think of it as the hall that grows explosively ever larger, thereby diluting its contents as it grows bigger. All of the entire visible universe – Diagram 12 in the overview sequence – must have started as a very small volume indeed. The fact that the observable universe looks so uniform in every direction we see today strongly suggests to physicists that the expansion we see today may have been preceded by rapid 'inflationary expansion'.

THE GEOMETRY OF THE UNIVERSE

Cosmologists do not see any preferred 'centre' to the Universe. The geometry of the Universe is likened to the surface of a sphere, where every point has equal status. Moreover, Einstein's theory of General Relativity allows the geometry of the Universe to have uniform positive curvature. If so, the Universe would have a limited volume, just as a sphere has a limited surface area, though it would grow larger as the Universe expanded, much like a spherical balloon being inflated.

This does not have to be the case; the Universe could have a flat geometry (like a flat piece of paper, rather than a sphere) or uniform negative curvature ('saddle shaped'). If so the Universe would have infinite volume. The concept of infinity is difficult to comprehend: However remote the chance of finding – for example – another Earth, or even another you, that chance is not absolutely zero. So in a truly infinite Universe it is possible!

But we cannot see the whole Universe! As indicated in the opening overview to this course, we can only see 13.7 billion light years. As described below, we have been able to measure the curvature of the Universe within that distance and it is flat. That is not to say the entire Universe is flat; if we only measured one square metre of the Earth's surface, it too would appear flat. The Universe may have a curvature, but on too large a scale we us to see.

THE FIRST FEW MINUTES

Clearly, stars planets and galaxies could not have existed when the Universe was highly compressed. Instead the mass content of the universe was almost uniformly distributed as hot gas. The laws of Physics tell us that as the Universe expanded, so this gas cooled. Alternatively, running back in time towards the 'Big Bang' itself, the gas would have been far far hotter.

Under the very hot, very dense, conditions of the extremely early universe, processes associated with high energy particle physics (like pair production) would have taken place. For the first few minutes, following the Big Bang, the Universe would have behaved like a nuclear reactor, much as does the centre of the Sun today. The outcome would be that almost all the matter in the universe would have ended up with three quarters hydrogen and one quarter helium and little else. After this, temperatures would have dropped enough that nuclear reactions ceased, but the gas was still very hot and incandescent, much like the Sun's interior outside its core. Like the Sun, the gas would have been opaque; 'visibility' in the early universe would have been limited, to say the least.

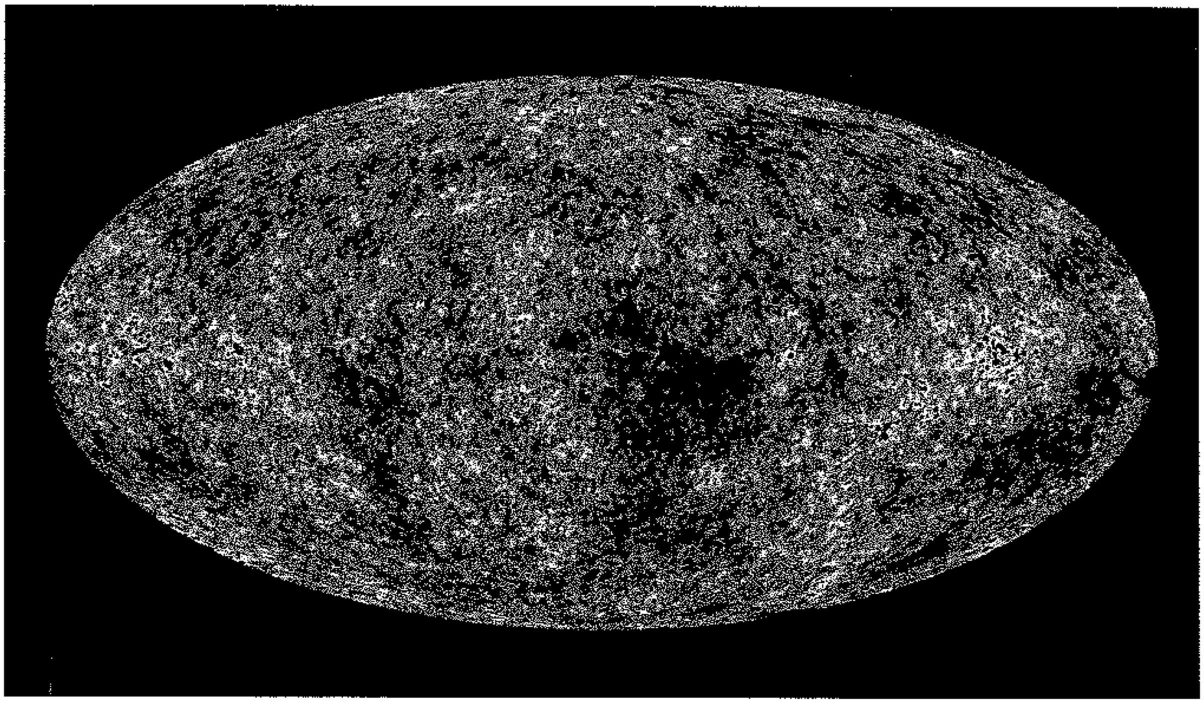
THE UNIVERSE BECOMES TRANSPARENT

At age 380 000 years, when the Universe was a thousand times smaller in dimension than it is today, the temperature would have dropped to around 3000 K, and the density accordingly. Quite suddenly (like the photosphere of the Sun), the gas would have changed from opaque to transparent. And the Universe has remained transparent ever since.

THE COSMIC MICROWAVE BACKGROUND

By looking out in distance, and thereby looking back in time (as indicated in the overview at the start of this course), we can see back through all the time that the Universe has remained transparent. At the point where/when the Universe becomes opaque, it looks as if we are enclosed in a spherical shell.

We are seeing a 'photosphere' where the temperature was 3000 K. Since this would be seen all over the sky, we ought to be fried alive! However the photons of light emitted by this blazing surface have been stretched by the expansion of space. Their wavelengths have become a thousand times longer, and their effective temperature a thousand times cooler. Hence the microwaves with a temperature of only 3 K, but still by far the most abundant radiation in the universe.



So the limit to the visible Universe appears as if it were a spherical shell with a radius of 13.7 billion light years. But the 'picture' we see on the inside of the shell is of the early Universe when it was only 380 000 years old. The picture has been stretched a thousand times bigger, to the scale of the Universe toady. What we see in the picture – the fluctuations described below – have (presumably) long since grown in galaxies, which we cannot see and in any case are now some 40 billion light years away and receding at three times the speed of light!

Many aspects related to the content and evolution of the universe can be extracted from the fluctuations found in the Cosmic Microwave Background. These fluctuations are very small - only a few parts in a million - but their recent mapping by the Wilkinson Microwave Anisotropy Probe (and other investigations) gives some remarkable results.

A musical instrument is the best analogy. We can identify instruments by the relative strengths of their fundamental modes and overtones. The same can be applied to sound waves travelling in the early dense Universe, the outcomes of which are apparent in the fluctuations.

The acoustic oscillations apparent in the Cosmic Microwave background tell us the following:
The observable Universe has a 'flat' geometry. The possible curvatures, allowed by Einstein's Theory of General Relativity, are not significant within the observable portion of the Universe.
The mass/energy content is determined as follows
4% - normal (Baryonic) matter
22% - dark matter (nature unknown)
73% - dark energy (the unknown 'anti-gravitational' force.
With these parameters known, cosmological models then tell us that the Age of the Universe is 13.7 billion years (+- 0.2) since the big bang beginning.

DARK MATTER

The apparent presence of dark matter in galaxies has already been mentioned. It seems that its presence is even stronger on larger scales, and various tests have shown that it cannot be normal Baryon matter. Its nature is one of major debate and concern in cosmology.

DARK ENERGY

When Einstein first used General Relativity to model the universe, he assumed the Universe was static, and he could not achieve a static solution without introducing a contrived 'Cosmological Constant' - effectively a 'fudge factor' that worked against gravity. When observational evidence suggested the universe was expanding, Einstein described his fudge factor as the biggest mistake he ever made.
Since then it had been assumed that gravity would slow down the expansion of the universe. A key question has been whether the expansion would be arrested and reversed, or whether the universe would expand forever. In 1996, a surprising result turned up. Observations of very distant Type 1a supernovae have indicated that far from slowing down, the expansion of the Universe is actually accelerating! However the nature of the force causing the acceleration - a sort of anti-gravity - is still completely unknown.
Observations of extremely distant supernovae indicate that in distant the past the expansion of the universe was decelerating, but it has since reversed and is now accelerating, and will continue to do so such that even neighbouring galaxies will eventually disappear from view. Apparently the Universe will never re-collapse. In tens and hundreds of billions of years, few dim stars will be left and eventually the universe will succumb to darkness.