Origin (?) of the Universe

5. Observational Cosmology

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This six-part series will cover: 1. Historical Background. 2. The Expanding Universe. 3. The Big Bang. 4. The First Three Minutes. 5. Observational Cosmology and 6. Present Challenges in Cosmology

In this part of the series we look at the present astronomical evidence both from distant parts of the universe as well as from our local region to test cosmological predictions. Included in this discussion are Hubble's law, source counts, angular diameters, the age of the universe, abundances of light nuclei and the microwave background. The significance of the findings for big bang models is discussed.

Cosmology As a Science

In the previous parts of this series we developed theoretical ideas in cosmology bringing the story so far to the standard big bang models. We saw that by using Hubble's law as the starting point in extragalactic astronomy we arrive at a picture of the expanding universe whose dynamical behaviour is modelled by Einstein's equations. The models of Alexander Friedmann developed back in 1922 still continue to serve as the basic models for cosmological studies.

We have been following the method of science in the study of the large scale structure of the universe. We began with a basic observation and then provided a theory to understand it. The scientific method then requires us to make new predictions to be tested by more sophisticated observations. This is what we will now proceed to do. We will follow the doctrine of Karl Popper who has argued that no scientific theory is ever proved. Its strength lies in making *disprovable* predictions. Thus we will consider the big bang cosmology like every scientific theory, to be on an indefinite probation. It continues to stay as a viable theory of the universe so long as the observational tests do not disprove it. By the same token, if we do encounter a conflict of the theory with observations and the latter are seen to be correct, then we should be prepared to modify or abandon the theory.

In this part of the series we will discuss this confrontation between theory and observations. To this end we will consider two types of observations:

- *Type I :* These are based on surveys of distant parts of the universe. As light travels with a finite speed, these surveys tell us about the state of the universe in the remote past. Thus we can compare it with the present state and decide whether the changes seen are consistent with the predictions of the model.

- *Type II :* Here we need not look at distant parts of the universe; studies of the local environment can tell us whether it is consistent with the model.

Although several such checks and tests exist in the literature, we will only look at a few to see how cosmology is no longer merely speculative but is subject to the rigours of science. We will first consider some *type I tests.*

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The Extension of Hubble's Law

The first measurement of importance in cosmology, as mentioned earlier, was Hubble's law. Hubble's original studies were confined to nearby galaxies and he got a value for the constant $H = 530$ kilometres per second per megaparsec. (The *parsec* is a unit of distance used by astronomers. Its value is approximately 3.10^{18}cm. Thus Hubble found that a galaxy at a distance of a million parsecs from us should have a radial velocity of recession of 530 km/second.

The questions that cosmologists would like to have answers to at this stage are:

(i) Is the value of Hubble's constant as given by Hubble in 1929 correct?

(ii) If we observe more remote galaxies would the velocity-distance relation still hold good?

Naturally, in the six and a half decades since Hubble's observations, astronomical techniques have improved enormously and one can carry out such observations on galaxies a thousand times farther away. Based on these measurements the answers to the two questions above are respectively *no* and *yes*. Let us see *why*.

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• *Hubble's constant:* The most recent measurements of Hubble's constant have been carried out by the *Hubble Space Telescope* (HST) as one of its key projects. With its abilitv to observe objects at least fifty times fainter than the best ground based telescope, the HST is admirably suited for this programme. In 1994 the telescope was able to observe twelve Cepheid variable stars in the galaxy M 100 situated close to the centre of the Virgo cluster. The Cepheids exhibit a periodic variation in their luminosity. Moreover, there is a well established relation which tells us how the mean luminosity of a Cepheid can be determined from its period. So, by observing the period of a Cepheid, we know its intrinsic luminosity. By measuring its apparent brightness we can then determine its distance.

Hubble himself had used the same method to measure distances of galaxies but these could not be very far away if the Cepheids in them were to be seen. Moreover, in many cases, he mistook other variable stars for Cepheids. And this led to an underestimate of distance and an overestimate of H. The HST determinations lead to an H value in the range 65-80 km/s/Mpc, that is, only about 12-15 per cent of the 1929 value!

It is as well to pause and review the difficulties in this basic measurement. The measurement of distance in astronomy has always been difficult, and the difficulty grows as we attempt measurements of more distant objects. The astronomer uses the 'standard candle' type argument; that is, if we have two similar sources of light, one bright and the other faint, the latter is expected to be farther away than the former. The basis for this is the inverse square law of illumination *and the assumption* that both sources are intrinsically equally luminous. In practice, these premises may not hold; for example there may be absorption of light *en route* or the two sources may not be equally luminous.

The second difficulty lies in the fact that in addition to the expansion of the universe the galaxies also possess 'peculiar' (i.e., random) motions within a cluster. When we measure the redshift of a galaxy and infer its radial speed, we are actually measuring the net speed. It becomes difficult to disentangle the true Hubble expansion speed from the net speed especially for relatively nearby galaxies. Thus our earth moves around the sun, which moves around the centre of the galaxy, which in turn is falling towards the centre of the Virgo cluster. (Recall that our cosmologies were based on the Weyl postulate which assumes that all such speeds are to be neglected.)

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Because of these difficulties the value of Hubble's constant has always remained controversial; even today another group of astronomers led by Allan Sandage believes that the true value of H is much lower, say in the range of 45-65 km/s/Mpc. Keeping in view the prevailing uncertainty, we will write H as 100h km/s/ Mpc, with h representing a fraction between 0.5 and 0.8.

- *Hubble's law at large redshifts:* Concerning the second question, observations of galaxies out to redshifts of the order unity have shown that a reasonably tight Hubble relation exists for them. As mentioned earlier, the astronomer does not measure distance directly but instead measures the faintness of a source. Allan Sandage has shown that if we pick the first ranked (i.e., amongst the brightest class) galaxies in clusters, they have approximately the same luminosity. That is, they serve as standard candles. Suppose a typical galaxy has luminosity L and is located at distance D from us. Then the flux from the galaxy will be $L/4\pi D^2$, as per the inverse square law of illumination. The astronomer measures the logarithm of this quantity on the so-called magnitude

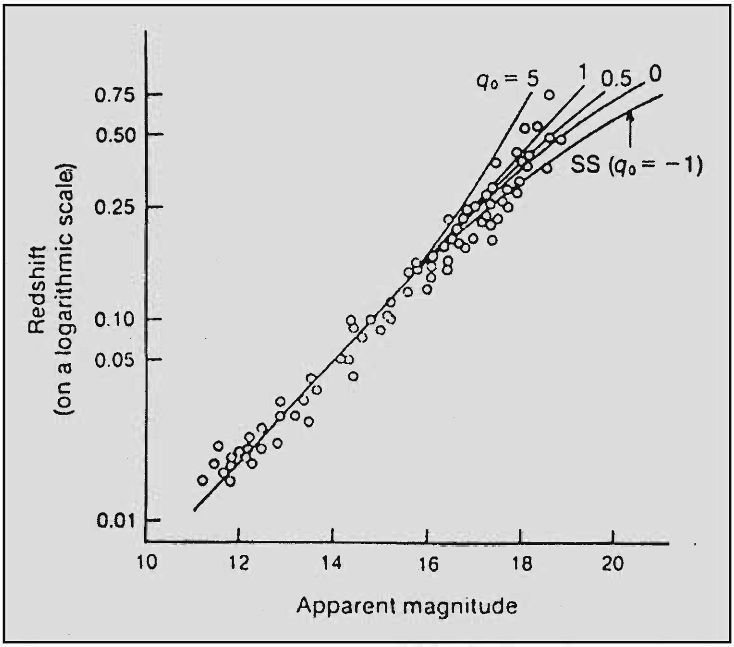

***Figure 1** The redshift magnitude relation for first ranked cluster member galaxies. A number of theoretical curves are superposed on the data. These curves are labelled by a parameter q_0 which measures the rate of slowing down of the expansion of the universe. It is called the* **deceleration parameter** *and its value for the flat Friedmann model is 0.5. We will refer to the steady state model in the final part of this series. (Based on J Kristian, A Sandage & J A Westphal, The Extension of the Hubble Diagram-III.* The Astro-physical Journal, *221, 383 (1978).*

scale. Thus we would write the magnitude as

$$m = -2.5 \log (L/4\pi D^2) + \text{constant}.$$

The constant arises from normalization of the magnitude scale.

What is D? Recall that the Friedmann models use curved spaces. Indeed, Einstein's general relativity assumes that spacetime itself has curvature and that the geometrical properties of spacetime are determined by the amount of matter and radiation in the universe, through their pressure and density. Thus care is needed in computing D for each Friedmann model. This calculation, which we cannot go into here, not only uses the spatial properties but also the temporal ones that lead to the redshift. The result is that each model predicts a unique redshift-magnitude relation.

The relation found by Hubble agrees with the above relation for small values of D. As we go towards higher redshifts we expect to have different relations for different Friedmann models. Thus if we have the actual measurements of m and z for distant galaxies we should be able to distinguish between the three types of models described in Part 3 of the series.

In the last few decades the m-z relation has been extended by Allan Sandage and others, to large values of these quantities, but several observational errors and uncertainties including those of distance determination intervene to prevent a decisive conclusion from being reached. The latest results suggest that models of type III are favoured by the data but considerable caution is still needed in basing our theoretical conclusions on such a result.

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The Counts of Discrete Sources

Another way of determining which of the Friedmann models is correct is to test the volume-radius relationship of space. Thus, recalling Part 3 of the series, the type I Friedmann models use flat Euclidean geometry in which the volume V of a sphere of radius R is given by

$$V = (4\pi/3)R^3.$$

The relation is different for other models.

The astronomer can use this result to test the models in the following way. Suppose there is a population of discrete sources distributed uniformly in space. Then by counting such sources out to distance R, we get a number N proportional to V. If all sources are identical, then the flux S of radiation from the faintest source in this set would decrease with R, being proportional to R^{-2} in a Euclidean universe. Thus we expect a relationship of the form

$$N S^{1.5} = \text{constant}$$

for a Euclidean space. A more complicated relatlon ls derlved for each Friedmann model.

Hubble used this test in the thirties to select the correct Friedmann model by counting galaxies out to fainter and fainter magnitudes. In view of the relation between magnitude and the flux received

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from a light source encountered earlier, we see that in Euclidean space the number-magnitude relation will take the form

$$\log N = 0.6m + \text{constant.}$$

A departure from this relation could possibly indicate what cosmology we should have.

In practice this did not work, for two reasons. First, there were far too many galaxies to keep count. Second, one needs to go down to very faint magnitudes to notice any possible distinction between models. In Hubble's time these difficulties were insurmountable. But today, with the use of computers to count images of galaxies and sensitive detectors to record images of very faint objects, this test has again become feasible.

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In the fifties, radioastronomers began to attempt this test for populations of radio sources. Radio sources are a much rarer species than galaxies and radio telescopes are capable of picking out distant radio sources more easily than their optical counterparts vis-à-vis galaxies. Thus it was felt that counts of radio sources may provide more decisive constraints on cosmological models. But here too, source counts have told us more about the physical properties of the source populations than about the large scale geometry of the universe.

Angular Diameters

In 1958, cosmologist Fred Hoyle proposed a new test of these models specially suited to radio sources. Its predictions are very striking and can be explained as follows.

It is a common experience here. on earth that if we view an object (like a tree or a house or a mountain) from increasingly larger

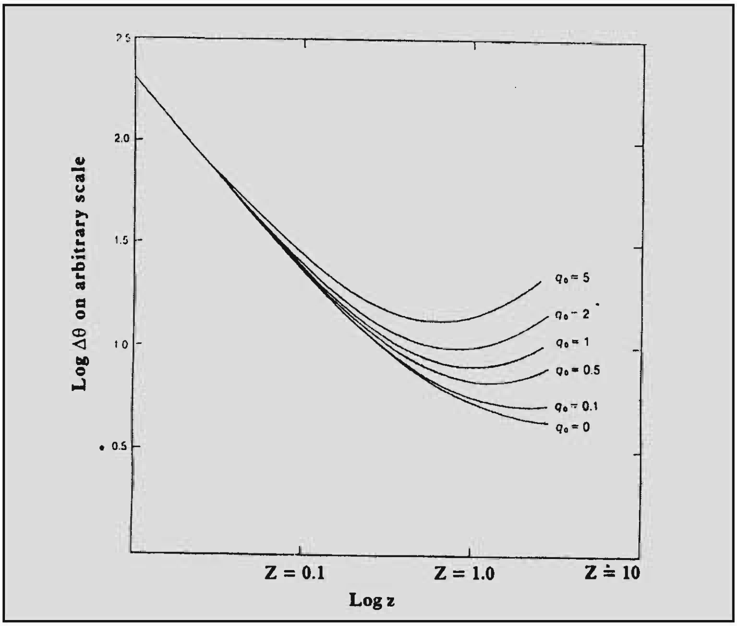

***Figure 2** This figure illustrates how the angular diameter varies with redshift in a Friedmann model. Notice that at a specific redshift the angular diameter is the least in contrast to a Euclidean universe in which the angular diameter steadily decreases with distance. The label q_0 denotes the deceleration parameter as explained in the caption of the previous curve.*

distances it appears smaller in size. This is because the angle θ subtended by it at our eyes gets smaller as our distance D from the object increases. If the linear size l of the object is small compared to D, and the angle is measured in radians, then a simple relation exists between θ and D in Euclidean geometry:

$$\theta = l/D.$$

This explains why distant objects look smaller since our brain relates the perceived size to the angle θ.

Hoyle showed that the corresponding situation in an expanding universe is more striking. Let us suppose we are viewing a population of identical objects located at varying distances in such a universe. Then we expect that their angular sizes should decrease with increasing redshift, since redshift is proportional to distance. Indeed, this is how θ behaves as z increases from zero. But the decline is not as fast as in the Euclidean case, and in most Friedmann models, the decline of θ is arrested at some redshift and thereafter θ increases with redshift! In the type I model ($k = 1$) discussed in Part 3 of the series, this minimum angular size is obtained at a redshift of 1.25.

It is not easy to measure the redshift of a radio source. It must first be optically identified and then its optical spectrum studied. Thus in many cases the redshifts are either not available or are estimated indirectly thus adding to the errors.

This nice and clean looking test also gets bogged down in uncertainty, because we cannot guarantee a sample of sources with nearly the same physical size, nor can we be sure that the sources we are looking at, at various redshifts, are not evolving. It is also not easy to measure the redshift of a radio source. It must first be optically identified and then its optical spectrum studied. Thus in many cases the redshifts are either not available or are estimated indirectly thus adding to the errors.

We will leave our discussion here, albeit in an unsatisfactory state because the tests proposed for distinguishing between cosmo–logical models are inconclusive. As our observations improve, we will be able to appreciate and allow for the various sources of errors and perhaps be able to draw some definitive conclusions.

We next briefly look at *type II tests* i.e. tests based on studies of our local neighbourhood. Here the idea is to find evidence that provides a consistency check on cosmological predictions.

Density of Matter in the Universe

Recall from our discussion of Part 3 that the three types of Friedmann models make three types of predictions about the present matter density in the universe. Let us define the *density parameter* Ω by the relation

$$\Omega = \rho / \rho_c$$

Thus, for open models $\Omega < 1$, for closed models $\Omega > 1$, while for the flat model, $\Omega = 1$. What is the 'true' value of Ω?

For this we first need to know the closure density. Using the formula in Part 3, with the Hubble's constant as 100/h km/s/Mpc, we get $\rho_c = 2.10^{-29} h^2 \,\mathrm{g\,cm^{-3}}$. Taking $h = 0.65$, the closure densitv of matter is approximately $8.5.\ 10^{-30} \mathrm{gcm^{-3}}$. So the question is, what is the actual density of matter in the universe?

This question demonstrates how a local measurement can be of cosmological significance. If we measure the density of luminous

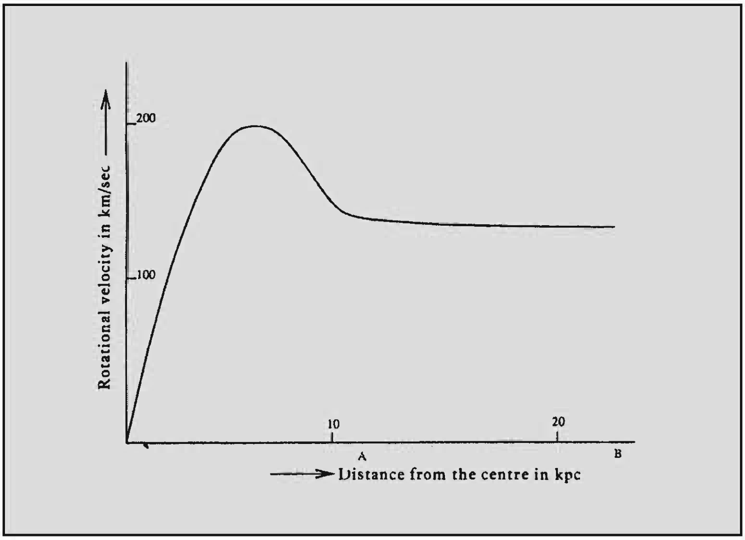

Figure 3 The typical flat rotation curve of a galaxy that indicates the presence of dark matter.

matter, we get a figure around 4. 10^{-31}g cm^{-3}, which is much less than the above closure density. However, this is only for matter seen as galaxies, clusters, intracluster medium, etc. There is also evidence for *dark matter.* Let us examine this briefly.

When we look at a galaxy we see a nebulous patch which is brightest in the centre and fades outwards. The luminosity of the patch arises due to stars which are most strongly concentrated at the centre and thin out towards the periphery. A typical spiral shaped galaxy may have stars distributed in a disc of radius, say, 15 kiloparsecs. Astronomers previously believed that the mass in a galaxy was confined to this visible disc. However, studies of clouds of neutral hydrogen emitting radiation at a wavelength of 21 cm showed their existence well beyond this radius. Such clouds are found rotating around the centre of the galaxy just as planets go around the sun. On the basis of Kepler's laws, we expect that if the attracting galactic mass is confined to this disc, the rotational speeds would decline as one examines cloud motions farther and farther out. *This is not the case!* The rotational speeds stay more or less constant for distances as far as 150 kpc.

The implication is, of course, that the 'driving mass'[1] extends well beyond the visible disc. Estimates show that it is not

[1] The phrase 'driving mass' refers to the total mass whose attraction on a particle keeps it in a circular orbit. To a good approximation, this is the mass enclosed in a sphere of the same radius.

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negligible, but in fact exceeds the visible mass. Such unseen matter or dark matter seems to occur widely, being found not only around galaxies but also in the intracluster medium. The idea that dark matter exists in clusters of galaxies, however, dates back to Fritz Zwicky in the 1930s! Estimates vary as to how much of it there is. Conservatively we may say that dark matter may be ten times as abundant as luminous matter, thus raising our density estimates to around 4. 10^{-30}g cm^{-3}.

We are still below the closure density, and so $\Omega < 1$, T but the gap now is not too wide and this has kept alive the other options $\Omega = 1$, or $\Omega > 1$. There are theoretical reasons for the first of these options which we will discuss in the final part of the series. We will also discuss the conjectures advanced on the composition of the dark matter.

Age of the Universe

All big bang models have finite ages which are not too difficult to compute; the age of a model is the time it has spent from the instant of big bang to the present epoch. The answer is best expressed in units of H^{-1}. The simplest answer is for the empty universe ($k = -1$, $\Omega = 0$ and is H^{-1}. For the flat universe, the answer is 2/3 of this value. In general, the age decreases as Ω increases.

Today, the most favoured Friedmann model is the flat one and for the value of Hubble's constant given by $h=0.65$, the age is ten billion years. Although this value comfortably exceeds the age of the earth (about 4.6 billion years), it is not high enough to accommodate old stars. For example, age estimates of stars in the globular clusters which are found to have evolved to the stage when their hydrogen fuel is finished, are as high as 12–18 bilion years. Thus only those models which have a very low value of Ω might possibly survive.

This has been a serious difficulty for all the standard models discussed so far and we will return to this issue in the final part of this series.

Abundances of Light Nuclei

A basic problem of cosmology is to understand how matter came into existence and how it acquired its present elemental composition. We saw in Part 4 that two different processes may have been at work, one acting in stars and the other in the early universe. The latter is believed to be responsible for the production of light nuclei, mainly helium, deuterium and a few others.

A basic problem of cosmology is to understand how matter came into existence and how it acquired its present elemental composition; two different processes may have been at work, one acting in stars and the other in the early universe.

As far as helium is concerned, its abundance by mass from primordial nucleo synthesis is expected to be in the range of 23-24 per cent, increasing slightly as the baryonic density (that is, the density in the form of baryonic particles like protons and neutrons) of the universe increases. A strong point in favour of the big bang picture is that measurements of helium abundance from various spectroscopic data are in broad agreement with this range. Moreover, the theoretical value is sensitive to the number of neutrino species that existed in the early universe and is based on the assumption that there are three species of neutrinos. The calculation described in Part 4 would yield a somewhat higher value of helium abundance (0.25-0.26, instead of 0.23-0.24) than if there were, say, four types of neutrinos. Thus one could claim that the primordial nucleosynthesis calculation predicts that there should be three neutrino species, a result borne out by particle accelerator experiments.

Coming to deuterium, the result is very sensitive to the baryonic density of the universe. The observed abundance of deuterium is very small, being in the range $9.\ 10^{-6}$ to $3.5.\ 10^{-5}$. The abundance predicted bv the standard models declines with increasing baryonic density and matches this range provided the density does not exceed $7.\ 10^{-31} \mathrm{gcm}^{-3}$. Beyond this density any deuterium produced is quickly destroyed. So, we have a problem. Evidence for dark matter suggests a density higher than this limit. So we have to think of this matter in a non-baryonic form. This 'non-baryonic' matter would not react with deuterium in the early universe. So measurements of deuterium do not constrain the quantity of dark matter present.

There are some additional constraints from observations of other light nuclei but they are more subtle and we will not discuss them here.

Microwave Background

As mentioned in Part 4 of this series, the discovery of the microwave background is the best evidence for big bang cosmology. It has been shown to have a Planckian (black body) spectrum with a temperature of 2735 K, thanks to the extensive work of the COBE satellite. Nevertheless, the following information emerges from measurements of this radiation background.

The radiation background would have been completely isotropic if we as observers were at rest in the cosmological frame (i.e., had no random motion relative to the Hubble motion of expansion). However, we do have motion and so the radiation background should show a 'dipole anisotropy' in our frame. Such an anisotropy has indeed been found with temperature being direction dependent:

$$T(\theta) = T_0 + T_1 \cos\theta.$$

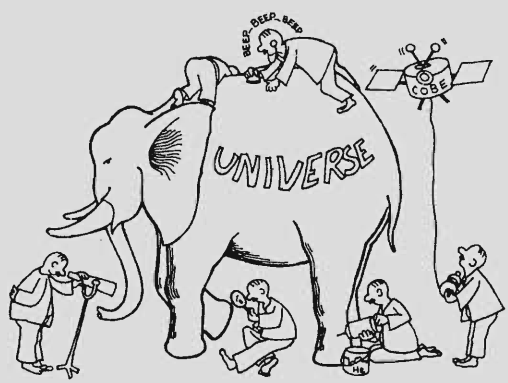
Suggested Reading

J V Narlikar. The Structure of the Universe. Oxford. 1977.

David Layzer. Constructing the Universe. Scientific American Library. 1984.

J V Narlikar. Introduction to Cosmology. Cambridge. 1993.

From all these observations hopefully a final picture would emerge.



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Here T_0 is the average temperature which is constant in all directions and $T_1 \cos\theta$ is the variable part, being maximum in the direciion $\theta = 0$, and minimum in the opposite direction . T_1 is approximately 3. 10^{-3}. *The direction in which* $T_1 \cos\theta$ *is maximum is the one in which the earth is moving.*

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The second type of anisotropy is on a small angular scale of about ten degrees which shows a fluctuation of $\Delta T / T$ of the order of 6. 10^{-6}. This was the second major discovery of COBE which was announced in 1992, and it held out the hope of linking this fluctuation to the theories of structure formation. We will return to this in the final part of the series.

Concluding Remarks

As far as type I tests are concerned, because of various uncertainties, studies of distant parts of the universe have so far failed to tell us which type of Friedmann model (if any) we live in. The type II tests are somewhat more clearcut, but their verdict has been mixed. On the one hand, we encounter a serious 'age' problem, whereas on the other, the observations of microwave background and light element abundances are in favour of the hot big bang cosmology.

In the final part of the series we will consider the overall situation in cosmology today and address some fundamental issues.