Cosmology in the Post-Einstein Era

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Introduction

No review of the remarkable developments in cosmology in post-Einstein era can do justice to the subject, if it does not first provide the background of the origin and growth of modern cosmology during Einstein's own lifetime. It was Einstein's pioneering effort that established cosmology firmly as a branch of science. I can do no better than repeat the tribute paid by Einstein's colleague Leopold Infeld[1] on the occasion of Einstein's seventieth birthday:

> Speculations about the Universe in which men live are as old as human thought and as old as art; as old as the view of shining stars on a clear night. Yet it was the general relativity theory which, only thirty years ago, shifted cosmological problems from poetry or speculative philosophy into physics. We can even fix the year in which modern cosmology was born. It was in 1917, when Einstein's paper appeared in the Prussian Academy of Science under the title 'Cosmological Considerations in General Relativity Theory.'

Einstein's paper[2] (op. cit.) attempted for the first time what the modern cosmologist today is still groping for: to provide a mathematical model which simulates the large-scale structure of the universe. To be judged 'successful' the model must describe and explain reasonably accurately the observations of the large-scale structure of the universe. Moreover, it must make predictions which can be tested by future observations.

In 1917, observational astronomy had hardly progressed beyond the confines of our galaxy. There was practically no observational data to really test the 'large-scale' predictions of a cosmological model. Under the circumstances Einstein looked for the simplest possible model of a homogeneous, isotropic and *static* universe. The so-called Einstein-Universe achieves just that goal, but at a cost. Einstein had to modify his field equations to the form

$$R_{ik} - \frac{1}{2} g_{ik} R + \lambda g_{ik} = - \frac{8\pi G}{c^4} T_{ik} \tag{1}$$

where the λ-term on the left hand side provides the force of repulsion which is needed to balance the self-gravity of the universe to produce the static model. The λ-term had to be small enough so as not to affect the local tests of gravity. Einstein showed that it was related to the *mean*

The steady state theory got round these objections by postulating an expanding but unchanging universe. This model is described by the de Sitter line element

$$ds^2 = c^2dt^2 - e^{2Ht}\,[dr^2 + r^2\,(d\theta^2 + \sin^2\theta\; d\phi^2)] \tag{4}$$

with $H =$ constant. This universe has no space-time singularity, an infinite age and its unchanging character ensures the validity of the same physical laws at all epochs. The sudden and infinite creation of matter of the big bang models is replaced by a finite and continuous creation of matter which can even be understood by a simple field theory.[9]

Rightly or wrongly the steady state model roused a great deal of controversy. Having taken part in some of these developments I can recall several occasions when the criticism of this theory was either genuinely misinformed or downright prejudiced. While the theoretical foundations of this theory were secure, it was vulnerable to observational tests. By making definite predictions (as opposed to the multi-parameter-dependent predictions of the big bang models) this theory, in the words of one of its originators Hermann Bondi 'stuck its neck out'.

The general hostility to this model and its observational vulnerability prompted many observational astronomers to devise tests to shoot it down. In this process the theory 'died' several times since its birth in 1948, but revived again. The reason for this has, curiously enough, nothing to do with the tenacity of the steady state theory. Rather, it owes its revival to the overconfidence displayed by the observational astronomer in the accuracy of his observations. I quote in this context the reaction of R.P. Feynman[10] to observational cosmology:

> When a physicist reads a paper by a typical astronomer, he finds an unfamiliar style in the treatment of uncertainties and errors.... The authors are apparently unwilling to state precisely the odds that their number is correct, although they have pointed out very carefully the many sources of error, and although it is quite clear that the error is a considerable fraction of the number. The evil is that often other cosmologists or astrophysicists take this number without regard to the possible error, treating it as an astronomical observation as accurate as the period of a planet....

I will describe below three important tests which had earlier claimed to have disproved the steady state model but which subsequently were seen to be somewhat indecisive. It is a fruitless exercise in speculation to ask whether these tests would have been followed up by the observers so enthusiastically, had there been no steady state theory to shoot down. The fact remains that this theory did figure repeatedly in the various cosmological tests for about two decades since its inception. That it does not do so now has nothing to do with the three tests being described below. The death-blow (or a near death-below!) to this theory came from an unexpected direction. But more of that in the following section.

THE REDSHIFT-MAGNITUDE RELATION

The original deduction of the velocity (V)/distance (D) relation

$$V = HD \tag{5}$$

was made by Hubble by plotting the logarithm of the redshift z against the apparent magnitude m for relatively nearby galaxies and by using the relations

$$V = cz \tag{6}$$

$$m = -2.5 \log \frac{L}{4\pi D^2} + \text{const.} \tag{7}$$

where L = luminosity of the galaxy.

In the expanding universe models the redshift receives a direct interpretation as the fractional increase in the expansion factor between the epoch of emission and the epoch of reception of the light wave from the galaxy. Equations (5) to (7) may be considered the flat-space approximations to the exact z-m relation in any cosmology. All big bang cosmologies as well as the steady state theory agree on (5) for nearby galaxies.

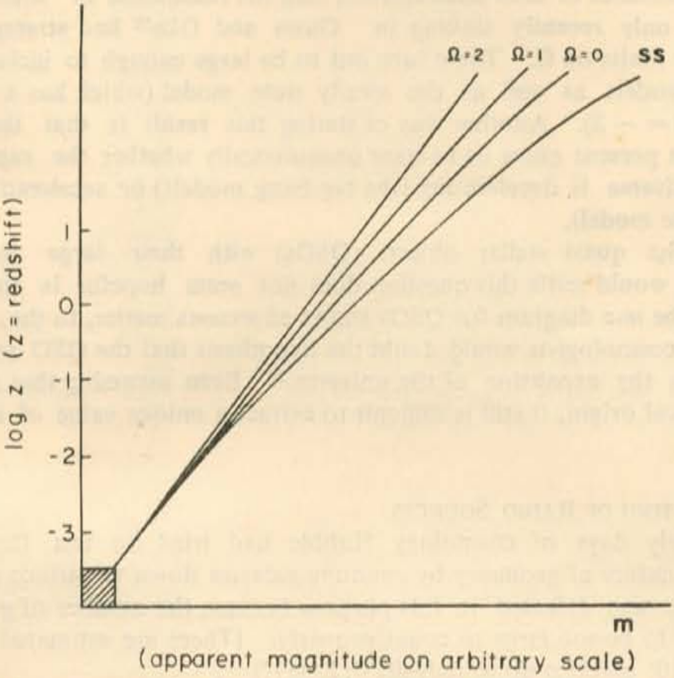

Fig. 2 The schematic m-z relation for three Friedmann models with $\Omega = 2, 1, 0$ and for the steady state (SS) model. Observationally there are not many galaxies with $\log z \gtrsim 0.7$. The shaded rectangle shows the redshift range covered by Hubble.

Figure 2 shows the schematic curves predicted by the various big bang models and by steady state model. The parameter

$$\Omega = \frac{\rho_0}{\rho_c} \tag{8}$$

labels the various big bang curves. Thus $\Omega = 1$ is the Einstein de Sitter model while $\Omega = 2$ represents a closed model. The redshifts of galaxies extend up to $z \sim 0.7$, although there are relatively few points above $z = 0.2$. Notice the shaded rectangle at the bottom which indicates the extent of Hubble's original observations. Modern data cover nearly 500 times more distance in space and time. The question is, whether any particular curve is singled out by the data as giving the most accurate fit?

Allan Sandage[11] and his collaborators at Mt Palomar quote a 'formal' value of Ω close to 2, corresponding to a closed universe which will eventually contract. To what extent does the formal value represent the correct model? Bearing in mind Feynman's remarks one has to be extremely cautious in exercizing judgement since no realistic error estimates are quoted. Do galaxy luminosities evolve with time? To what extent intergalactic absorption is likely to be important for this test? What is the scatter in the standard candle luminosities like? It is difficult to quote realistic estimates of such uncertainties, and the realization of these difficulties is only recently sinking in. Gunn and Oke[12] had attempted to place error limits on Ω. These turn out to be large enough to include all bigbang models as well as the steady state model (which has a formal value of $\Omega = -2$). Another way of stating this result is that the data does not at present allow us to state unequivocally whether the expansion of the universe is decelerating (the big bang models) or accelerating (the steady state model).

That the quasi stellar objects (QSOs) with their large redshifts ($z \leqslant 3.53$) would settle this question does not seem hopeful in the near future. The m-z diagram for QSOs shows enormous scatter, to the extent that some cosmologists would doubt the hypothesis that the QSO redshifts arise from the expansion of the universe.[13] Even assuming that z is of cosmological origin, it still is difficult to extract a unique value of Ω from this data.

THE COUNTING OF RADIO SOURCES

In the early days of cosmology Hubble had tried to test the non-Euclidean nature of geometry by counting galaxies down to various magnitudes. He was defeated in this purpose because the number of galaxies turned out to be too large to count properly. (There are estimated to be around $\sim 10^8$ galaxies up to redshift 0.2, say!)

The number count test was, however, considered feasible with the advent of radio astronomy. The number of extragalactic radio sources is believed to be much smaller than the number of galaxies. Moreover, the radio astronomers believed (many still do) that the faint radio sources picked up by their instruments are considerably further away than typical galaxies. So whether Euclidean geometry holds out to great distances can be tested by counting radio sources. More specifically, the assumptions to be tested are as follows:

(a) The space-time geometry is Minkowskian.
(b) The radio sources are uniformly distributed in space.
(c) The radio sources are identical in their intrinsic power.

Under these assumptions if S is the flux density (i.e. the amount of radiation crossing unit are normally per unit time per unit frequency range) of a typical source at distance R, and N_0 the number of radio sources brighter than S, then we get $S \propto R^{-2}$ and $N_0 \propto R^3$,

i.e.
$$N_0 S^{3/2} = \text{const.} \tag{9}$$

The radio astronomer plots the ratio N/N_0 against S, where N is the actually observed number of radio sources brighter than S. Pioneering work in the 1950s was done by Sir Martin Ryle and his co-workers at Cambridge and by B. Y. Mills et al. at Sydney. The early surveys have by now been replaced by many more mainly in England (Cambridge). Australia, and the U.S.A. These surveys not only extend to much lower values of S than the early surveys but they also span several frequencies of observation. The N/N_0 plots made from different surveys[14] are shown at different frequencies in Fig. 3.

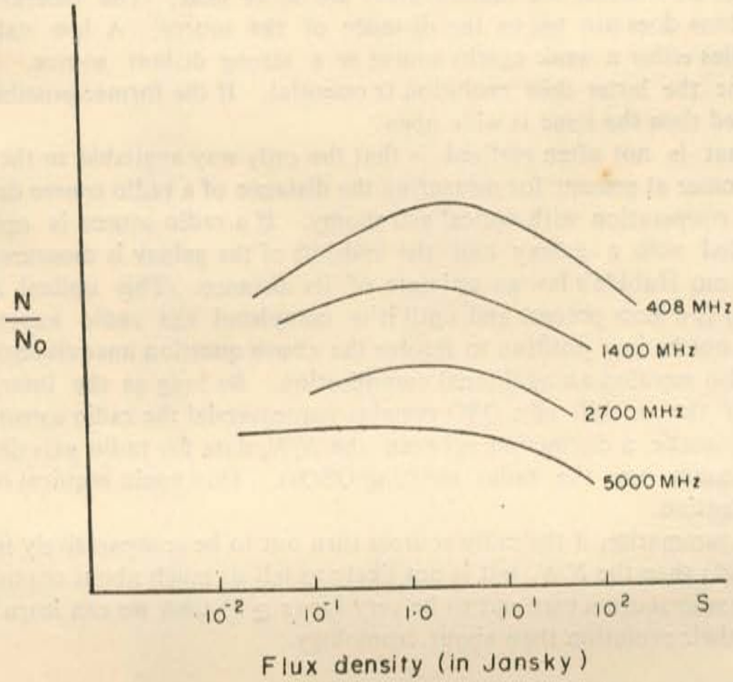

Fig. 3 The N/N_0 curves at different frequencies obtained from many different surveys. At higher frequencies the 'flattening' is noticeable.

Several interesting features emerge from these surveys. At high frequencies there is a fairly good agreement with the Euclidean curve (i.e.

$N = N_0$). At low frequencies there is a departure in that the N/N_0 curve is concave with respect to the S-axis. The difference arises because the lower frequency surveys miss sources with flat spectrum, i.e. with intensity (I)—frequency (ν) relation of the form

$$I(\nu) \propto \nu^{-x}, \quad x \lesssim 0.5 \tag{10}$$

Steep spectrum sources therefore predominate at lower frequencies.

If we believe that radio sources are indeed very far, then redshift effects must predominate at low S. The agreement between N and N_0 at low S then becomes inexplicable unless we postulate that strong evolutionary processes are at work. These conspire with the redshift effect to produce the illusion of Euclidean geometry in space. The evolution refers to the changes in the number density and power of the radio sources with epoch. Evolution is also usually invoked to obtain exact fits with the curves at lower frequencies also. This exercise therefore shifts the emphasis of the test from cosmology to the evolutionary properties of radio sources. Nevertheless, it must be admitted that if epoch dependent evolution is shown to be necessary then this rules out the steady state theory.

Is evolution really necessary to explain the N/N_0 data? The answer depends on whether the radio sources are far or near. The measurement of S alone does not tell us the distance of the source. A low value of S implies *either* a weak nearby source *or* a strong distant source. If we opt for the latter then evolution *is* essential. If the former possibility is accepted then the issue is wide open.

What is not often realized is that the only way available to the radio astronomer at present for measuring the distance of a radio source depends on his cooperation with optical astronomy. If a radio source is optically identified with a galaxy and the redshift of the galaxy is measured, we have from Hubble's law an estimate of its distance. This optical identification is a slow process and until it is completed the radio astronomer would not be in a position to resolve the above question unequivocally.

I also mention an additional complication. So long as the interpretation of the redshift of a QSO remains controversial the radio astronomer should make a distinction between the N/N_0 data for radio galaxies and for quasars (i.e. the radio emitting QSOs). This again requires optical identification.

To summarize, if the radio sources turn out to be comparatively nearby ($z \lesssim 0.5$) then the N/N_0 test is not likely to tell us much about cosmology. If the radio sources turn out to be very far ($z \gtrsim 1$) then we can learn more about their evolution than about cosmology.

ANGULAR SIZE AND COSMOLOGY

In 1959 Hoyle[15] proposed a test of the non-Euclidean geometry of the universe. This involves, in principle, the variation of the angular size α of an object of fixed linear size l as its distance (D) from us is changed. In Euclidean geometry the relation is simple:

$$\alpha = \frac{l}{D} \tag{11}$$

The corresponding relation in the Einstein-de Sitter model shows how α changes with the redshift of the object:

$$\alpha = \frac{lH}{2c} \cdot \frac{(1+z)^{3/2}}{(1+z)^{1/2}-1} \tag{12}$$

And similar relations can be worked out in the different big bang models and in the steady state model. In the big bang models, as in the special case described in (12), α has a *minimum* at a finite value of z which depends on the parameter Ω. The larger the value of Ω the closer is the minimum, as shown in Fig. 4. This curious effect is a manifestation of the non-Euclidean geometry of space-time. Or, it may be interpreted as the consequence of the matter in the universe acting as a gravitational lens. I am sure this result would have delighted Einstein, had it come in his lifetime.

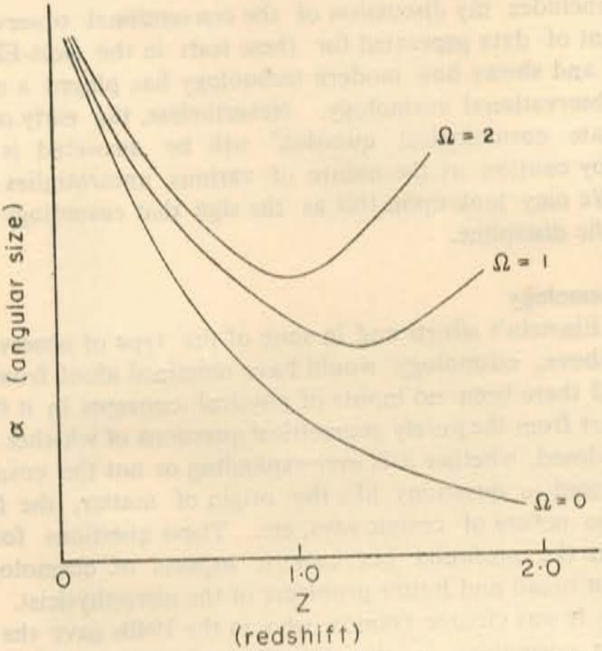

Fig. 4 Curves showing the apparent angular size α as a function of redshift z for Friedmann cosmologies with varying values of Ω. The existence of the minimum of α is in practice masked by various non-cosmological factors.

Hoyle had suggested observations of radio sources for this test. Unfortunately, as a practical proposition for deciding which cosmological model is right this test is not so promising. First, the theoretical result stated above becomes suspect if the universe has inhomogeneity as discussed by Roeder.[16] Secondly, as mentioned earlier, the radio astronomer cannot measure z directly and hence has to rely on S to provide a measure of distance. As the intrinsic powers of radio sources vary over a range of $\gtrsim 10^5$, the $S \leftrightarrow z$ correspondence has a lot of scatter. Finally, the radio sources are not spherical in shape but tend to have linear structure. So α stands for the separation between the two components of a typical double source. Unfortunately, l varies over ~ 10 kpc $- \sim 1$ Mpc. and this variation, including the effects of projection perpendicular to the line of sight causes a scatter in the values of α.

Recently, Swarup[17] and Kapahi[18] have done an extensive analysis of the angular size-flux density relation and have concluded that the observed relation is explicable only if an evolution in l implying $l \propto (1+z)^n$, $n \sim 1$ is introduced. Whether an evolution is really needed is still open to debate. It can be shown, for example, that a correlation between l and P can also produce results in satisfactory agreement with the data, without requiring evolution[19]. The trouble is that the test is still too vague to yield a clear-cut result.

This concludes my discussion of the conventional observational tests. The amount of data generated for these tests in the post-Einstein era is impressive and shows how modern technology has played a useful role to promote observational cosmology. Nevertheless, the early optimism that the 'ultimate cosmological question' will be answered is now being tempered by caution as the nature of various uncertainties is becoming clearer. We may look upon this as the sign that cosmology is maturing as a scientific discipline.

Physical cosmology

In spite of Einstein's efforts and in spite of the type of observational tests described above, cosmology would have remained aloof from the rest of physics, had there been no inputs of physical concepts in it from time to time. Apart from the purely geometrical questions of whether the universe is open or closed, whether it is ever-expanding or not the cosmologist has been interested in questions like the origin of matter, the formation of galaxies, the nature of cosmic rays, etc. These questions form the vital link between the profound but esoteric aspects of cosmology and the mundane but bread and butter problems of the astrophysicist.

Probably it was George Gamow who in the 1940s gave the first significant turn to cosmology in the direction of physics. In the big bang universe the matter density ρ and the radiation density u in the absence of any mutual interaction depend on the scale factor according to the formulae

$$\rho \propto \frac{1}{S^3}, \quad u \propto \frac{1}{S^4} \tag{13}$$

Thus, however small u may be in comparison with ρ *now*, there must have been an early enough phase in the life of the universe when radiation was more dominant than matter. Thus in the very early stages the universe must have possessed a very high radiation temperature.

Gamow seized upon this important consideration to argue that in the first few moments after the big bang the radiation of the universe had been high enough to set off thermonuclear reactions. The outcome of these reactions would be to synthesize matter from a primordial brew of elementary particles like protons, electrons, neutrinos, photons, etc., into 'higher forms' like the nuclei of elements. The work of Hans Bethe a few years earlier had demonstrated the feasibility of

$$H^1 \rightarrow He^4 \qquad (14)$$

within the interior of the sun. Gamow, Alpher, Hermann and Bethe attempted the more ambitious task of producing all the nuclei in the first few moments of the life of the universe.

It is now known that this type of approach achieves only a limited goal. Light nuclei like D and He can indeed be produced this way, but the primordial nucleosynthesis cannot surmount the barrier of unstable nuclei in the atomic number range 5-8. The important work a decade later by E.M. Burbidge, G.R. Burbidge, W.A. Fowler and F. Hoyle[20] showed that stellar interiors provide ideal sites for nucleosynthesis. It should be mentioned, by the way, that this work was also inspired by cosmology. It used to be argued that the Gamow process of nucleosynthesis could not be invoked in the steady state cosmology because of its lack of a high temperature epoch. The stellar nucleosynthesis process was designed to show that a high temperature cosmic epoch is not really necessary. This had two consequences, one positive the other negative. On the positive side, this is an example of how cosmological consideration can generate important astrophysical contributions.

The negative consequence was to divert attention of the cosmologists from the primordial nucleosynthesis theory. And probably for this reason one important guess made by Gamow, Alpher and Hermann[21] remained in the background—the guess that as a relic of the early hot era we should now be seeing a low temperature radiation background.

During 1963–64 several workers took renewed interest in primordial nucleosynthesis: Zeldovich[22] in Moscow, Hoyle and Tayler[23] in Cambridge and Peebles[24] in Princeton. Hoyle, for long regarded as the prime opponent of 'the big bang' was impressed by the fact that the estimates of the ratio of Helium to Hydrogen from various astronomical observations were significantly higher ($\sim 25\%$ by mass) than what could be explained by stellar nucleosynthesis ($\sim 10\%$ by mass). If these estimates were to be regarded as 'universal' they implied that the matter in the universe had passed through a high temperature ($\sim 10^{10}$ °K) in the past. If one does not want the big bang one has to postulate supermassive objects ($M \gtrsim 10^6 M_\odot$) in whose centres high temperatures might be possible. The work of Tayler and Hoyle was, however, directed more towards re-doing Gamow's early calculations with the fresh inputs available from nuclear and particle physics. They found that the observed high abundance of Helium can be comfortably explained in the big bang scenario. Later work of Wagoner, Fowler and Hoyle[25] confirmed this result as well as the earlier expectation that for heavier nuclei (carbon and upwards) stellar nucleosynthesis is definitely needed.

Peebles had reached similar conclusions. His work also brought out another of Gamow's early prediction that a relic of the primordial hot era should be the background radiation at a temperature a few degrees Kelvin. His colleague R.H. Dicke[26] at Princeton had arrived at a similar conclusion from his own discussions of cosmology. Dicke also realized that if this radiation was in the microwave region it could be measured from a ground-based antenna. At his suggestion his experimentalist colleagues P.G. Roll and D.T. Wilkinson began to set up an experiment for the detection of the background radiation.

However, they were overtaken by events. The background radiation at 7.3 cm was detected unexpectedly by two physicists at the Bell Telephone Laboratories, A.A. Penzias and R.W. Wilson.[27] The results of Penzias and Wilson were reported in the spring of 1965, some six months before the results of Roll and Wilkinson.[28] Penzias and Wilson had in fact detected this radiation in 1964 but as they were unaware of the cosmological background, they were puzzled about its origin. It was only when they compared notes with the Princeton group that they realized the enormous significance of their observation. The paper of Penzias and Wilson in the Astrophysical Journal was preceded by that from Dicke and others[29] giving the cosmological interpretation.

In retrospect it is surprising that such as important prediction of

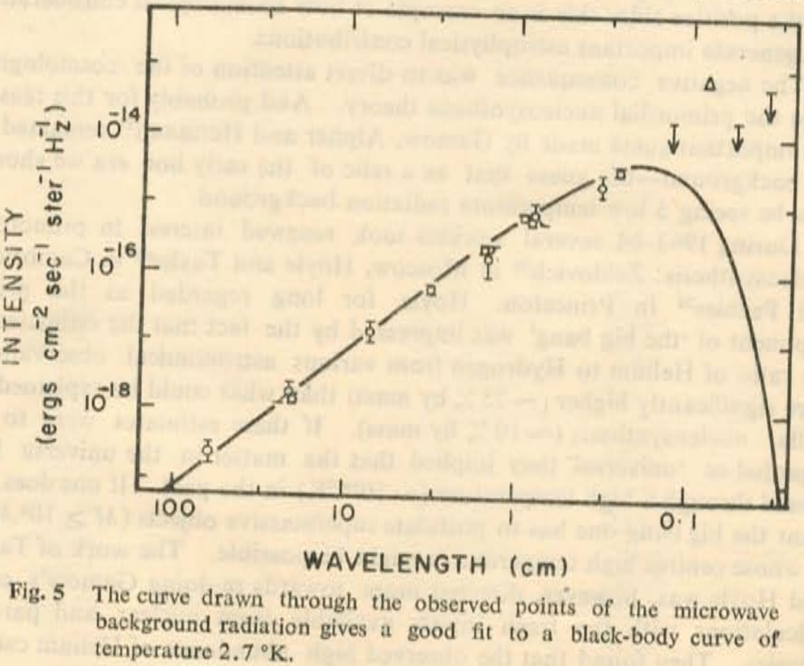

Fig. 5 The curve drawn through the observed points of the microwave background radiation gives a good fit to a black-body curve of temperature 2.7 °K.

Gamow remained untested for so long. It is even more surprising that the Princeton group was also unaware of this prediction! By hindsight it is possible to argue that theoretically and observationally the existence of the background radiation could have been established a decade earlier than it actually was.

Subsequent to 1965, however, the work on the measurement of the background radiation progressed rapidly. Fig. 5 shows the measurements at different wavelengths together with a 'best fit' black body curve of 2.7° K. The measurements at wavelengths shorter than $\sim$1 mm have to be done above the atmosphere and here the accuracy of the observations available to date is far from satisfactory. The short wavelength side of the black body curve still remains to be confirmed.

The black body interpretation has given a tremendous boost to the big bang concept of the universe. It has also inspired cosmological theorists to be bold and apply the local physics to primordial conditions. And thus has emerged in the last dozen years considerable literature on physical cosmology which attempts to answer questions such as: 'When were hadrons formed?', 'In what sequence were elementary particles combined into nuclei?', 'When did atoms and molecules form?', 'How did galaxies come into existence?', 'Did black holes dominate the primordial era?', etc. While many of these theories are highly speculative, the fact that they draw heavily upon the current knowledge of physics indicate how much cosmology has become an integral part of physics.

Non-standard cosmology

Anyone who reads the highly persuasive account of the big bang universe as given by Steven Weinberg[30] will come away with the impression that the problem of the origin of the universe is now more or less solved and that only a few details need to be filled in. If this impression were confined to the layman it would not be so important. That it is now being accepted by the run-of-the-mill physicist is disturbing, for it has the danger of removing the critical scientific ability so essential to the cosmologist if he is to function effectively as a scientist. Against such a complacent attitude Hoyle[31] has remarked in the course of his talk at the Vatican Conference in 1970: "I think it is very unlikely that a creature evolving on this planet, the human being, is likely to possess a brain that is fully capable of understanding physics in its totality, I think this is inherently improbable in the first place, but, even if it should be so, it is surely wildly improbable that this situation should just have been reached in the year 1970."

Einstein himself never asserted that his general theory of relativity was the ultimate theory of gravity. His attempts to unify the basic interactions indicate his aspiration to find a more comprehensive framework for physics. His interest in Mach's principle, his dissatisfaction with the foundations of quantum mechanics or his flirtation with the λ-term are examples of his unconventionality in the quest of solutions to the mysteries of the physical world.

Similar motivation has inspired several research workers to depart from the standard big bang picture of the universe and to look for alternative cosmological theories. I have already discussed the steady state cosmology as an example of this 'non standard' group of cosmologies. I mention below a few more examples of non-standard cosmologies which have come up after the death of Einstein. Even to the most conservative standard big bang theorist a review of non-standard cosmologies should be of interest if only to judge how the standard cosmology compares with them.

The appearance of large number of ratios between typical units in cosmology and elementary particle physics had been noticed even in Einstein's lifetime. For example:

$$\text{(i)}\quad \frac{e^2}{Gm_p m_e} \sim 10^{40}, \quad \text{(ii)}\quad \frac{c/H}{e^2/m_e c^2} \sim 10^{40} \tag{15}$$

Of these, (i) denotes the ratio of the electrostatic force between an electron and a proton to their gravitational force, while (ii) is the ratio of the 'radius' of the universe to the 'radius' of the electron.

Is the appearance of similar large numbers in different contexts above a coincidence? Dirac[32], in 1937 had interpreted this coincidence in terms of an epoch-dependent property of the universe. Thus the figure 10^{40} in (ii) could be considered the 'age' τ of the universe in atomic units, and (i) could be looked upon as giving an epoch-dependent gravitational constant ($G \propto \tau^{-1}$) In 1973 Dirac[33] developed these ideas further and his cosmological theory makes use of two time-scales. The atomic time-scale τ governs the atomic processes where as the macroscopic time-scale t may be used to write the gravitational equations in the standard Einstein form. However, since a non-linear transformation connects the two time-scales the Dirac cosmology differs from relativistic cosmology in a non-trivial way. For example, the gravitational constant decreases at a rate

$$\frac{\dot{G}}{G} = -\alpha H \tag{16}$$

where α is of order unity.

The variability of the gravitational constant with epoch is a consequence of other cosmologies too. For example, the Brans-Dicke theory[34] and the Hoyle-Narlikar cosmology[35] make somewhat similar predictions. Both these theories make Mach's principle as their starting point. In the Brans-Dicke theory the gravitational constant G is replaced by a scalar field ϕ which measures the relative strengths of inertial and gravitational forces so that $G \sim \phi^{-1}$. The gravitational field equations of this theory include ϕ and its derivatives in addition to the Einstein-like terms. The recent measurements of the solar system tests seem to rule out the effect of ϕ except in a very weak way. The cosmological solutions of the Brans-Dicke theory are somewhat similar to the standard big bang models with the difference that the effective gravitational constant decreases with epoch.

In the Hoyle-Narlikar theory the Machian concept of inertia is built into the theory right at the beginning by defining the mass of a particle as a scalar quantity satisfying a wave equation with sources in the rest of the particles in the universe. Besides its Machian origin, the theory is conformally invariant and in a special conformal frame called the Einstein frame it looks like general relativity. Recently it has been shown that the cosmological singularity of general relativity arises because the conformal function needed for going over to the Einstein frame vanishes on the zero mass hypersurfaces.[36] The theory can also be modified easily to introduce a 'fourth' cause of redshift which might be required to describe the anomalous redshifts of quasars[37].

On the physical side a significant departure from the standard cosmology is found in the matter-antimatter symmetric cosmology[38] of Alfven and Klein. This cosmology attempts to explain how from a primordial era of symmetry, matter and antimatter got separated so that we now live in a large region ($\gtrsim$ size of cluster of galaxies) dominated by matter.

Limitations of space and time severely restrict this discussion of non-standard cosmologies (see, however, Narlikar and Kembhavi[39] for a comprehensive review). These cosmologies have to be judged by the elegance of their theoretical framework and by their success or failure on the observational front. As an example of the latter, consider a recent discussion by Gunn and Tinsley[40] of standard cosmologies. Taking into account the various observational inputs available, these authors conclude that to be within the various observational limits it may become necessary to reinstate the λ-term in Einstein's field equations.

Concluding remarks

To the conventional cosmologists this review of cosmology in the post-Einstein era will appear tilted towards a non-conformist point of view. I have deliberately adopted this attitude because I feel that on an important occasion like the Einstein centenary the subject of cosmology should be presented not as a 'closed book' but as an area brimming with activity and with many unsolved problems and controversies. To this end, I have attempted to convey the remarkable strides made by the subject in the comparatively short span of less than a quarter century after the death of the man who was so intimately connected with its early development.

I also take the liberty of exposing my personal bias by making a couple of long term predictions about cosmology. It is my expectation that in due course the microwave background will receive a purely astrophysical interpretation which will divest it of its present cosmological significance. As for the big bang I expect that it will turn out to be a relatively local explosion of high temperature and density rather than the primary event describing the origin of the universe. And, with the tremendous growth rate of information in extragalactic astronomy continuing in the future, I do not think that one will have to wait until Einstein's second centenary for this to come about!

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Discussions

J Pachner: (1) There are three measurable quantities in cosmology, the mean mass density, the Hubble constant, and the deceleration parameter. In the steady state cosmology the deceleration parameter is −1. The recent observations show that this parameter is positive (with a reasonable probability). I consider this as a decisive argument against the steady state cosmology.

(2) There are some modifications of the steady state cosmology (McCrea, Pachner, N. Rosen) but since they introduce some cosmic field, I consider them too arbitrary (one can easily develop several cosmologies by assuming an ad hoc cosmic field).

J V Narlikar: I do not agree with you that the deceleration parameter q has been accurately determined. There are several sources of 'errors' of astrophysical origin which make a realistic determination of q very difficult.

The cosmic field used by Hoyle and me was the 'simplest' possible modification: it was a zero rest mass scalar field. Thus by choosing simplicity as a criterion one can counter the criticism of its being ad hoc.

C Sivaram: How would you account for the initial helium abundance in steady state theories?

J V Narlikar: Ordinary stellar nucleosynthesis is inadequate to account for the He/H ratio as high as is observed. One has to postulate the existence of supermassive objects ($M = 10^6 M_\odot$) for this.

N D Hari das: Do you think the recently discussed Hawking phenomena applied either to mini black holes or to cosmological metrics (if you do not believe in black holes) can be utilized as a source of black body radiation for *SS* theories?

J V Narlikar: To make this work you have to produce a theory of continuous creation of mini black holes and to demonstrate that their integrated radiation is thermal and of 2.7°K in a steady state. Off hand, I don't think this can be done.

N Panchapakesan: The data points on the 3°K curve do not seem to imply a bending of the curve. Is the black body nature of radiation still in doubt?

J V Narlikar: The data points on the short wavelength side of the 'peak' at 1 mm are few and not very accurate (in my opinion). They are, however, consistent with 2.7°K black body.