

A LOOK AT COSMOLOGY AS A BRANCH OF SCIENCE

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"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".....

—Richard Feynman
Lectures on Gravitation (Caltech)

Cosmology deals with the problem of the origin of the universe, its evolution with time and its development in the far future. How did the matter we see around us originate? Is the vast expanse of space around us, finite? Is it bounded? Did the 'whole thing' have a beginning at a certain epoch a finite time ago? Or is it without a beginning? Questions like these have troubled the intellectuals in the past as they continue to do now. In the past, from the ancient mythologies and through numerous religious channels there have been deep philosophical speculations which reflect man's yearning to find 'the ultimate' answer. The endless discussions and numerous controversies of modern cosmology are testimony to the fact that this goal is still far off.

In the twentieth century science has picked up the challenge. What progress can we make in this direction using the methods of science? In the scientific approach also there are theories and speculations, arguments and controversies but here one is required to follow the discipline imposed by science. In particular, there is the paramount requirement that what is asserted about the Universe not only agrees with the present observations but that it also has a predictive power. To what extent does modern cosmology meet the requirements of science? The purpose of this article is to survey the trials and tribulations of cosmology as it tries to function within the scientific discipline.

The inherent difficulties of cosmology

Before assessing cosmology as a science it is necessary to recognize and make due allowance for some of the intrinsic difficulties of the modern cosmologist. By intrinsic difficulties, I mean those which cannot be cured under **any** circumstances (e.g. under the idealized circumstance of being endowed with **perfect** instruments). These difficulties are not confined to cosmology alone; they are shared by the astronomer in general.

But these are practically unknown to the scientist working in the terrestrial laboratory. I illustrate some of these below.

The astronomer is limited to **observing** the heavenly bodies; he cannot experiment with them. All his information is conveyed by the radiation from these distant objects. With suitable ingenuity he tries to design apparatus to extract the maximum information from this radiation. **He cannot alter the conditions under which this radiation was, or is being emitted.** To see the effect of this type of limitation compare the case of an astronomer trying to verify the mass-luminosity relation for stars with that of a physicist trying to verify Ohm's law. The latter can verify the proportionality of voltage difference and the current flowing by altering the former and by choosing a variety of conducting objects for such measurements. The astronomer, on the other hand is in a less fortunate position. He is told that there exists a relation of the form

$$L = f(M) \quad (1)$$

between the luminosity L and mass M of a certain type of stars, to which the Sun belongs. He may substitute the values of M and L for the Sun and check that (1) holds. But that is not enough. Ideally he should vary M and check that (1) holds for other values of M also. But he does not readily have Sun-like stars of varying masses at his disposal to make this verification.

Indeed, Sun is the only star in his immediate neighbourhood. He must therefore look for other stars further away. Sure enough star clusters with stars of varying masses do exist in our Galaxy; but because of their enormous distance there are difficulties in estimating L and M for them. For example, one must be sure of the extent of interstellar absorption by dust while estimating L . That the astronomer has succeeded in verifying the existence of his relation in spite of such difficulties is a tribute

to his ingenuity. The cosmologist, dealing with considerably farther objects, situated well beyond our Galaxy, is even more hampered by these problems as we shall soon see.

Another major difficulty lies in the extrapolation of physical laws. The laboratory physicist has discovered and tested these laws within the narrow confines of the Earth. The astronomer seeks to apply them to conditions much more extreme than ever found on the Earth. To what extent is he justified in this? When he talks of nucleosynthesis in the early universe at temperatures of the order of 10^{10} K, when he studies the structure of neutron stars of densities 10^{14} g cm⁻³, when he applies the law of gravity to distances of the order of 10^{28} cm, the only confidence that sustains him is his belief that the well known laws of physics continue to hold when so extrapolated. This confidence is sufficient so long as the theory agrees with observations. What happens when there is a disagreement between the two? Should the theoretician place the blame on the observer, claiming that the theory is right but the observations are incorrect? Or should the observer argue that what he is observing is undoubtedly correct and that the theoretician should go back to the drawing board and return with new laws of physics?

This happens to be one major issue of the current cosmological controversy.

The expansion of the universe

In the late 1920s, Edwin Hubble discovered a remarkable relation between the 'faintness' of distant galaxies and the 'redshift' of light coming from them. Before interpreting Hubble's relation let us relate the faintness to distance. If L is the luminosity (i.e. the rate of emission of energy) of the galaxy and D its distance from us, the amount of energy received by us from the galaxy per unit area, per unit time is given by

$$I = \frac{L}{4\pi D^2}$$

The faintness is measured by the so-called 'apparent magnitude'

$$m = -2.5 \log I + \text{constant}.$$

Thus larger the value of I the lower is the value of m . Equal intervals of m measure equal ratios of I , which explains why the astronomer uses this peculiar scale. The eye is usually able to judge the ratios of I rather than its linear differences. Thus one can say about three objects A, B, C that A is as much brighter than B as B is than C*. A difference of 5 on the magnitude scale corresponds to a factor of 100 in I .

The redshift z is the fractional change in the wavelength of light reaching us from the distant galaxy.

* This is based on Fechner's law that differences in intensity which correspond to the same fractional part of the whole are equally perceptible by the senses whether the whole intensity is great or small.

Thus if λ_0 is the emitted wavelength the received wavelength is

$$\lambda = \lambda_0 (1+z) \quad (4)$$

Hubble discovered a relation of the following form:

$$m = 5 \log z + \text{constant}. \quad (5)$$

Using (2) we get, in terms of L and D ,

$$m = -2.5 \log L + 5 \log D + \text{constant}. \quad (6)$$

A comparison of (5) and (6) gives us

$$\log z = \log D - \frac{1}{5} \log L + \text{constant}. \quad (7)$$

In other words, if all galaxies have the same L , and we identify the frequency shift as arising from a Doppler shift with the source speed given in terms of the light speed by $v = cz$, we get a relation of the form

$$v = DH \quad (8)$$

where H is a constant, now known as **Hubble's constant**.

Figure 1 gives the linear plot based on Hubble's original data¹. The constant H as originally determined by Hubble had the value ~ 530 km s⁻¹ (mpc)⁻¹, mpc is short for **megaparsec** or a distance of about 3.085×10^{24} cm.

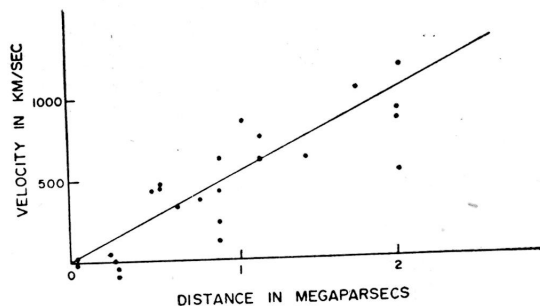


Fig. 1 The Hubble relation for nearby nebulae, published by Hubble in 1929.

This unit is used by the astronomer because of the trigonometric parallax method used for measuring stellar distances. A **parsec** is the distance of a star at which the Earth's orbital radius subtends an angle of 1".

Suppose a linear relation does exist between v and D , for all galaxies. What will happen if we plot m against z ? The first thing we notice is that not all galaxies will have the same L and so there will be a scatter about the relation (5). For example the scatter found for a much bigger sample by Humason, Mayall and Sandage² is shown in Fig. 2. Although there is a scatter in this figure, the linear trend originally found by Hubble is still quite apparent.

At this stage let us see how the theoreticians reacted to Hubble's data. Earlier, in 1917 Einstein³ had constructed models of a **static** Universe from his general theory of relativity. At that time there was no reason for suppo-

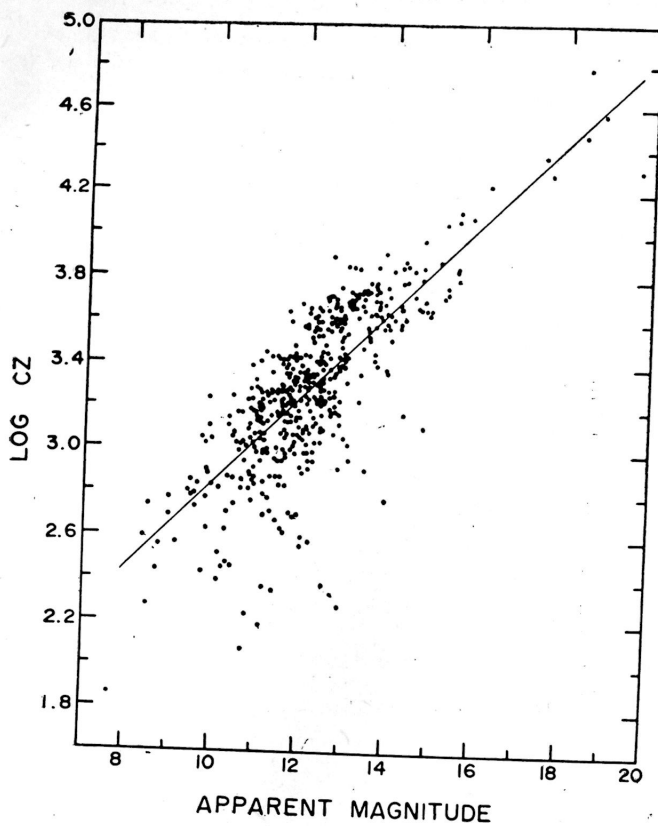


Fig. 2 The magnitude - redshift relation for all types of nebulae, obtained by Hymason, Mayall and Sandage.

sing the Universe to be anything but static. However, to be able to construct this model Einstein had to postulate a **repulsive** force, the so-called λ -force which became appreciable only at large distances. A balance between this force and gravity led to a static Universe. However, Hubble's observations demonstrated that the Universe was not static after all. The galaxies in it were moving away from us according to Hubble's law(8).

In 1924, A. Freedmann⁴ had in fact obtained other models from Einstein's general relativity in which Hubble's observations could be explained. These were models of the expanding Universe, in which the redshift arose because the geometry of the expanding space-time structure was non-Euclidean. **And, these models did not require the λ - term.**

Basically these models represent a Universe which exploded into existence at a past epoch which may be labelled by a cosmic time* $t=0$. The details vary according to two parameters. One is the sign of curvature of spaces $t = \text{constant}$ which are assumed homogeneous and isotropic. This curvature parameter k takes values 0, +1 or -1. The other parameter is the so-called deceleration parameter q_0 of the Universe at the present epoch. To understand the significance of q_0 consider the scale function $S(t)$ representing the expansion of the Universe (see Fig. 3 for details), and define the present epoch by $t=t_0$. Then the present value of Hubble's constant and q_0 are given by

$$H = \left(\frac{1}{S} \frac{dS}{dt} \right)_{t=t_0}, \quad q_0 H^2 = - \left(\frac{1}{S} \frac{d^2 S}{dt^2} \right)_{t=t_0}$$

I shall discuss q_0 later.

The Hubble constant is the first essential information we should have about the structure of the Universe. The fact that a theory (e.g. Friedmann models) comes up with an explanation of the phenomenon of expansion within the framework of an established physical law (i.e. the general theory of relativity) is the first indication that cosmology is a science. If we can measure H , we should be able to say something about the large scale structure of the Universe. For example, in the case of the closed Universe ($k = +1$) the spaces $t = \text{constant}$ are finite but unbounded (like the surface of a hyper sphere) and have a volume at the present epoch equal to

$$V(t_0) = 2\pi^2 \left(\frac{c}{H} \right)^3. \quad (10)$$

The measurements of H have had a chequered history. As noted above Hubble obtained a value ~ 530 units (the unit in this connection is $\text{km s}^{-1} \text{Mpc}^{-1}$). This was subsequently and progressively revised downwards until in 1974, Sandage and Tamman⁵ obtained a value ~ 53 units, i.e., one tenth of the original value.

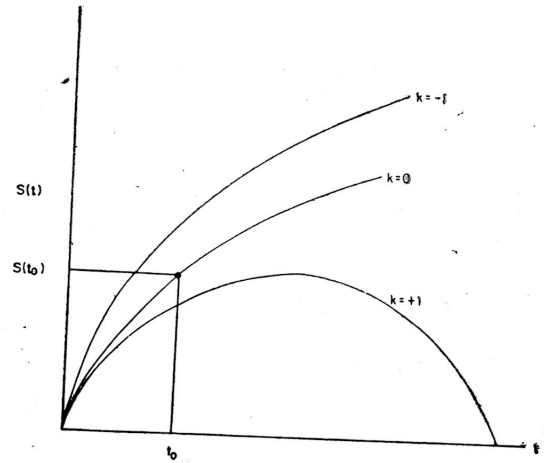


Fig. 3 The typical scale functions of Friedmann models for $k = -1, 0, +1$. The cosmic time t_0 , the present epoch is fixed by the requirement that $\dot{S}/S$ equals Hubble's constant. In the figure this is shown for the $k=0$ model.

This revision is not a reflection of a slowing down of the expansion rate from the early 1930's; to the early 1970's. Rather it emphasizes the role of the systematic corrections that have had to be made in the estimation of distances. In the relation (8) the spectroscopic determination of z is fairly accurate and unambiguous except in a few cases. The estimation of D , i.e., the extragalactic distance scale has however, turned out to be full of difficulties.

The estimation of extragalactic distances is the weakest point in any current cosmological argument. Unlike stellar distances in our galaxy, the distances of remote galaxies cannot be measured by the normally reliable method of trigonometric parallax. The only method available to the astronomer is the so-called 'standard candle' me-

* The postulated symmetries of model universes enable the cosmologist to talk of a cosmic time t . The subspaces $t = \text{constant}$ are homogeneous and isotropic.

thod. In this we assume that a remote galaxy whose distance D_1 we want to know is similar in some respect to a nearby one whose distance D_2 we know. For example if the two possess objects of similar properties, then we could argue that these objects serve as standard candles.

If the rate of the amount of light received per unit area from such an object in the remote galaxy is I_1 and from the nearby galaxy, I_2 , then

$$D_1 = \sqrt{\frac{I_2}{I_1}} \cdot D_2. \quad (11)$$

The optical astronomer, over the years has gained more expertise in the selection of the standard candles and this has resulted in the above revision. Also care must be taken in applying (11) because absorption of light by intervening matter modifies the inverse square law. Are we now at a stage where the Sandage-Tamman value of the Hubble constant can be accepted with some confidence? Alas no! Already there are indications that H may be underestimated. De Vaucouleurs⁶ has made a systematic analysis of the extragalactic distance-scale and he concludes that H should be close to 80-90 units, and may even be higher!

To the laboratory physicists the disagreement of this magnitude ($\sim$ a factor of 2) among leading observers for such a fundamental quantity as the Hubble constant may appear very peculiar and unsatisfactory. Imagine two leading terrestrial laboratories quoting the charge of the electron with a range of factor 2! Yet the inherent difficulties in the accurate measurements of H , such as the ones I mentioned earlier, are only now being appreciated by the astronomers in general. In calibrating the extragalactic distance scale one must go through stages—from nearby to remote standard candles and each stage has its own uncertainties. It looks as if any value quoted today for H must carry with it large error-bars which reflect these difficulties. Unfortunately these error bars are often forgotten when cosmologists argue about the value of H .

The deceleration parameter

Like the Hubble constant the deceleration parameter q_0 has played a similar tantalizing role in observational cosmology. In the mid-1960s Allan Sandage found that if the m -log z relation is plotted for the galaxies of a special class, there is very little scatter. These galaxies are the brightest members of their respective clusters. They are giant elliptical galaxies which dominate the other members in mass and brightness. There is very little variation in the intrinsic brightness of these brightest cluster members from cluster to cluster; so that these galaxies serve as standard candles.

The theoretical Friedmann models predict definite m -log z relations which can be compared with the observed data. On the basis of the plot of the type shown in Fig. 4 Sandage⁷ concluded that the Friedmann model with $k=1$, $q_0=1$ fits the data best. Subsequent work of Sandage in 1972 confirmed this result.

However, gradually it became apparent that the value of q_0 determined in this way glosses over many uncertainties, some of which I describe below.

First there is the question whether there is a systematic change in the luminosity of the 'standard candle' galaxies. Work by Tinsley⁹ and others shows that if the galaxies formed at a certain fixed epoch in the past, say at $t=t_f$ then as they grow older they become less and less bright. This is because, the stars in them become older and consequently less and less luminous. Now if we look at a high red shift galaxy, we see it at a large distance and hence at an early epoch. Thus the high redshift galaxies will be younger and hence intrinsically more luminous (provided of course that they are seen at an epoch $> t_f$). How big is this effect? The answer naturally depends on our knowledge of stellar evolution. Although this is by no means very precise, it is accurate enough to show that this effect is comparable to that due to a change of q_0 from 1 to 0. In other words, the Sandage estimate of $q_0=1$ has to be revised down to $q_0 \approx 0$ if the luminosity evolution of galaxies is taken into account.

Another effect is that of intergalactic absorption. A moderate amount ($\sim 1\%$ of density of visible matter) of intergalactic dust can induce corrections to the observed magnitudes which are comparable to the luminosity evolution effect discussed above, but in the opposite sense¹⁰. Thus it would require an upward revision of q_0 .

Finally there is the Scott effect which essentially means that the observer tends to pick out selectively more powerful light sources at large redshifts. This is because at the limit of the sensitivity of the observers's photographic plates it becomes very difficult to pick out images of any but the very bright (intrinsically) sources. Hence the standard candle is biased on the brighter side. This effect tends to require a **downward** correction to q_0 .

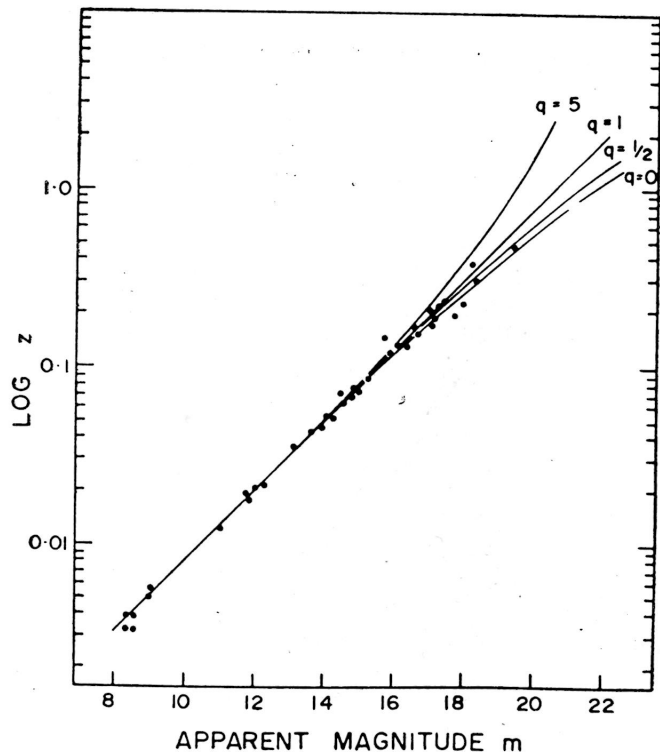


Fig. 4 The m - z plot for brightest cluster members. The continuous curves are drawn for different theoretical Friedmann models with q_0 ranging from 0 to 5.

Taking these effects and other corrections into account it will be extremely difficult at present to attach any realistic error-bars to q_0 . While many astronomers now prefer to take $q_0 = 0$ as a 'canonical' value, they are aware that large positive ($q_0 \sim 1$) and negative ($q_0 \sim -1$) values are not ruled out.

A large positive value of q_0 tends to present two main difficulties to the big bang models. For $q_0 = 0$, the 'age of the Universe', i.e., the time elapsed since the big-bang, is given by

$$t_0 = H^{-1} \quad (12)$$

For the Sandage-Tamman value of $H \sim 53 \text{ km s}^{-1} (\text{mpc})^{-1}$ this is around 1.8×10^{10} years. This is larger than the estimated age of the Galaxy which is in the range $1-1.5 \times 10^{10}$ years. However, it is already clear that galaxies very much older than ours are difficult to accommodate within age of the Universe which must necessarily be an upper limit to the ages of its constituents.

The difficulty is accentuated if we push up the value of q_0 since this lowers the age of the Universe. For example.

$$t_0(q_0 = \frac{1}{2}) = \frac{2}{3} H^{-1}, t_0(q_0 = 1) = (\pi/2 - 1) H^{-1} \quad (13)$$

Thus at the Sandage-Tamman value of $q_0 = 1$, the Universe is barely 10^{10} years old.

The second difficulty is about the mean density ρ_0 of matter in the Universe at the present epoch. The Friedmann models give this value as

$$\rho_0 = \frac{3H^2}{4\pi G} q_0 \quad (14)$$

where G = Newton's constant of gravitation. With $H = 53$ units, $q_0 = 1$ we get $\rho_0 \sim 10^{-29} \text{ gm cm}^{-3}$. This is some 30-100 times higher than the estimated density of matter actually detected in the Universe. Is there a large quantity of unseen matter in the intergalactic space, e.g. in the form of black holes? There may well be, but it is somewhat disconcerting to have to postulate such large quantity of unseen matter. This difficulty of course disappears if q_0 is as low as say ~ 0.1 .

Gunn and Tinsley¹¹ have reviewed the available data and have found very little in it to comfort the classical general relativist. One of their conclusions is that the more likely negative value of q_0 may require the reinstating of the λ - term originally used by Einstein!

Radioastronomy and cosmology

The appreciation of the various difficulties in the optical observations of the Universe has been a relatively recent phenomenon. The possible uncertainties associated with the remote surveys of the Universe are not yet fully estimated but their awareness has prompted caution in attaching any significance to the canonical (aver-

age) parameters of the Universe. Modern cosmology which was born with Hubble's law has only now begun to enter a state of maturity so far as optical astronomy is concerned.

In this respect it is interesting to compare and contrast the situation in the optical astronomy with that in the radio astronomy. Radio astronomy grew essentially after World War II and its progress has been remarkably rapid, thanks to the input provided by modern technology. The hope of the radio astronomer has been to probe even deeper in the Universe than his optical counterpart and to arrive at more definitive conclusions. To what extent has this been realized?

A first look at the modern radio-astronomer's canonical picture of the Universe suggests that he has a much clearer idea of what is going on than the optical astronomer. The picture is one of an evolving big-bang Universe in which the radio sources (which are the counterparts of the galaxies used in the optical cosmology) change their properties with epoch. For example the radio-astronomers have claimed to have shown that the radio sources were by and large more densely distributed in the past, they were smaller in size, and probably more luminous. This picture has emerged largely from the group of radioastronomers at Cambridge under the leadership of Sir Martin Ryle. The recent survey of angular sizes of radio sources by Swarup¹² and Kapahi¹² tends to confirm this view. Indeed, so readily is this view accepted by many astronomers that some theoreticians have worked out evolutionary scenarios in which the radio sources change according to the above canonical picture.

Yet, a minority of cosmologists (of which I am one) have misgivings about this picture. The weakest point in the entire argument is the inability of the radioastronomer to measure the distance of an extragalactic radio source. What the radio astronomer measures is the flux density, i.e., the amount of radiation received from the source in a given narrow band of frequencies per unit area per second. Then a formula analogous to (2) is used:

$$S = \frac{P}{D^2} \quad (15)$$

where P is the 'power' of the source, i.e., the radiation sent out by it in the narrow band of frequencies per second per unit solid angle.

If we know P , we know D , from (15). But do we know P ? Is there a standard candle as in the optical astronomy? Unfortunately not: P varies in a range of $10^{23} - 10^{28}$ units (unit = watts per steradian per Hertz) at typical radio frequencies. To take into account this variation the radio astronomer has to use the radio-luminosity function giving the number of sources per unit volume in a given range of P . The problem of interpreting data then becomes mixed up with sorting out the statistics. A change in the postulated radio luminosity function can change the cosmological conclusion drawn from the data. The same difficulty arises when interpreting the angular size data which requires the postulating of a linear size distribution function. These difficulties have been discussed extensively in a recent paper by S.M. Chitre and myself¹³.

Basically the point is as follows. If a radio source of linear size a is seen from a distance D , it will subtend an angle at the observer,

$$\theta = \frac{a}{D} \quad (16)$$

provided the geometry is Euclidean. In the non-Euclidean geometry of the expanding Universe (16) is replaced by

$$\theta = a f(z) \quad (17)$$

where $f(z)$ is a function of the red-shift z of the source. For small z , the distance $D \propto z$ and hence $f(z) \propto z^{-1}$ so that (16) and (17) agree. At large z , $f(z)$ does not vary as $1/z$. For the Friedmann Universe with $q_0=1/2$, the relation (17) is

$$\theta = \frac{aH}{2c} \frac{(1+z)^{3/2}}{(1+z)^{1/2} - 1} \quad (18)$$

Thus (18) shows that θ has a **minimum** at $z=1.25$, and for $z > 1.25$, θ **begins to increase with z** . This is a very unusual behaviour and the use of such a relation was suggested by Hoyle¹⁴ as a possible cosmological test. Fig. 5 shows theoretical curves for a number of models.

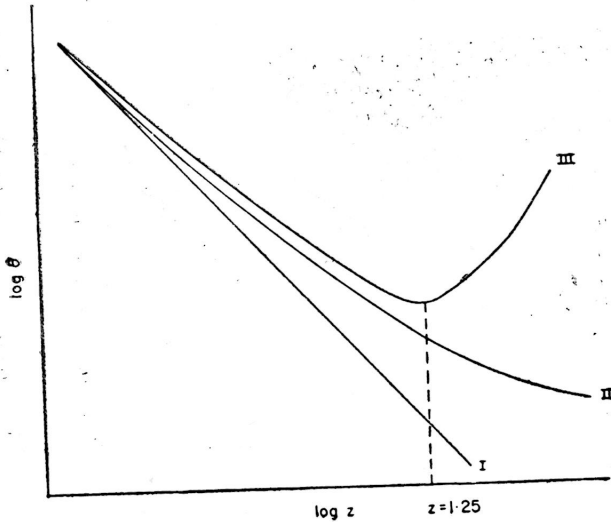


Fig. 5 The $\theta - z$ plot showing how θ changes with z for (I) Euclidean model, (II) the Steady model referred to later (III) the Einstein de Sitter model which has $k = 0$, $q = \frac{1}{2}$.

So much for theory. When we come to the hard reality of observations what do we find? First, the radio sources are not spherical. They have a general **linear** double structure of the type shown in Fig. 6. The so called 'linear size' a must therefore represent the separation of the two blobs A, B shown in the Fig. 6. However, with a linear structure it is not obvious that the quantity to go into (17) will always be a . In fact it will be $a_{\perp}$ the projection of a perpendicular to the line of sight. Depending on the alignment of the line AB with respect to the line of sight, $a_{\perp}$ will vary between 0 and a . Thus even

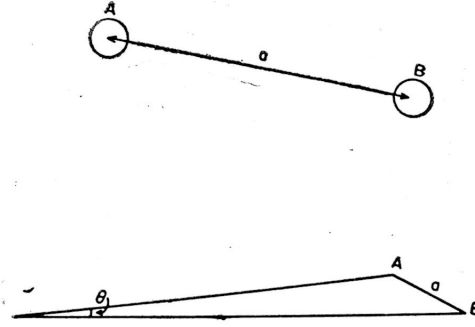


Fig. 6 A typical double radio source with components A and B. Below is shown the angle subtended by the source at a remote observing point.

if all sources had the same size a there will be a scatter round the expected relation (17).

In practice the situation is worse. First there is a good deal of variation of a from source to source (from 30 kiloparsecs to 5 megaparsecs). Second, the redshifts of very faint sources are not known. What is more easily known are their flux densities. Hence in practice it is more convenient to plot θ against S . This was done by Swarup and Kapahi (op. cit.) and their plot is shown in Fig. 7.

The high flux values refer to about 200 sources from the 3CR, the revised third Cambridge catalogue. The low flux values are of the (~ 160) sources from the Ooty survey. Swarup and Kapahi argue that at the low fluxes of the Ooty survey the red shifts z are larger than the values ~ 1.25 for minimum θ in (18) or similar values for other models with different q_0 . However, on the basis of the plot in Fig. 7 the median value of θ , θ_{med} is not showing any upturn. To explain this they postulate that the radio sources at large z are intrinsically smaller than the sources at small z . In particular, a relation

$$a(z) \propto (1+z)^{-n}, \quad n \sim 1-1.5, \quad (19)$$

which tells us that the 'a' - value at large z was smaller than the 'a' value at small z , gives a good fit to the (θ_{med} S) relation.

Nevertheless, I find the scatter in Fig. 7 to be too large to warrant this categorical conclusion. It is a well known dictum in statistics that an average is reliable only if the spread around it is small. This is far from the case in Fig. 7. Indeed, Chitre and I find that models **without** a size-evolution are also compatible with this plot within the normal statistical uncertainty.

To make the test more sharp it is desirable to establish the distances of the Ooty sources. In view of the controversial interpretation of redshift for quasars, it is desirable to restrict the test to radiogalaxies. The determination of redshifts by using the 21 cm line in radio

Naturally the cosmologist hopes that the QSOs will tell him a lot about the Universe, especially its remote past.

Unfortunately, the interpretation of z for QSOs is not so unambiguous as it is for galaxies. For the galaxies the $m-z$ plot shows a clear Hubble relation. It was this relation which led to the theory of the expanding Universe. Yet could any one on the basis of Fig. 8, have arrived at the Hubble law from the $m-z$ relation for QSOs? The reader is left to form his own conclusion.

There are a number of issues which I cannot mention for lack of space which enter into the present controversy. The majority of astronomers **believe** the red shift to be cosmological, i.e., arising from the expansion of the Universe. I have emphasized the word 'believe' because there seems to be a lack of objectivity in many of the discussions. This is shown by the inclination to doubt or ridicule any evidence which appears to go against this belief and the ready acceptance of any evidence for it. Certainly by the standards set by the laboratory physicist the case for the cosmological nature of the QSO redshift is not very firm. It should also be emphasized that so far no satisfactory alternative to the cosmological hypothesis has been found. My own view is that one should temporarily shelve one's 'belief' in cold storage and await more data before claiming to have resolved the controversy.

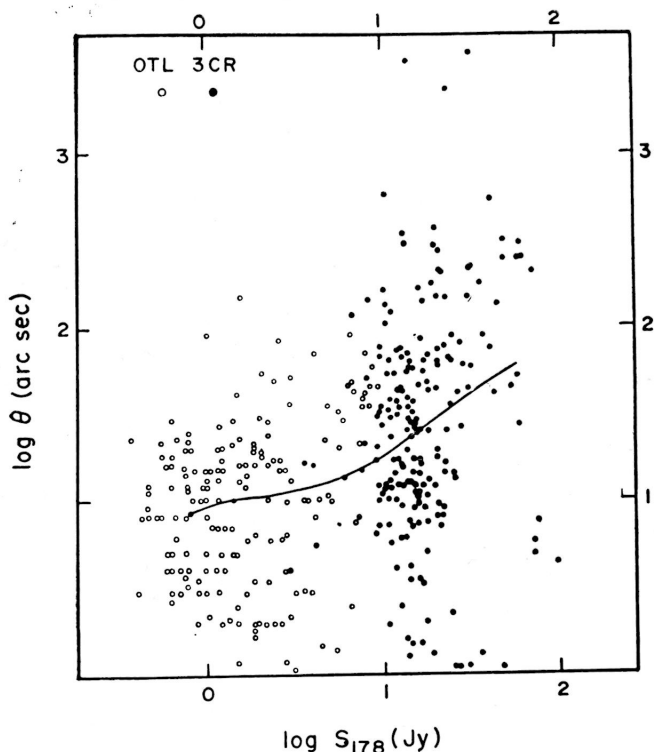


Fig. 7 The θ - S plot for the Ooty (OTL) and Cambridge (3CR) sources. The continuous curve is the (θ_{med}, S) curve.

astronomy is still in its infancy but it may be used more and more in the future. Meanwhile the astronomer must use the process of optically identifying the radio source with a galaxy and measuring the redshift of the latter. For such an identification the radio and optical positions must be very accurately known (see cover picture). What constitutes a 'proper' identification is still a matter of debate and this method is not as fast as one would like it to be. Still it is the best one available at present.

The Quasi Stellar Objects (QSOs)

As is apparent from Hubble's law, objects with large redshifts naturally are distant and hence are seen as they were a very long time ago. They are therefore expected to provide the information about the state of the Universe in the remote past.

In the late 1950's the radio source 3C-295 was identified with a galaxy whose redshift turned out to be 0.46. For a long time, throughout the 1960's and the early 1970's this was the record redshift for any galaxy. Only recently has this record been broken. In 1974, Spinrad identified the radio source 3C-123 with a galaxy of redshift 0.637. At the time of writing the largest galactic redshift is 0.752 for the radio galaxy identified with 3C-318.

Meanwhile a new class of objects have become known to the astronomer, with considerably higher redshifts. As their name indicates, the quasi-stellar objects (QSOs) are star like in appearance besides being very bright and usually with large redshifts. The largest so far known is $z=3.96$ for the QSO with the catalogue number 2142-75.

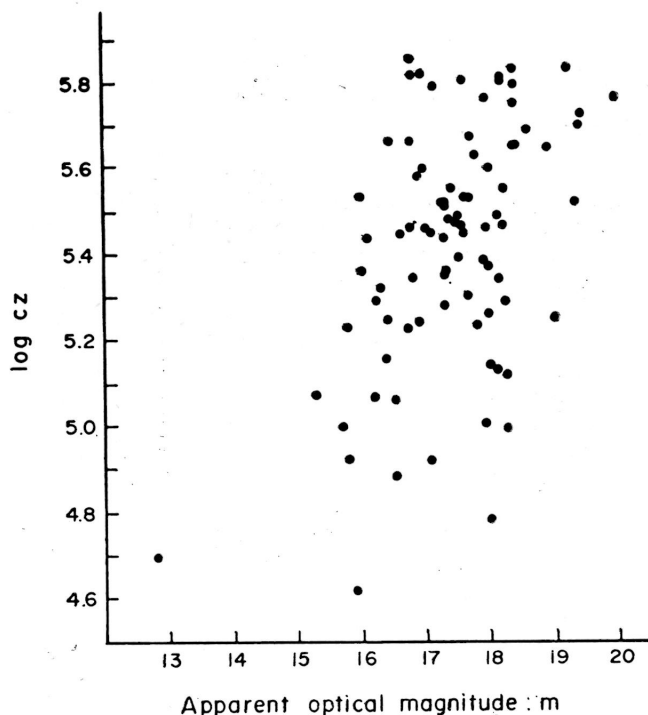


Fig. 8 The $m-z$ plot for the QSOs made in the late 1960s. Now some 600 QSOs have known z -values; but the $m-z$ plot shows no Hubble-trend.

I illustrate the situation with one example. Suppose a QSO is a radio source of redshift z and a double structure of the type shown in Fig. 6. Let θ be the angle subtended by AB at the observer, AB being perpendicular to the line of sight. Then if z is cosmological, we have the length AB as given by (on ignoring the non-

Euclidean corrections)

$$a \sim \frac{c}{H} z \theta. \quad (20)$$

If now θ is found to change with time, the velocity of separation of AB is

$$v = \frac{da}{dt} \simeq \frac{c}{H} z \frac{d\theta}{dt} \quad (21)$$

Now $d\theta/dt$ has been measured for a number of radio sources by the latest very long baseline interferometry (VLBI). In quite a few cases determined in this way v comes out to be greater than c .

What is one to make of this? Does faster than light motion exist in the Universe? Or are we encountering an illusion of some sort so that the apparent separation of AB is not the actual motion of physical objects? Or is the estimate $(c/H)z$ of distance wrong? If the QSO is closer than this distance the motion observed need not be superluminal. But this last possibility would mean that the cosmological interpretation of redshift is not valid. Further VLBI measurements may resolve the impasse and it would be interesting to see which of the above alternatives, if any, is correct.

The Microwave Background

The issues discussed so far have many uncertainties attached to their interpretation. I will now consider what is universally regarded as the strongest evidence for the big-bang.

In the late 1940's George Gamow had argued that the nucleosynthesis of elements could take place in the first few moments after the big-bang. For this Gamow required a 'hot' big-bang in which there was radiation with temperature $\sim 10^{10}$ °K just one second after the original explosion. This temperature falls off as the Universe expands, much as it would fall inside an adiabatically expanding black-body. What should be the temperature of this relic radiation at the present epoch? Nobody knew the answer. Gamow himself had made only a rough guess. But this much was clear that the relic radiation should have the character of a black-body.

It was very exciting therefore when in 1965, Arno Penzias and Robert Wilson¹⁵ reported the discovery of background radiation at 7 cm, which corresponded to a black body temperature of ~ 3 °K. Subsequent measurements at different wavelengths confirmed the long wavelength part (the classical Rayleigh-Jeans part) of the black-body spectrum. The current state of affairs is reproduced in Fig. 9. The black-body character of the curve will be confirmed only by observations in the microwave and long infrared range. The peak of the curve is at $\lambda \sim 1$ mm, corresponding to a temperature of 2.7 °K. At these wavelengths one has to rely on rocket observations above the atmosphere and technical difficulties have so far prevented settling the issue. Preliminary observations do seem to suggest a turn-over of the curve in the millimeter range.

There is an intriguing feature of the microwave back-

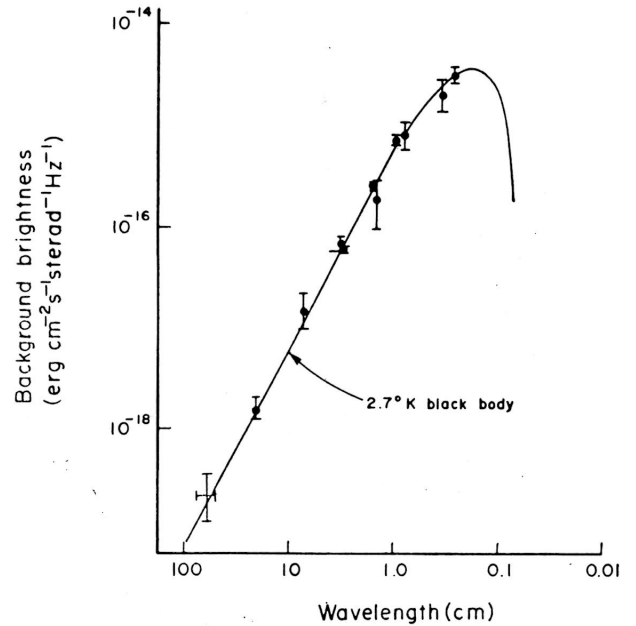


Fig. 9 The observed intensity distribution of the microwave background compared with the black-body curve at 2.7 °K. The turnover is suspected but not confirmed.

ground which needs to be pointed out. At $T \sim 2.7$ °K the radiation energy density is $\sim 4 \cdot 10^{-13}$ erg (cm)⁻³. This is comparable to the energy density of cosmic rays in the Galaxy, the energy density of starlight in the Galaxy and the energy density of galactic magnetic field. Yet none of these processes are of cosmological significance; they are usually associated with the astrophysical processes in our Galaxy. Why should the microwave background turn out to have the energy density of the same order? Personally I think that this is not a coincidence and it may turn out to be an indicator of something of deeper significance. It may well be that the association of the observed microwave background with the big-bang is altogether wrong.

However, for the present at least one does not have any satisfactory alternative explanation for this background. Until such an explanation is forthcoming or until the black-body character is not ruled out by observations the present interpretation will stand.

The Origin of the Universe

In 1948, H. Bondi¹⁶, T. Gold¹⁶ and F. Hoyle¹⁷ had proposed an alternative to the big-bang models. This is the well known steady state model which, as its name implies, postulates a Universe which is unchanging over a large time-scale. There are many aesthetic qualities in this model. It had many scientific merits and it also attracted considerable criticism. One particular criticism was that it violates the law of conservation of matter and energy. This comes about because, in order to preserve the density of matter (required by the steady state) in an expanding Universe new matter had to be created. Where did this matter come from? The proponents of big-bang considered this a major objection to the theory without realizing that it applied well to their models also. Where

did the matter come from when the Universe exploded into existence? At least, it was possible in the steady state theory to describe the phenomenon of creation **without** violating the conservation law of matter and energy¹⁸.

What is the present status of the steady state theory? At present the **only** unambiguous objection to it is that it cannot account for the microwave background. Until an astrophysical explanation for the background radiation can be found, this theory must be set aside.

No dramatic progress has been made in understanding the nature of the big-bang or how matter is originally created. The space-time singularity which is characteristic of the big-bang represents a breakdown of the laws of physics at $t=0$. That such a situation should arise in Einstein's general relativity has been considered one of its shortcomings. Can the singularity be averted by any artifact? So far no resolution of this difficulty is in sight in the conventional relativistic framework, classical or quantum.

A somewhat unconventional way out is indicated by the conformal gravitation theory of Hoyle and myself²⁰. This theory is more general than relativity in that it is invariant under conformal as well as coordinate transformations. Under a conformal transformation the space-time metric is multiplied by a scale function, Ω^2 so that the element of proper distance or time is multiplied by Ω . In the conformal theory this results in a transformation of particle masses

$$m \rightarrow m/\Omega \quad (22)$$

General relativity is the frame in which all masses are constant. However, is this the correct frame to use in practice?

If we consider Friedmann models we see that they are obtained by a conformal transformation from the flat space of special relativity. Thus in the conformal theory we can describe the Universe with the Minkowski space-time but with varying particle masses, which vanish at $t=0$. Now, when we transform to the constant mass frame by using (22) we see that the conformal function vanishes at $t=0$. **But this renders the conformal transformation invalid**, because it is always required that $0 < \Omega < \infty$. In other words, the Friedmann singularity at $t=0$ arises from the **wrong** choice of the conformal frame.

Is this result general? Does it hold with respect to kinds of singularities that arise in general relativity? Do all such cases result from the choice of an inadmissible conformal frame? This intriguing question is currently under investigation and preliminary work shows the answer to be in the affirmative²⁰.

Conclusion

In this brief survey of cosmology I have tried to summarize the difficulties faced by the modern cosmologist. There is no doubt that cosmology is now a full fledged branch of science. Yet it must never be forgotten that the cosmological observations will forever continue to have certain ambiguities of interpretation. The error-bars around the averages will be considerably larger than what the laboratory physicist would be happy with or what the observer himself may wishfully quote. The theories, unlike those of terrestrial physics, will have certain speculative elements and the theorist has to be very careful when drawing conclusions from any data. These are inherent difficulties of the subject which has set out to tackle the **biggest** problem in science.

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