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THEORIES AND OBSERVATIONS IN COSMOLOGY

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This account is meant to be both a review and a resource article for modern cosmology. In this sense it will highlight the recent developments in the subject and point to future trends; but in addition it will indicate to the reader wishing to go deeper into the various aspects of this field, the databases and sources in the form of reviews, texts and conference reports.

Key words: Cosmology; Astronomy; Big Bang; Discrete Sources; Early Universe; Cosmic Galaxies Quasers Historical Background

Historical Background

Cosmology is the branch of astronomy that deals with studies of the large scale structure of the universe. In this respect its subject matter is by definition, the largest and all inclusive. Observationally it requires data on the most remote objects while theoretically it demands the largest possible extrapolations of the basic laws of physics. Despite these severe constraints, cosmology has of late emerged as a very important branch of science where predictions can be made and tested. This article will specially highlight this aspect.

When did modern cosmology begin? Depending on the age of the person answering this question, the answer will be one of the following: 1917, 1929, 1965 or 1981. While these dates represent landmarks in the development of cosmology, the subject itself is much older. Indeed, one should go back to Isaac Newton, and his correspondence with Richard Bentley from December 10, 1692, to January 17, 1693 [*see* Whiteside, (1976)][1]. It is interesting to read Newton's attempts to construct the model of a homogeneous and isotropic but static universe and his realization that it is unstable. Later attempts within the Newtonian framework, before relativity came on the horizon were by Neumann (1896)[2] and Seeliger (1895, 1896)[3,4].

The advent of general relativity offered a possible resolution of the conflicts which were beginning to surface between the Newtonian law of gravitation and special relativity. For example, how can one have an instantaneous propagation of gravitational effects when special relativity required all physical interactions to follow the light speed limit? How can one arrive at an inertial frame so basic to special relativity when the universality of gravitational force did not allow a force-free environment? The classic paper by Einstein (1917)[5] has to be read with this background in mind.

Like Newton, Einstein also found that a static model was not permitted by his 1915 equations of relativity and introduced the so-called cosmological constant, λ, which implied (in the Newtonian approximation) a repulsive force that varied directly with distance. The static model that emerged required the universe to be closed. Einstein felt that the emergence of such a model was a demonstration of a unique and consistent relationship between spacetime geometry and the matter contents of the universe,

However, the paper by W. de Sitter (1917)[6] which followed shortly, demonstrated that the model was not unique. de Sitter found a model universe which was empty but expanding. As we shall see later, this model has played a key role in cosmology on a number of later occasions.

In the second decade of this century, there was no systematic study of galaxies, although observers like V.M. Slipher (1914)[7] had reported nebular shifts, mostly redshifts, that indicated a radial recessional motion of these nebulae. However, despite these findings, the general belief in a static universe was quite strong and de Sitter's solution was treated more as a curiosity. Indeed, a few years later, A Friedmann (1922, 1924)[8,9], obtained models of the expanding universe for which the cosmological constant was not necessary; but these were also ignored by Einstein and others. Later Abbe Lemaitre (1927)[10] and H P Robertson (1928)[11] also obtained similar models independently.

It was the announcement of the velocity distance relation by E P Hubble (1929)[12] that turned the tide in favour of these models. For, after a careful analysis of data on nebular redshifts Hubble arrived at what is today known as "Hubble's Law", namely that the radial velocity of a typical galaxy away from us is proportional to its distance from us. More exactly, the data show that the redshift of a galaxy increases with its faintness. If the redshift is interpreted as Doppler shift and faintness as due to distance, then Hubble's law follows. Although there might be other interpretations of the data, all cosmological models had to take cognizance of this basic fact about the universe.

Thus, soon after Hubble's law became accepted, Einstein and de Sitter (1932)[13] jointly wrote a paper proposing what was really the simplest of the Friedmann models. Here one specifies the scale of the universe as a time dependent factor *S(t)*, to be multiplied to the distance between any two galaxies. In an expanding universe, *S(t)* increases with *t*. The Einstein-de Sitter model had the universe expanding with $S(t) \propto t^{2/3}$. The model was without a cosmological constant and with just enough energy to expand out to a state of infinite scale factor. In fact, at this stage Einstein abandoned the cosmological constant as the ''greatest blunder" in his life. There were others, however, who thought otherwise and as we shall see, this constant continues to feature in cosmological literature even today.

In the 1930s, Milne and McCrea (1934)[14] demonstrated how Newtonian ideas of gravitation and cosmology can be suitably adapted to give the standard models of relativity. For a discussion of Newtonian cosmology from a modern standpoint see Narlikar (1996)[15]. We will conclude our historical narrative here and refer the reader, interested in knowing who did what and when in those early days, to the excellent source book by J D North (1965)[16].

2 The Big Bang Models

The assumption of homogeneity and isotropy allows the cosmologist to define a "cosmic time". The spatial sections at a given cosmic time are supposed to be homogeneous and isotropic. H P Robertson (1935)[16] and A G Walker (1936)[17] independently worked out the most general line element describing such a spacetime. Taking any observer as the local origin of spherical polar coordinates (r, θ, ϕ) and t for the cosmic time, the Robertson-Walker line element is given by

$$ds^2 = c^2dt^2 - S^2(t)[\frac{dr^2}{1 - kr^2} - r^2(d\theta^2 - sin^2\theta d\phi^2)]. \quad ...(1)$$

The function *S(t)* is the scale factor mentioned earlier: its increase with time signifies the expansion of the universe. The constant k in the above is a parameter specifying whether the space t = constant is of positive ($k = +1$), negative ($k = -1$) or zero ($k = 0$) curvature.

The Friedmann models which are obtained by solving the Einstein equations, also fall in three classes, called closed, open or marginally open models, depending on whether the spatial sections have positive, negative or zero curvature. Theorists use these models to work out the physical evolution of the universe and observers use them to test the theoretical predictions.

The simplest Friedmann model is the Einstein-de Sitter model which has $k = 0$. For matter in the form of dust (see definition later), this model has $S \propto t^{2-3}$.

That the geometrical features of the model are linked to its physical matter contents is demonstrated by the different behaviour of these models for different matter density ρ. Thus we define the following quantities:

$$H(t) = \frac{S}{S}, \quad \rho_c = \frac{3H^2}{8\pi G} \qquad ...(2)$$

as the Hubble constant and the critical density at epoch t. We will denote their values at the present epoch t_0 by suffix zero. The density parameter is defined by

$$\Omega = \frac{\rho}{\rho_c}. \qquad ...(3)$$

Then for the Friedmann solutions, we have the following result: the universe is closed for $\Omega_0 > 1$ and open otherwise ($k=0,-1$). Actually the case $k = 0$ is the marginally open case with $\Omega_0 = 1$; if the density exceeds ρ_c the universe is of the closed type. This is why the density ρ_c is called the *closure* or *critical* density.

In all models the scale factor was zero at some epoch in the past, commonly called the big bang epoch. At this epoch the curvature of spacetime was infinite and so was the density of matter and radiation in the universe. What about the future behaviour of the universe? There the answer depends on the geometry of space. In the open models the universe expands for ever, with the scale factor going to infinity. In the closed models the scale factor attains a maximum value before decreasing back to zero.

In the above argument, it is assumed that the matter in the universe is in the form of *dust*, that is, with zero pressure. This is a reasonable approximation at present when the random motions of galaxies in clusters are no more than ~ 300 km/s, that is the pressure is no more than a few parts in a million of the energy density. While this is a good approximation at present, it was not so at much earlier epochs. For, if one looks at random motions, they change with the scale factor as S^{-1} and therefore, pressure was higher in the past than it is now. In fact, the more dominant term in the past was the radiation term. One can show that

$$\rho_{matter} \propto S^{-3}, \quad \rho_{radiation} \propto S^{-4}, \qquad ...(4)$$

so that at a sufficiently early epoch when S was small enough, the radiation term dominated over the matter term. This of course does not alter the earlier conclusion about the existence of the big bang epoch; in fact we now conclude that the universe was infinitely hot at that epoch.

In the Robertson-Walker spacetimes, the redshift is simply related to the scale factor. Calculation shows that a source with redshift z is being observed at an epoch when the scale factor of the universe was $(1+z)^{-1}$ times its present value. Observations at the present epoch indicate that matter density is at least ~ 10^3 times the radiation density. Thus we can estimate that the universe was radiation dominated at epochs prior to that of redshift ~ 10^3.

With the realization that the basic Friedmann models give an adequate description of the expanding universe, there have been many developments in cosmology in the last five decades, that are based on these models. These developments may broadly be divided into investigations of

(a) The large scale structure, through discrete sources,

(b) The history of the universe, through relics,

(c) The evolution of the universe from particles to galaxies,

(d) The basic physical laws operating in the extreme conditions a few moments after the big bang and

(e) Alternative cosmologies.

We will briefly outline the developments in these fields.

3 Observations Of Discrete Sources

A relativistic cosmological model uses curved spacetime and as such there are effects of non-Euclidean geometries that may, in principle, be observable. This was the expectation which prompted optical and radio astronomers of the 1950s and 1960s to push their observing capabilities to the limit. By observing the distributions of discrete source populations (galaxies, quasars, radio sources, X-ray sources, etc.) the cosmologist hoped to find which of the various theoretical models came closest to reality.

The benefit of this attitude was that observing techniques improved considerably and today the most challenging areas of observation are in extragalactic astronomy. The disappointment was that the early expectations of distinguishing between different world models based on their different geometries, were not realized. This was because the inherent uncertainties of observations themselves, and the possible evolutionary changes in the sources mask any geometrical differences in the models.

The observations include *(i)* the measurement of Hubble's constant, *(ii)* the extension of Hubble's law to galaxies of large redshifts, *(iii)* the counts of galaxies and radio sources out to larger and larger distances, *(iv)* the angular diameter redshift relation, and *(v)* the relationship of surface brightness of a galaxy to its redshift. For details of these cosmological tests see recent textbooks and review articles, e.g. Sandage (1988)[18], Hartwick and Schade (1990)[19], Branch and Tammann (1992)[20], Narlikar (1993)[21].

As mentioned before, the trend of such studies has shifted from determining the geometry of the universe to determining how the discrete sources evolve. These studies are expected to tell us about the evolution of the physical environment of the universe, but so far no clear picture has emerged amidst a series of parameter fitting exercises. The reader may catch a flavour of this field from the IAU Symposium in cosmology of 1986 [see Hewitt *et al.*, 1987][22] Here we summarize some recent highlights.

The True Value of Hubble's Constant

A key measurement that continues to be controversial is that of Hubble's constant. Hubble originally obtained the value of 530 km/sec/Mpc, but in retrospect, we find that there were several systematic errors in his measurements. Even today there are several calibration problems:

(i) The extragalactic distance scale is built up through several stages with stars and galaxies serving progressively as standard candles. There are errors at each stage which may multiply. The Hubble Space Telescope has identified this as a key problem to solve and the recent use of the HST to identify and study Cepheid variable stars in galaxies as far as 15-20 Mpc shows the remarkable progress possible with improved facilities.

(ii) Another, rather intricate issue is to identify the cosmological rest frame (the frame in which the Robertson-Walker coordinates r, θ, ϕ are constant). Strictly speaking no galaxy satisfies this ideal condition: it has a small random motion relative to this frame. Thus it is necessary to know what the random motion of a galaxy is while correcting for its redshift. For relatively nearby galaxies, say at ~ 5Mpc, the random motion may be comparable to the Hubble motion and will introduce a substantial correction to the value of H_0.

It is only now that a clear appreciation of these issues is emerging, and approaches towards determining the true value of Hubble's constant are beginning to converge. Although the gap between different determinations has narrowed, the present estimate of Hubble's constant is about 55-75km/s/Mpc. For a recent review of measurements, including those by the Hubble Space Telescope *see* Kennicutt Jr (1996)[23] and Hoyle *et al.* (1997)[24].

Deceleration Parameter

Since early days in observational cosmology there was hope of distinguishing between the different cosmological models by plotting the Hubble relation to large redshifts. Theory predicts that a typical model has a Hubble relation of the form

$$m = f(z, q_0), \qquad \text{...(5)}$$

where each model is uniquely characterized by a parameter q_0, called the deceleration parameter defined by

$$q = \frac{\ddot{S}}{S} \qquad \text{...(6)}$$

and evaluated at the present epoch. For example, for the Friedmann model with k = 0, we have

$$S(t) = \text{constant} \times t^{2/3}, \quad q_0 = 1/2. \qquad \text{...(7)}$$

For open models with $k<0, 0<q<1/2$ while for closed models, we have $q_0 > 1/2$. The efforts to determine this parameter by plotting the relation (5) for galaxies of redshifts upto ~ 0.5, however, failed as the observed curve was shown to be affected by many other effects (*see* Narlikar 1993)[21]. Recently, the use of Type Ia supernovae out to redshifts in the range 0.35 to 0.5 has begun to throw up some relatively tight bounds on this parameter, indicating that it is positive (Perlmutter 1998)[24]. This of course admits all Friedmann models discussed here, but may rule out some which have large cosmological constant (we will discuss this in section 7).

Counts of Galaxies and Radio Sources

Take for example, the counting of radio sources down to varying levels of faintness. If we were living in a Euclidean universe with a uniform distribution of radio sources of identical physical properties, then, the number of sources in a sphere of radius R will be $N \propto R^3$. The faintest of these *sources* will have a flux density $F \propto R^{-2}$. Therefore, as we vary R, we will generate an N-F curve. The curve will have the functional form:

$$N \propto F^{-1.5}. \qquad \text{...(8)}$$

By comparing the actual curve with the theoretical one, we can decide whether the initial assumptions were valid. Radioastronomers find it convenient to plot the numbers and flux densities on logarithmic scale. Then as per (8), the log N- log F curve will have a slope of -1.5.

In practice, the curve shows a steeper slope of -1.8, which gradually flattens to the Euclidean value and then flattens further to sub-Euclidean values as F decreases. Clearly our basic assumptions are wrong. But can we keep other assumptions the same and replace the Euclidean universe by a Friedmann one ? *The fact is that no Friedmann model can reproduce the observed behaviour*. To make the theory match with observations therefore, the cosmologist introduces evolution, both in the number density of sources and their luminosities. By choosing a suitable set of evolutionary parameters a good fit is obtained.

This is an exercise in consistency and has no predictive value. It can at best tell us about how in a self consistent scenario, the source population evolves in *any given Friedmann model*. It cannot tell us which model could be right and which is wrong.

A similar situation obtains for galaxy counts. In the early days Hubble (1936)[12] had hoped to use this test for distinguishing between the different models. He did not succeed in this objective primarily because there are far too many galaxies to count if one wants to go far enough in space to notice the geometrical differences between the Friedmann models. This test has now become feasible because of computerized systems of counting very faint galaxy images. Again, the prediction of a Euclidean universe with a uniform and unevolving source population is that the number N of galaxies brighter than apparent magnitude m is given by

$$\log N = 0.6m + \text{constant} \qquad \ldots(9)$$

What do the actual counts show ? The conclusion from such tests going to magnitudes as faint as 24^m indicate that there may be evolutionary effects present, although their importance is debated. Certainly the test is not able to distinguish between the basic Friedmann models.

Angular Sizes of Quasars and Radio Sources

F Hoyle (1959)[25] had shown that the dependence of the angular size of a source on its redshifts departs significantly from the Euclidean behaviour at high redshifts. For the typical Friedmann model, the angular size θ reaches a minimum value at a finite redshift $z_m(q_0)$. For the Einstein de Sitter model this redshift is 1.25, while for the closed model with $q_0=1$, $z_m = 1$. Thus this test has the potentiality of identifying the "right" model.

Radioastronomers therefore attempted various tests in which they obtained the (z,θ) values for different classes of radio sources. However, here too, the inhomogeneity of the sample, the projection effects and likely evolutionary effects stepped in to make it impossible to draw any definitive conclusion as to which model is favoured.

Recently, however, there has been some progress in that Kellerman (1993)[26] argued that if one selects a class of ultracompact radio sources which are buried within the large scale radio galaxy or a quasar, there is less chance of these sources being affected by the evolutionary changes in the outer environment. Thus even going to high redshifts, one may be able to conduct this test with relative confidence. His preliminary finding was that the data were consistent with the Einstein-de Sitter model. Later, Jackson and Dodgson (1997)[27] have carried out a more comprehensive testing and concluded that the fit of this cosmology is not very good, and much better fits are obtained for models with negative cosmological constants.

The Surface Brightness Test

This test has the advantage of distinguishing between standard cosmology which depends on the expansion of the universe to explain the nebular redshift, and several other models which use other reasons to explain the redshift.

In standard cosmology, the *total* surface brightness at all wavelengths of the typical extragalactic source decreases as the inverse fourth power of $(1 + z)$. In several other cosmologies the dependence is different. Recent comprehensive studies of galaxies by Sandage and Perelmuter(1990)[28] decidedly favour the standard cosmology.

4 Relics Of The Early Universe

The universe can be probed by direct observations to limited distances, as we shall shortly see. That means we can "see" what the universe was like only upto limited look-back time. The observations of discrete sources take us to redshifts not greater than 5. Since in the Friedmann models the redshift of a source can be related very simply to the epoch when light left the source, such observations do not take us very far back in time, certainly not to those when the universe was radiation dominated. For such epochs, our observations are indirect, that is, they look for relics that can tell us unequivocally of events that took place in those early epochs. There are two such important relics.

Light Nuclear Abundances

The big bang concept hinges on the fact that at a time $t = 0$, the universe came into existence in a singular event. Thus no physical description of the original event is possible, although physical theories can examine the subsequent behaviour of the universe. One of the early attempts to go close to the big bang epoch was made in the late 1940s by George Gamow, who appreciated the fact that the early universe was radiation dominated, that is, its contents were made up of photons and other particles which were mostly relativistic in their energies. We had referred to this early epoch before. Thus, one could approximate the equation of state by pressure $p = 1/3\ \rho$, both p and ρ being dependant on temperature as its fourth power, as for radiation in thermal equilibrium. Gamow and his collaborators [*see* for example, Gamow (1946)[29], Alpher and Hermann (1948)[30] and Alpher, Bethe and Gamow (1948)[31], the last work being called the ''alpha- beta-gamma" theory!] worked out the physics of the universe when it was around 1-200 seconds old.

Gamow had hoped to demonstrate that in the high temperatures prevailing in this era, particles like neutron and proton would be synthesized into heavier nuclei, thereby determining the chemical composition of the universe. In the end, this work was partly successful in that light nuclei like deuterium, helium, etc. could be made in the primordial soup, but not the heavier ones like carbon, oxygen and metals. Later it became clear from the important work of Burbidge, Burbidge, Fowler and Hoyle [(1957)[32], referred to as the B^2FH work] that these nuclei are made in stars. Nevertheless, the abundances of light nuclei worked out according to the modern version of Gamow's pioneering attempt, show a broad agreement with the observed ones. For a pedagogical account of this work see Wagoner (1979)[33].

We should mention one consequence of the primordial nucleosynthesis calculations which has a bearing on the density of baryonic matter in the universe. If the present Hubble constant is expressed by the dimensionless number h in units of 100km/s/Mpc, then the baryon density parameter Ω_B (baryonic density expressed in terms of the critical density) should not exceed $0.02h^{-2}$. If it does exceed this value, then hardly any deuterium can be made in the early universe.

The Microwave Background

A further check on the early hot universe scenario was the discovery of the cosmic microwave background by Penzias and Wilson (1965)[34]. Gamow and Alpher Herman had predicted such a background as the relic of the early era, although the discoverers had been unaware of these results. See, for example the paper by Alpher and Herman (1948)[29], cited above which was the first prediction of relic background with an estimated temperature of 5K. Present big bang calculation, however, cannot estimate the temperature of the background: it has to be taken as a parameter.

A modern textbook in cosmology describes the current status of these observations (see for example, Narlikar 1993)[21]. In particular the most spectacular development of recent years has been the achievement of the COBE satellite in measuring the spectrum and small scale anisotropy of the microwave background [*see* Mather *et al.* (1990)[35], Smoot *et al.* (1992)[36]]. The background shows a black body temperature of $2.7K$ and is highly homogeneous, with temperature fluctuations $\Delta T/T \sim 6\times10^{-6}$.

The microwave background, its spectrum and anisotropy have provided strong prima facie support for, as well as strong constraints on theories of structure formation in the universe. These issues are extensively debated these days: see, for example, a review by White, Scott and Silk (1994)[37] and the book by Padmanabhan (1993)[38].

The microwave background is at present decoupled from matter, as there is hardly any absorption of photons in the intergalactic space. In the past, however, there was an epoch before which the universe was so hot that atoms could not retain their composite structure and were ionized. The free electrons were efficient scatterers of radiation, which was therefore in continuous interaction with matter. This epoch had a redshift of $\sim 10^3$ and is known as the *epoch of last scattering*. Whatever imprints were left by matter inhomogeneities on the radiation background at this epoch would survive to this day, essentially diluted by the expansion process. These are the inhomogeneities seen by COBE today.

This interpretation of inhomogeneities therefore gives us an initial set of conditions at the epoch of last scattering, from which to evolve any matter inhomogeneities to the present times. We should mention that the ideas on how these inhomogeneities were linked to the present large scale structure have changed over the last three decades. Earlier it was assumed that all matter in the universe is baryonic, an assumption that led to trouble with the lack of any imprints of the form $\Delta T/T$ on the microwave background. By the end of the 1980s no imprints were found at the level of 10^{-5} and the only way of salvaging the big bang scenario was to *assume* that bulk of the matter in the universe had to be in a *non-baryonic* form. It was against this background that the positive findings of COBE (Smoot *et al.* 1992)[36] came as a great relief to the workers in the field. This result therefore boosted the claim that most dark matter is nonbaryonic. We will return to this aspect later.

5 Evolution of Structure in the Universe

As indicated above, there is a major thrust in cosmology today to demonstrate how in the standard big bang model, first nucleons and leptons evolved out of more primordial particles and from them eventually the large scale structures in the universe formed. The former process involves the frontier of particle physics and cosmology and will be discussed in the next section. The latter idea is based on evolving tiny fluctuations in the spacetime metric as well as in matter density in the expanding universe to see if they match the observed large scale structure.

The Inflationary Phase

Of particular interest in this work is the role of the inflationary phase first discussed by A Guth (1981)[39], K Sato (1981)[40] and D Kazanas(1980)[41]. The basic idea is the following. The big bang universe was infinitely hot at $t = 0$, but its temperature dropped with time according to the law

$$T = \text{constant} \times t^{-1/2}. \qquad ...(10)$$

The temperature is an indication of the typical particle energy $E = kT$, where k is the Boltzmann constant. The typical particle energy in the initial moments is therefore very high and as the universe aged the particle energy dropped. Thus, at the early epoch the universe was hot and energetic enough to have typical particle energy of 10^{16} GeV, the energy at which grand unification of basic interactions is possible. As the matter in it cooled further, it passed through a phase transition when the grand unified interaction split into the strong and the electroweak interaction. This change resulted in a switchover from the original vacuum to a new vacuum, a process that generated extra energy tensor corresponding to a cosmological constant term in Einstein's field equations.That in turn made the universe expand in the de Sitter mode. Here was the old de Sitter solution resurfacing, with the original cosmological constant of Einstein appearing in a stronger form, stronger by some 108 orders of magnitude!

Inflation was originally proposed to 'cure' the standard big bang cosmology of some generic problems like the horizon problem, the flatness problem and the monopole problem. Rather than describe these problems and how inflation sought to resolve them, we refer the reader to standard texts (see for example, Narlikar 1993)[21]. The success achieved by inflation in solving these problems is debatable. However, its main attraction lies in providing a scale invariant spectrum of inhomogeneities which act as seeds for large scale structure which does appear to show such a spectrum.

Apart from the original papers, there is extensive literature on inflation. While most literature is from the particle physics point of view, the article by Narlikar and Padmanabhan (1991)[42] stresses the astronomical rather than the particle physics aspects of inflation.

Structure Formation Scenarios

Most theories of structure formation rely on initial fluctuations as they evolve through inflation and their subsequent growth. The latter takes place through gravitational interaction and clustering. Here cognizance must be taken of the interaction of the growing lumps of inhomogeneities not only with the visible matter but also with dark matter. In particular, the results are sensitive to the type of dark matter, cold or hot or a mixture of both. A review of structure formation is found in books by Padmanabhan (1993)[38] and Peebles (1993[43], while for dark matter see a review by Trimble (1987)[44]. The following issues are considered:

(i) The spectrum of the scale of inhomogeneities: how it is controlled by gravitational interaction and the expansion of the universe.

(ii) The growth of inhomogeneities is initially calculated through linearized hydrodynamic equations. As the density fluctuations $\delta\rho/\rho$ approach unity, the linearized equations have to be replaced by variants of the Zel'dovich approximation (Shandarin and Zeldovich, 1989)[45], and computer simulations. For an excellent review see Sahni and Coles (1995)[46].

(iii) The nature and distribution of dark matter, to what extent it simulates the distribution of visible matter (see below).

(iv) The end-conditions which the theoretical results must match, include the COBE-discovered inhomogeneities, the large scale motions of galaxies and clusters and their two-point correlations.

The exercise is still continuing, so far without a claim that all observed constraints can be explained this way. The key issue occupying the workers, concerns dark matter.

Dark Matter

Dark matter is the name given to matter that is not normally seen through any waveband of the electromagnetic radiation. It was Fritz Zwicky (1933)[47] who first pointed out the possible existence of the ''missing mass'' in clusters of galaxies. However, it took nearly four decades for the astronomical community to catch up with him ! In the seventies, the studies of motions of clouds of neutral hydrogen showed that they were moving with near constant rotational speeds around a typical spiral galaxy, *even if they were located at progressively larger distances beyond the visible mass of the galaxy.* These flat rotation curves indicated that the mass M(R) of a galaxy upto a distance R from its centre increases with R even if R vastly exceeds the visible boundary of the galaxy.

Likewise, Zwicky's expectations about hidden mass in clusters were also borne out with the findings that the galaxies in a typical cluster were moving with such high speeds that if one uses the virial theorem for a relaxed cluster

$$2T + \Phi = \text{constant} \qquad ...(11)$$

where T is the kinetic energy and Φ the gravitational potential energy, then one needs a lot of hidden mass to make up for the latter. What is this dark matter made of and how much of it exists in the universe ?

Basically dark matter is classified into two categories: baryonic and nonbaryonic. The baryonic part is made of ordinary matter and may exist in the form of planets, brown dwarfs, black holes, etc. The non-baryonic part may be made of hitherto undiscovered particles which we shall refer to in the next section.

6 Astroparticle Physics

The big bang cosmology came into prominence at a time when the particle physicists were exploring the possibilities of attaining their holy grail of unification of all interactions. The standard model of particle physics suggests that the energy needed for grand unification of all physical interactions except gravity, would be in the range of 10^{16} GeV. No man-made accelerator could be expected to energize particles to that kind of energy, nor can any astrophysical scenario generate them. And so these theories would have remained mere speculations but for the hot big bang. In the big bang model the typical energy of a particle was of the above order when the universe was ~ 10^{-36} second old. We shall refer to this as the GUT-epoch, as this was when the grand unified theory would have been in full operation.

The big bang cosmologists also need new ideas from particle physics, such as inflation, non-baryonic dark matter, strings, etc. to provide insights into the formation of large scale structures. For this reason, the field of "astroparticle physics" is gaining prominence amongst theorists. Although conferences in this area are many, the reader may find the proceedings of the Vatican Conference (Bruch *et al.* 1982)[48] particularly illuminating. Also worth reading is Weinberg's (1989)[49] review of the status of the cosmological constant.

A conventional physicist may object to astroparticle physics in the big bang model on the grounds that *(a)* it describes operation of physics that occured only once, i.e., its repeatability has not been tested, *(b)* there are no directly observable consequences of the GUT epoch, and *(c)* the theoretical extrapolation of observable physics to GUT energies is by over 12 orders of magnitudes, which is unprecedented. The sole justification for this subject is in predicting relics that clearly indicate its stamp.

This is where the dark matter assumes significance. If it is the case that all dark matter in the universe is baryonic, it leads as we saw earlier in this article, to two problems. The process of deuterium production in primordial nucleosynthesis creates hardly any deuterium if the baryonic density exceeds a certain critical value, which may be exceeded if all matter, visible and dark were baryonic. Secondly, the close interaction between baryonic matter and radiation would have left too large an imprint on the microwave background, had all dark matter been baryonic. For these reasons, nonbaryonic options have become popular with cosmologists.

These options come in two groups: hot and cold. The hot dark matter (HDM) is made of particles which were moving fast with speeds ~ c at the time they ceased to interact with baryonic matter and radiation. The cold dark matter (CDM) particles were moving slowly or were at rest at a similar stage. (The force of gravity is not counted in this interaction.) Photinos, gravitinos, axions, etc., are examples of CDM while massive neutrinos are examples of HDM. Currently the structure formation experts seem to favour a combination of CDM and HDM.

The Era of Quantum Gravity

Somewhat apart from these discussions, there is a select band of people working in quantum gravity and cosmology which relates to an even earlier era of the universe, when the particle energies were three to four orders of magnitude above the GUT energy. One possible outcome of this work could decide whether the spacetime singularity is avoided in quantum cosmology.For references see Isham *et al.* (1981)[50] and Narlikar and Padmanabhan (1983)[42]. The subject of how to quantize gravity is of course much more vast and it continues to be very difficult to tackle in its entireity [see for example: Ashtekar (1997)[51], Isham (1997)[52]].

Another set of approaches involve the existence of cosmic strings, and other topological structures which could have arisen in the very early universe at the time of the GUT-phase transition. These also might affect the way large scale structures evolve in the universe. For an account of such approaches see Abel *et al.* (1997)[53], Moessner and Brandenberger (1997)[54].

7 Alternative Cosmologies

From time to time there have been alternatives proposed to the big bang cosmology, although the majority of cosmologists has always believed in the validity of the latter. In the late 1940s, the steady state theory of H Bondi, T Gold (1948)[55] and F Hoyle (1948)[56]livened up the cosmological scenario by offering a clearly testable alternative. This cosmology had the spacetime geometry described by the model proposed by de Sitter in 1917, although the physical rationale was different. The discovery of the microwave background in 1965 robbed the theory of much of its credibility. Other major initiatives in the field were the Brans-Dicke cosmology proposed by C Brans and R H Dicke (1961)[57] as a theory with its origins in the Mach's principle and the cosmology proposed by P A M Dirac (1973)[58] based on attempts to explain the very large dimensionless numbers that appear in cosmology and microphysics. For details of several alternative cosmologies see Narlikar (1993)[21].

Quasi-Steady State Cosmology

Lately, the steady state theory is attempting to stage a comeback in the modified form called the Quasi-Steady State Cosmology (QSSC), proposed in 1993 by Hoyle, Burbidge and Narlikar [see Hoyle *et al.* 1993][59]. In this theory there is no singular epoch of big bang; instead matter is created in a continuing series of small but explosive and nonsingular events in a universe that is without a beginning. The universe expands in a quasi-steady fashion with a scale factor given by

$$S(t) = \exp(t/P)[1 + \eta\cos\tau(t)], \qquad ...(12)$$

where $0<\eta<1$, the function $\tau\ (t)$ is approximately proportional to t and increases by 2π when t increases by Q. The time scale P is much larger than Q, say, $P/Q \sim 20$, with $P\ \sim\ 10^{12}$years. Thus the universe oscillates around an exponentially expanding long term trend. This new cosmology copes with the various observational checks like the discrete source data, the light nuclear abundances and the microwave background, with reasonable success. However, we will not go into details but refer the reader to a review of this theory see Hoyle *et al.* (1996)[60].

A Come-Back for λ

As the observational details about the universe become more and more focussed, the big bang cosmology gets more and more constrained. For example, the ages of stars in some very old globular clusters are in the range 12-15 billion years, perhaps even more. This time period exceeds the typical age of a Friedmann universe. This and other astrophysical and cosmogonical constraints were discussed by Bagla *et al.* (1996)[61] who found that the room for manoeuvre for the standard model has almost disappeared and for survival it may be necessary to reinvoke the cosmological constant at this epoch. If the origin of this constant is in the inflationary epoch of the very early universe, then we face the problem of understanding why only a very tiny fraction of the original cosmological constant (smaller by about 108 orders of magnitude) survived (Weinberg 1989)[49].

Such a cosmological constant can prolong the age of the universe and make it large enough to accommodate the globular clusters which are at least 15 billion years old. The age problem can be solved in the QSSC which has the universe without a beginning.

8 Conclusion

In the last analysis, what cosmological theory survives would depend on how the observational challenges are met. Unlike the situation at the start of this century, when there were hardly any cosmological parameters to constrain the theory, we now suffer from the embarrassment of riches. Let the fittest theory survive.

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