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Modern Cosmology: The Harmonious and the Discordant Facts

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Six months before the meeting at Les Treilles, I gave an invited talk on observational cosmology to an international conference of relativists in Goa, India. Although at the meeting in France, we were discussing the more philosophical aspects of the way a beginning can be thought of, I believe it is worthwhile for us all to look critically at the modern evidence concerning cosmology. For this reason I reproduce below the text of the lecture that I gave in Goa. Some parts of this were discussed in Les Treilles.

1. INTRODUCTION

Modern cosmology rests on two major observational pillars—the law of the redshifts and the existence of the microwave background radiation—and a third observational fact, the existence of the light isotopes D, ^{3}He, ^{4}He, and ^{7}Li in abundances comparable with those being made in the first few minutes of a hot big bang.

I start by discussing each of these in turn.

1.1. The Redshift–Distance Relation

Hubble (1929) first demonstrated a clear relation between distance and redshift for nearby galaxies. Unfortunately, as we now know, many of the galaxies he used are too close. Their motions are dominated by local gravitational effects, and they are not representative of the overall Hubble flow. We also know now that the distance estimates for these galaxies were highly inaccurate. Hewitt and Burbidge (cf. Burbidge, 1981) replotted Hubble's original relation using the same galaxies, but the modern distance

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estimates. As can be seen from Figure 1a, it is not now clear whether or not Hubble would have claimed that there was a linear relation between velocity and distance had he known what the correct distances were. That he found such a relation (Figure 1b) from which it was widely deduced that the universe is expanding, using many galaxies which are not properly partaking in the expansion, again demonstrates that very good scientists are often also very lucky scientists.

In modern times, the linear velocity-distance relation has been under attack, particularly by Segal (1980), who has continuously claimed that the relation is of quadratic form as is expected in his chronometric cosmology. It is generally argued that this result is incorrect, and is due to selection effects, though this is vehemently denied by Segal.

Sandage and Tammann (1975), using the sizes of HII regions in a sample of Sc galaxies, none of which partakes significantly in the local departure from the Hubble effect, find that a good linear relationship does exist between redshifts and distances (Figure 2).

Extension of the redshift-distance relation has been continued over the last 60 years. It has been found empirically that the brightest galaxies in such clusters all tend to have the same luminosities, they can be used as

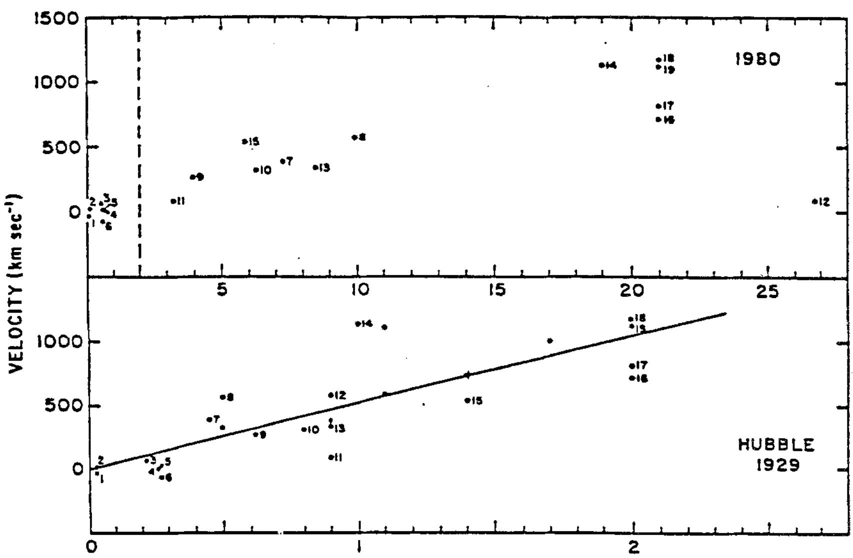

Fig. 1. In the lower panel the original diagram of Hubble is plotted and each galaxy is given a number. In the upper panel the diagram is replotted using the better distance estimates available in 1980.

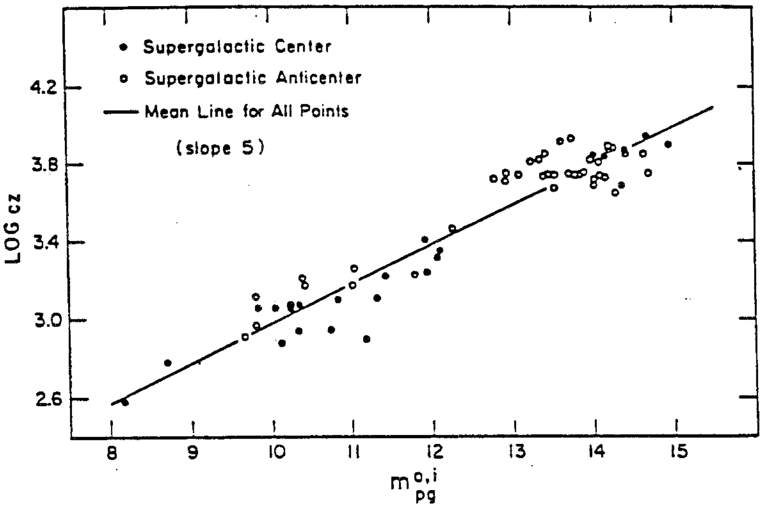

Fig. 2. Modern redshift-apparent magnitude relation for nearby galaxies, taken from Sandage and Tammann (1975).

"standard candles." Out to a redshift $z = 0.5$ it is found that the redshift-apparent magnitude (distance) relation is strictly linear. This in itself is an extremely important result.

The original result of Hubble was immediately interpreted as the observational evidence for an expanding universe following Lemaitre's and Friedmann's solutions to Einstein's equations. This implied that we are seeing a velocity-distance relation and that the redshift is a Doppler shift. Is this the case? Unfortunately, the direct test has never been successfully carried out. In the 1930s, Zwicky and others argued that the redshift-distance relation might be explained by the "tired light" hypothesis. This proposal was revived again in the 1950s by Born and others. The difficulties with the theory are well known—loss of energy in photon-photon scattering or photon-ion scattering, or Compton scattering, will lead to a blurring of the images of distant objects and this is not seen. However, a direct test can be made. If the redshift is a Doppler shift, the surface brightness of an extended source should fall off as $(1+z)^{-4}$, but in the tired light theory, the dependence goes as $(1+z)^{-1}$. This test has never been carried out successfully.

1.2. The Microwave Background Radiation (MBR)

In the 1950s, Gamow, Alpher, and Herman showed that a blackbody radiation field would be generated in a hot big bang. They estimated its temperature, but apparently did not consider that it could be detected. Dicke and his colleagues rediscovered the phenomenon and set out to detect it. In 1965, Penzias and Wilson discovered what we now believe to be this radiation field.

Given the prediction, this discovery was immediately heralded as the relic radiation. However, in the late 1960s, there were not yet measurements at enough wavelengths to demonstrate that the radiation had truly blackbody form. Thus, alternative explanations were put forward, in particular that the radiation was due to a large number of discrete sources which might be galaxies in earlier states of evolution, or diffuse radiation from hot dust. By 1980, there were enough measurements so that it could be fairly claimed that the spectrum is consistent with a Planck curve with a temperature 2.5–3.0 K.

Measurements near the peak of the curve in the range 1–5 mm are difficult to carry out, but precise measurements in the range from about 1 mm to 12 cm—the Raleigh-Jeans part of the curve—using both direct methods and spectroscopic measurements based on interstellar CN have led to the conclusion that the spectrum over this range is well described by a 2.75 K blackbody with distortions of less than 5%. At much shorter wavelengths in the range 1 mm–100 μm, recent rocket observations by Matsumoto *et al.* (1988) show a departure from the blackbody curve amounting to about 10% of the energy under a 2.75 K blackbody curve.

This distortion is large enough so that if it is to be maintained that the MBR arose in a big bang, the source of the distortion must be understood. The alternative possibility is that the MBR did not arise in a hot big bang. In this connection, it must not be forgotten that the energy density in the microwaves $\rho_{\rm mbr}$ is the same as that found in the starlight in our own galaxy. In fact, the result that

$$\rho_{\rm mbr} \simeq \rho_{\rm starlight} \simeq \rho_{\rm cr} \simeq \rho_{\rm gal.mag.field.} \simeq 0.4 \text{ eV}$$

remains one of the strangest results of cosmology, since at least some of these equalities must be accidental.

It should also be remembered that some workers, particularly Hoyle, have never given up the idea that the MBR arises from radiation of needle-shaped dust grains in the intergalactic medium. The existence of the MBR and the Hubble relation interpreted as being due to expansion are the two major pillars on which the belief in a hot big-bang (Friedmann) universe is based.

1.3. The Abundances of the Light Isotopes D, ^{3}He, ^{4}He, and ^{7}Li

While the theory of stellar nucleosynthesis explains the existence of nearly all of the isotopes, D and ^{7}Li are easily destroyed in stellar interiors, and there appears to be too much helium relative to hydrogen for it all to have been synthesized in stars through the age of the universe.

Thus, in 1964, first Hoyle and Tayler, followed in 1966 by Peebles, and in 1967 by Wagoner, Fowler, and Hoyle calculated the abundances expected in big-bang nucleosynthesis and compared these abundances with observation. In the period since then, there have been some improvements in the calculations and a great deal of work has been done on determining observationally the abundances of these isotopes. The general conclusion is that the predictions of the standard model with $N_\nu = 3$, $\tau_n = 10.6$ min are in agreement with the estimates of the primitive abundances derived from the observational data. The results are shown in Figure 3, taken from Boesgaard and Steigman (1985).

However, the baryon density is a key parameter in this conclusion, as is the value of the Hubble constant H_0. There is still considerable uncertainty in the value of H_0. It is well known that a debate concerning the value of H_0 has been underway for more than a decade, with the value lying between ~ 50 km sec^{-1} Mpc^{-1} and 100 km sec^{-1} Mpc^{-1}. It has become customary to put $H_0 = 100h$ km sec^{-1} Mpc^{-1}, and in the discussion to allow h to vary between 0.5 and 1. In my opinion, the strongest case has been made by

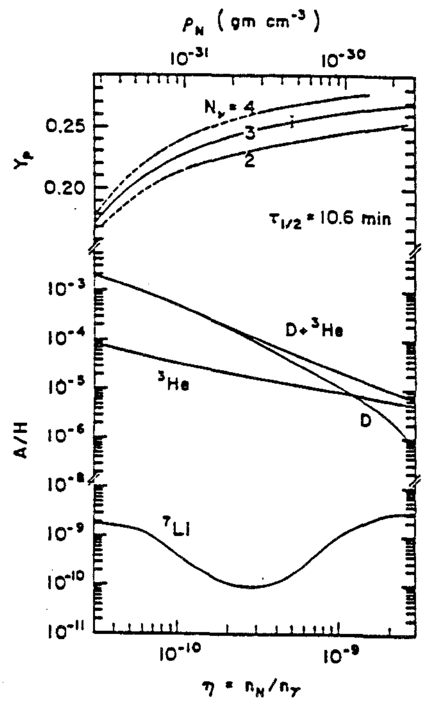

Fig. 3. Diagram taken from Boesgaard and Steigman (1985) showing the nuclear abundances versus the nucleon/photon ratio (lower abscissa) in the nucleon mass density (upper abscissa) divided by the cube of the temperature in units of 2.7°K. Note expanded scale for Y_P; the three curves are for $N_\nu = 2, 3, 4$ neutrino types. Neutron half-life is taken to be 10.6 min.

Sandage and his colleagues, who advocate the smaller value for H_0. Sandage (1988*a*,*b*) has recently given two separate analyses, leading to values of H_0 of 42 km sec^{-1} Mpc^{-1} and $\Omega_0 = 1$, and $H_0 = 55$ km sec^{-1} Mpc^{-1}, respectively. In what follows, I shall put $H_0 = 50$ km sec^{-1} Mpc^{-1}.

Using this value, one finds the critical (Einstein–de Sitter) density

$$\rho_c = \frac{3H_0^2}{8\pi G} = 1.88 \times 10^{-29} \text{ g cm}^{-3} \qquad (1)$$

The requirement that early nucleosynthesis produces enough, but not too much, D leads to upper and lower bounds, respectively, on the baryon density, and we find that

$$2 \times 10^{-31} \text{ g cm}^{-3} < \rho_B < 7 \times 10^{-31} \text{ g cm}^{-3}$$

Thus,

$$\rho_B / \rho_c = 0.01\text{–}0.02$$

It can also be seen from Figure 3 that the primordial abundance of ^{4}He cannot fall below a value $y \simeq 0.22$. This means that if it could be shown that the fraction of the observed helium which is primordial is less than 22%, it could not have been made in a big bang. As can be seen from Figure 3, the current best estimate is claimed to lie between 0.23 and 0.24.

It is the fact that, overall, the abundances of the light isotopes are compatible with big-bang nucleosynthesis that has led to the view that this is a third strong argument in favor of the Friedmann cosmology.

2. IS THE MAJORITY RIGHT?

For majority opinion to change on the correctness of the hot big-bang cosmology, it is clear that one or more of the arguments given above must be seen to fail. To most cosmologists, this appears, at present, to be very unlikely. However, if a change does occur, it will probably come from one of three directions:

a. A demonstration that the redshifts are not (all) Doppler shifts associated with the expansion of the universe.
b. A demonstration that there is another plausible mechanism which could be responsible for the MBR, probably related to the idea that it does not have a perfect blackbody spectrum and/or that it could not have been coupled to the matter at an earlier epoch.
c. Revised abundance determinations for the light isotopes which lead to the conclusion that they could not have been made in early nucleosynthesis.

I shall return to evidence for these heretical statements after I have discussed how far the observations allow us to refine the conventional model.

Accepting the general relativistic models, the observational data can in principle allow us to discriminate among models as was first described by Robertson more than 50 years ago (Robertson, 1933) and in more detail by Sandage (1961).

We have several observational ways to determine q_0 and the mass-energy density in the universe ρ_0. In addition, other observational quantities are the ages of the oldest objects which we can find in the universe. In all evolutionary models, the age of the universe t_0 must be greater than or equal to the ages of the oldest stars or the elements.

3. THE DECELERATION PARAMETER q_0

3.1. Determination of q_0 from the Hubble Diagram

The classical method to determine q_0 is to use the Hubble diagram. Mattig (1958) and Sandage (1961) showed that the apparent magnitude is given by

$$m = \text{const} + 5 \log z + 1.086(1 - q_0)z + O(z^2)$$

Thus, the Hubble relation is strictly linear to first order in z only if $q_0 = +1$.

As was stated earlier, the observational data suggest that the Hubble relation is linear out to about $z = 0.5$. The difficulties which have been encountered in first demonstrating a departure from linearity in the observational data, and then determining a value for q_0, have stemmed from several factors. Originally the problem was to find very faint galaxies at large redshifts. Modern techniques have to some extent solved this problem (Gunn *et al.*, 1986). Also, optical identification of strong radio sources in the 3C catalogue has progressed remarkably in the last decade. Most of the galaxies have had redshifts determined, and many of them have redshifts ~ 1 or greater (Spinrad *et al.*, 1985).

Thus, we can now plot Hubble diagrams going out far enough in z so that departures from linearity can be measured. For many years, the most serious difficulty has appeared to be the problem of galaxy evolution, i.e., when we look back to large redshifts we are seeing the galaxies as they were several billion years ago, and these standard candles "then" are less evolved than the standard candles "now." To take into account this evolution, model calculations have to be made, and into these models we have to put on a star formation function and trace its evolution in time.

If we restrict ourselves to the brightest cluster galaxies, the results are still very disappointing. Gunn *et al.* (1986) have pointed out that the formal value of q_0 still differs by 2 in the recent analyses. They attribute this uncertainty to the lack of a properly chosen selection of both bright and faint clusters to measure, the difficulty of observing accurate redshifts and magnitudes for such faint objects, and the uncertainty in the evolutionary correction just referred to. Use of radio galaxies has possibly led to more progress. Both Spinrad and his colleagues (cf. Spinrad and Djorgovski, 1987) and Longair and his colleagues (cf. Lilly and Longair, 1984) have studied such samples.

Figure 4 is a plot from Spinrad and Djorgovski (1985) combining 3CR galaxies and brightest cluster galaxies with magnitudes measured in the visible region. The data are plotted against two cosmological models for $q_0 = 0$ and $q_0 = 0.5$, respectively, and two galaxy evolutionary models calculated by Bruzual. It can be seen that the observations do not allow us to discriminate between these models.

If the galaxies are observed in the near infrared, near 2 μm, the light is largely coming from very old stars, so that changes in luminosity due to evolution in the stellar content are minimized. Figure 5 shows this Hubble diagram. From this, Spinrad and Djorgovski "chose" a value of $q_0 = 0.2$, $\lambda = 0$, to give the best fit.

It is clear that the large-redshift radio galaxies are much brighter than the brightest cluster galaxies at low redshifts. Either this apparent increase in brightness is due to luminosity evolution as has just been described, or it indicates a much larger value for q_0; i.e., it is due to the geometrical structure of the universe. Wampler (1987) has chosen to believe in a much

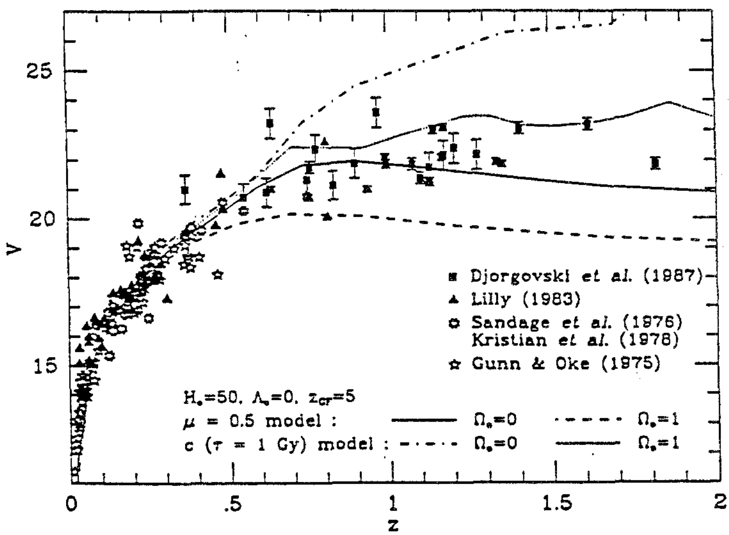

Fig. 4. Hubble diagram for 3CR radio galaxies and brightest cluster galaxies using visual magnitudes, together with the curves expected for various theoretical models (Spinrad and Djorgovski, 1985).

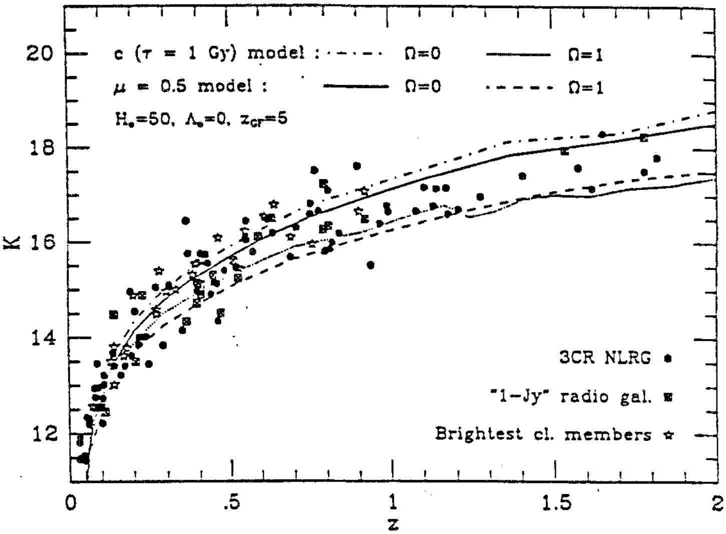

Fig. 5. Hubble diagram for 3CR radio galaxies and brightest cluster galaxies using K-band (near-infrared) magnitudes together with theoretical curves (Spinrad and Djorgovski, 1985).

larger value of q_0. He has argued that both radio galaxies and QSOs (Wampler and Pons, 1985) give a well-defined Hubble relation if the Baldwin luminosity criterion is used to correct the observed magnitudes of the QSOs. Plotting them together, the raw data give a value of $q_0 \simeq 3$ (Figure 6).

Such large values for q_0 lead to more problems. For a model with $\lambda = 0$ and $q_0 \simeq 3$, $t_0 \simeq 0.4 H_0^{-1} \approx 8 \times 10^9$ years. Furthermore, the density is

$$\rho_0 = \frac{3H_0^2}{4\pi G} q_0 = 6\rho_C \tag{2}$$

Thus, the density is far higher than the baryonic density required if the light elements are made in a hot big bang.

To avoid the problems of the short lifetimes and large densities, Wampler and Burke (1987) have gone to models with nonzero λ. They find then acceptable fits for values of $H_0 t_0$ between 0.65 and 0.8.

3.2. Determination of q_0 from the Angular Diameter–Redshift Relation

Hoyle (1959) showed that the angular diameter of a standard object $\theta(z)$ has a comparatively strong dependence on q_0. The metric diameters decrease more slowly than $\theta \propto z^{-1}$, and reach a minimum which depends on the value of q_0. This measurement has been attempted for the first ranked galaxies in clusters by Djorgovski and Spinrad (1981). There is no indication of a turnup at the largest value of z (~ 1) measured. Much more work has

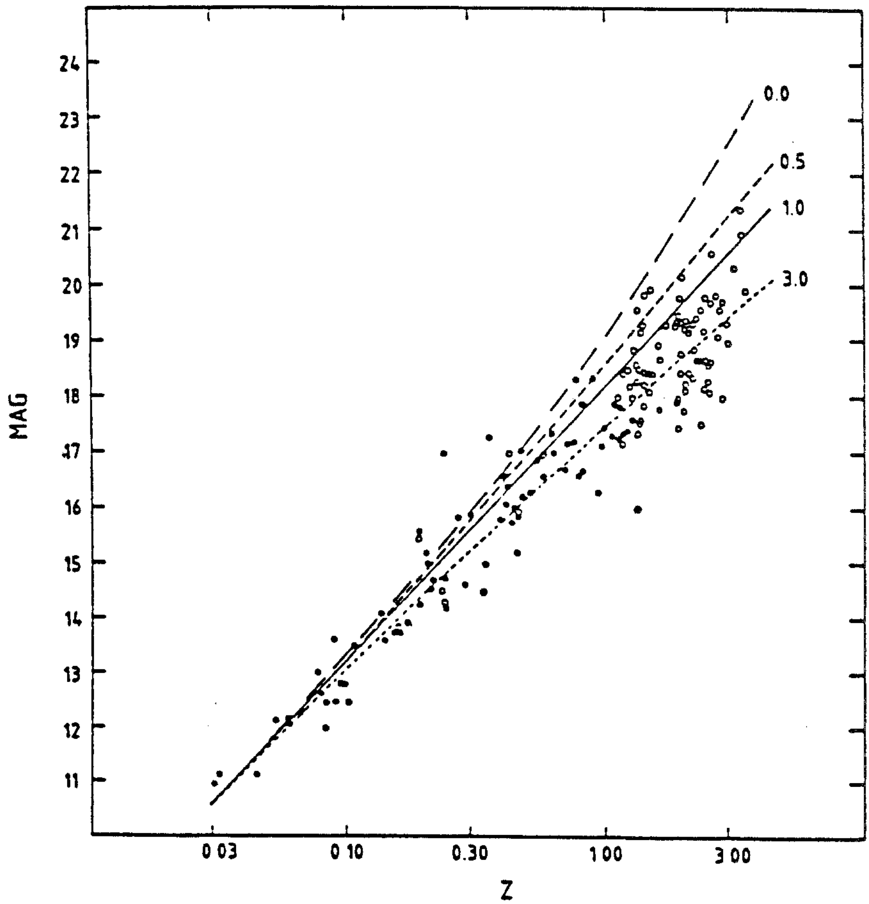

Fig. 6. Hubble diagram for 3CR radio galaxies and QSOs (corrected using the Baldwin effect) plotted by Wampler (1987), with theoretical curves corresponding to different values of q_0.

been done using as a standard metric diameter the separations between double radio sources. Using the redshifts for radio galaxies or QSOs with which these radio sources were identified, we can go to much larger values of z than has been possible so far for galaxies. However, as can be seen from the work of Kapahi (1987) and earlier references, no departure from linearity is seen i.e., the relation which is found is $\theta \propto z^{-1}$, as would be expected in Euclidean space. Thus, this test does not work.

This remarkable result is usually explained as being due to the evolution of the double source separation as a function of z. If the separation $l(z) \propto (1+z)^n$, then, as Kapahi has shown, for $q_0=0$ to $q_0=0.5$ the data can be fitted for values of n in the range $n=1$ to $n=2.5$.

3.3. Determination of q_0 from the Mass Energy Density

Since for $\lambda = 0$ we have simple relations between ρ_0 and q_0, we can obtain estimates of q_0 by measuring the mass energy density in galaxies. This is done for individual galaxies by measuring either the rotation curves for spiral galaxies or velocity dispersions in elliptical galaxies to derive masses (cf. Burbidge and Burbidge, 1975). Alternatively, statistical mass determinations can be made for pairs of galaxies assumed to be bound, or groups and clusters of galaxies through the virial relation. These methods have all been discussed by Faber and Gallagher (1979). From such analyses, we can obtain average masses and then mass-to-light ratios (in solar units). By then counting galaxies comparatively nearby and assuming isotropy and homogeneity it is possible to estimate the space density of galaxies and hence determine ρ_0. The energy density in radiation and high-energy particles and in diffuse matter is negligible compared with the mass energy density in galaxies. The flat rotation curves of spiral galaxies indicate the presence of unseen matter whose amount it is difficult to estimate. In bright spirals where the "visible" matter may amount to about $5 \times 10^{10} M_\odot$ it has often been supposed in modern times that "dark" halos with masses $\sim 10^{12} M_\odot$ may be present, though such large masses are not demanded to explain the rotation curves. Estimates of the masses of clusters from the virial theorem always lead to the conclusion that there must be a large amount of dark matter present, often about ten times the visible mass. If we concentrate on the luminous matter alone, we conclude that the density is of the order of 3×10^{-31} g cm^{-3}, so that if this were all that were present, a value of $q_0 \simeq 0.03$ is indicated. Even if we allow for a significant amount of dark matter, e.g., that indicated from the virial argument in clusters, the value of q_0 will only be increased to $q_0 \simeq 0.1$–0.3. The lower value is clearly about the same as the value required if the light isotopes came from the hot big bang.

If there is a great deal of dark matter of baryonic form so that $\rho \simeq \rho_c$, then there is a difficulty with the production of the light elements. This is one of the reasons why it has been proposed that the dark matter is nonbaryonic. Since there is no observational evidence for this apart from the argument just given, I shall not pursue that line of discussion further here. However, it might be added that recently it has been argued that the light isotopes could be produced in a universe at critical density if there were nonlinear fluctuations in the neutron–proton ratio (Alcock *et al.*, 1987).

3.4. The $N(m)$ test for q_0

Hubble (1936) attempted to measure the curvature of space by obtaining the counts of galaxies $N(m)$ as a function of proper volume. He found a large departure of the observed $N(m)$ curve from 0.6. He thus concluded that either the curvature was very large or that the redshifts were not due to expansion. However, he was mistaken, because he did not use the correct expression for the distance as a function of the curvature, which was worked out later by Mattig (1958). Hubble had put $d \propto cz$ for all values of the curvature. When the analysis is carried out correctly, it turns out that $N(m)$ is independent of q_0 to first order in z, and it only enters in terms of order z^2. Thus, the $N(m)$ test is quite insensitive to q_0. However, $N(z)$ is sensitive to q_0 in first order, and therefore counts of all objects to a given z may in principle be used to determine q_0. Modern work on the $N(m)$ test has born out these conclusions. It has been used largely to look for luminosity evolution in galaxies (cf. Ellis, 1987) and it tells us little about q_0.

Loh and Spillar (1986) and Loh (1987) have measured the redshifts and fluxes of a flux-limited sample of galaxies and have claimed the geometry and the effects of evolution can be separated. They believe that their results are compatible with the Einstein–de Sitter model $k=0$, $\rho=\rho_c$. One problem with their method is that the redshifts are measured photometrically, so that there is considerable uncertainty in the values they obtain. Also, the effect of large galaxy concentrations and large galaxy voids is hard to estimate.

Another approach has been to use the absorption spectra of QSOs. It is widely believed, but not by any means proved, that the large numbers of Ly α lines, often known as the Ly α forest, which are found in the spectra of high-redshift QSOs shortward of Ly α emission are due to intervening clouds. If these clouds do not themselves evolve in time, and if the redshifts are of cosmological origin, then it can be shown that for zero cosmological constant, the number $N(z)$ depends on the geometry so that

$$\frac{dN(z)}{dz} = N_0(1+z)(1+2q_0 z)^{1/2} \tag{3}$$

where N_0 is the value of $N(z)$ for $z=0$. The effective cross section of a cloud and the number density of clouds per unit volume may also be functions of z, i.e., N_0 may vary with z.

Attempts have been made to determine $dN(z)/dz$ observationally by putting equation (3) in the form

$$\frac{dN(z)}{dz} = \text{const} \times (1+z)^{\gamma} \tag{4}$$

where

$$\gamma = \frac{1+q_0 z - q_0}{1+2q_0} \tag{5}$$

Then, for values of $q_0 = 0$ and 0.5, $dN(z)/dz = (1+z)$ and $(1+z)^{1/2}$, respectively. However, it is found observationally (Murdoch *et al.*, 1986) that the Lα clouds show a dependence of the form $dN/dz \propto (1+z)^{2.17}$ and this is too strong a dependence on $(1+z)$ to be fitted by any value of q_0. Thus, evolution in the number density and cross sections is implied, and once again the method fails to determine q_0 unless we know independently the form of the evolution.

Attempts have also been made to derive a value for q_0 by looking at the value of $dN(z)/dz$ for Lyman limit systems—those which show a discontinuity at the Lyman limit—meaning that they are the high-density part of the distribution of absorbing systems which are thought to be intervening galaxies. In this case (Snijders and Tytler, 1987) it is found that the data are compatible with a value of $q_0 = 0$, but not with $q_0 = 0.5$.

3.5. Summary

None of the observational methods of determining q_0 leads to results which we can take very seriously. Within the framework of models with $\lambda = 0$, a small value of q_0, $0 < q_0 < 0.5$, can be made compatible with most of the observations, provided we assume that evolution in time of the objects being observed, luminous galaxies, radio galaxies, QSOs, or the sizes of radio sources, is taking place with the correct dependence on z. However, other alternatives are clearly possible.

4. THE AGE OF THE UNIVERSE AND AGES OF THE STARS AND THE ELEMENTS

In all evolving models it is obvious that the age of the universe must be greater than or at least equal to the ages of the oldest objects in it. Forty years ago, when the value of the Hubble constant was stated to be 550 km sec^{-1} Mpc^{-1}, so that H_0^{-1} was less than 2×10^9 years, the contradiction between this age and the ages derived from geochronology was one of the principal motivations for the steady-state cosmology.

Today, we have two methods of determining ages. We can determine the ages of the stars, and the ages of the elements. The ages of the stars are determined by fitting models to the color magnitude diagrams for clusters of stars.

Using the globular clusters, Iben and Renzini (1984) showed that

$$\log t_G = 1.071 - 1.88(Y - 0.3)$$

where Y is the primordial helium abundance described in Section 3. Using the most accurate value for Y yet claimed ($Y = 0.232 \pm 0.004$) (Pagel *et al.*, 1986), we find that

$$t_G = 15.8 \pm 2.4(1\sigma) \times 10^9 \text{ years}$$

It has recently been proposed that mass loss may be important in the early main-sequence lives of globular-cluster stars (Wilson *et al.*, 1987). If this is the case, they conclude that the ages may be significantly less than the value given above. It also may be possible to determine the age of the galaxy from measuring the frequency of white dwarfs as a function of luminosity. Winget (1987) has shown that the density of white dwarfs increases rapidly with decreasing luminosity, and then shows a sharp cutoff. If the luminosity at cutoff is a measure of the ages of the oldest white dwarfs, then this suggests an age of about $9.3 \pm 2 \times 10^9$ years.

Ever since it was established that the elements are made in the stars, estimates of the age of the heavy elements using the methods of nuclear cosmochronology have been made. The isotopes which we used are ^{232}Th, ^{235}U, and ^{238}U, all of those parent nuclei are made in the *r*-process in supernovae. It is supposed that they are made steadily in supernovae until the material out of which the solar system formed was segregated 4.6×10^9 years ago. Since the first determinations by Burbidge *et al.* (1957), the calculations have been revised several times and Fowler has done the most extensive work. In his most recent studies (Fowler, 1987) he has concluded that the age of the elements is $11.0 \pm 1.6(1\sigma) \times 10^9$ years. In Section 1, I chose a value of the Hubble constant of $H_0 = 50$ km sec^{-1} Mpc^{-1} corresponding to $H_0^{-1} = 19.5 \times 10^9$ years. It is obvious from the discussion of the other age determinations made above that provided $H_0 \leq 50$, the ages of the oldest stars and the elements are less than H_0^{-1}. For the Einstein–de Sitter model, $k = 0$, $\rho = \rho_c$, $t_0 = 2/3H_0 = 13 \times 10^9$ years and this marginally accommodates the age determination for the globular clusters.

Closed-universe models, e.g., $k = +1$, $q_0 = +1$, give $t_0 = 0.57 H_0^{-1} = 11.1 \times 10^9$ years. This is much harder to accommodate to the ages derived above. Larger values of q_0 than 1 are suggested by the work of Wampler. They can only be accepted if we go to Lemaitre models with nonzero values of λ. Larger values of H_0 would obviously force us in this direction also.

The current prejudice is to believe in an Einstein–de Sitter model with critical density ρ_c. However, as shown earlier, there is no real evidence that the critical density of matter is present. This problem will briefly be discussed in the next section.

5. WHAT ABOUT INFLATION?

Clearly the most popular view among cosmologists at present is that we live in an Einstein–de Sitter universe with critical density. As shown earlier, the observational evidence is compatible with a small value of q_0, but there is no observational evidence that compels even this view. Even more remarkable, while the search for missing mass has been very extensive, no one except Loh and his colleagues has provided any observational evidence for the critical density.

The arguments have all come from the inflationary models. It is not my intention to describe inflationary models here, but a few comments are in order.

As is well known, inflation has been proposed by Guth and enlarged on by many others to solve the so-called flatness problem and the so-called horizon problem. The first of these is based on the result discussed earlier. The mass density which is found to be present is a few percent of the critical density ρ_c, where ρ_c is what we expect if the universe is flat. This has struck many people as a very remarkable result, because there is no apparent reason why the density should have any particular value, and certainly not a value very close to, but not exactly, the critical value. If we look at the way the density has evolved with time, this leads to an even more difficult problem, because a current value of $\rho \approx 0.1\rho_c$ means that when the universe was only 1 sec old, it was flat to within one part in 10^{15}, and at $t = 10^{-35}$ sec, when all of the forces acted as one, the universe was flat to within one part in 10^{50}. To me, this means that the problem is one of initial conditions, and since it is not accessible, it is metaphysical in origin. I take a similar approach to the second problem, the horizon problem, which was first discussed by Rindler more than 30 years ago. By simply examining the horizon as a function of epoch, Rindler showed that as we go back in time, a smaller and smaller fraction of all of the photons in the universe could be observed, 10^{60} out of 10^{87} at 1 sec, only about 10^{6} out of 10^{87} at 10^{-35} sec, and at the Planck time, 10^{-43} secs, none was within the horizon. Thus, as we go back in time, a larger and larger fraction of the universe was unobservable, and since the particles would not communicate, there was no way to smooth out any irregularities. Thus, we are forced to the conclusion that if the universe is homogeneous and isotropic now as we believe it is, this is because it was created this way. This, again for me, means that we must believe that this initial condition is a metaphysical construct. Many physicists reject metaphysical arguments, and this is where Guth's inflation comes in. By supposing that a sudden expansion took place at $t \simeq 10^{-35}$ sec, lasting for about 10^{-30} sec, Guth and his followers showed that these two conditions, the flatness and the isotropy, could be "explained".

But since there is no way of testing the inflation hypothesis by direct observation, it has always seemed to me that it also is an idea with only a metaphysical basis. It is unfortunate at least that the inflationary idea has been so widely accepted primarily because it is an elegant mathematical solution to a problem, without sufficient attention being paid to the fact that it solves a problem which may not be a real problem at all, and which certainly cannot be proved to be one. Yet another aspect of the bandwagon approach to cosmology is the fact that the only good account of the anti-inflationary thesis, by Rothman and Ellis (1987), has been relegated to a popular journal.

There is another aspect to the current approach to evolutionary cosmology which has always struck me as remarkable. It is customary nowadays to attempt to develop the theory of the evolution from 10^{-43} sec, onward, and it is the early epochs which have attracted the particle physicists so much. Everything is expected to evolve as a function of time *except the laws of physics*. These are considered immutable. If they were not, then it would not be possible to carry out work in this field. But, there is no evidence that they remain constant or that they have not changed with time. Thus, we have two immutables, the act of creation itself and the laws of physics which came fully fashioned and complete in the act of creation. What physicists are really saying, I believe, is that the laws of physics equate to God.

What bearing does all of this have on the observed universe? In my view, it has none. Thus, any conclusions which stem from the inflationary ideas, for example, that $\rho = \rho_c$, and therefore that there is a large amount of nonbaryonic matter present, should not be taken too seriously unless or until some direct astronomical evidence for its presence is found.

6. THE LARGE-SCALE STRUCTURE OF THE UNIVERSE

It has long been known that the luminous matter in the form of galaxies is not distributed uniformly, but is heavily clustered. In modern times, a good deal of work has been done on this distribution. Following the pioneering work of de Vaucouleurs, it is now generally accepted that our galaxy lies in the outer regions of a supercluster with the Virgo cluster approximately at its center. Many more superclusters with sizes ~ 10 Mpc or greater have been identified. Structure on larger scales than this has also been found. In particular, the redshift surveys carried out over the last few years by several groups (Chincarini and Vettolani, 1987; Geller *et al.*, 1987) show that very large scale structures exist in which the galaxies lie on the surfaces of bubblelike structures. These sheets are very thin corresponding to redshift differences $\Delta V \leq 500$ km sec^{-1}, and contain voids where there is almost complete absence of bright galaxies. It is not my intention to discuss these results in any detail. The main thrust of modern research in this area has been to construct a theory of galaxy formation which is consistent with these results.

The fundamental difficulty is, of course, that within the framework of the hot big-bang cosmology, this extremely lumpy distribution of visible matter was once strongly coupled to the microwave background radiation which is extremely smooth and in which, so far, no fluctuations on any scale have been firmly established.

While all of these theories rely on the idea that the galaxies originated from quantum fluctuations at an exceedingly early epoch, it is argued that the fluctuations expected in the microwave background will be reduced if there is an underlying density of nonbaryonic matter (much favored by those who believe in inflationary models) and by the so-called biased galaxy formation. However, it appears that we are on the verge of a critical test, since the fluctuations due to galaxy cluster formation should be detectable on a scale of ~10 arc min with an expected $\Delta T/T \simeq 2\times 10^{-5}$.

Another problem which has been raised for the conventional theory is the existence of ordered motions of order 500–1000 km sec^{-1} of large numbers of galaxies extending over hundreds of megaparsecs, motions which can be separated out from the Hubble expansion (Rubin *et al.*, 1973; Lynden-Bell, 1987). These motions are currently being interpreted as infall, due to a very large (unseen) mass (Lynden-Bell, 1987). They are very hard to understand in terms of the current theories of galaxy formation.

This concludes my discussion of the observations interpreted in terms of a hot big-band model. In the next section, I briefly summarize the observations which are normally left out when the conventional models are discussed, but which must be taken into account at some stage.

7. THE ANOMALOUS REDSHIFT PHENOMENA

I mentioned in Section 1 that it has never been proved that the redshifts of normal galaxies are Doppler shifts and how this could be tested. However, the existence of a smooth Hubble relation for luminous galaxies strongly suggests that for these objects, the majority of the redshift is of cosmological origin, and is due to the Doppler shift.

In general, if z_0 is the observed redshift, z_c is the cosmological redshift, z_r is the redshift due to random motion (or local gravitational effects), and z_i is a redshift component due to some intrinsic property, then

$$(1+z_0)=(1+z_c)(1+z_r)(1+z_i)$$

For the very luminous galaxies, the very existence of the Hubble law suggests that

$$z_c \gg z_r, \qquad z_c \gg z_i$$

However, this does not appear to be the case for all classes of extragalactic objects.

7.1. Quasistellar Objects

These objects, first discovered in 1960, characteristically have very large redshifts, ranging from $z \approx 0.1$ to $z \approx 4.4$. Their Hubble diagram shows a very large scatter (Hewitt and Burbidge, 1987).

There is a considerable amount of evidence suggesting that large parts, if not all, of the redshifts of many of these objects are not due to the expansion of the universe, i.e., that $z_i \gg z_c$, $z_i \gg z_r$. The observational evidence has accumulated since about 1970, and much of it has been summarized by Burbidge (1981) and Arp (1987), who is himself responsible for a great deal of the work. The essential point is that QSOs are rare in the sky compared with galaxies. Thus, with about 3500 objects with redshifts known and on the average very large, very few are expected to be physically associated with bright galaxies. However, several cases of QSOs with distinct connections to galaxies with very different redshifts have been found, the best case being Mk 205 and NGC 4319, while very many apparent associations between bright galaxies (with small redshifts) and QSOs (with large redshifts lying close to them) have been found.

Statistical arguments strongly suggest that the associations are real. In some cases, several QSOs are found in one galaxy; e.g., NGC 1073, in which three QSOs have been found within 2 arc min of its center. In addition to this, there is evidence of alignments of QSOs with very different redshifts presumably ejected from nearby bright galaxies.

Finally, patterns in the values of the observed redshifts, involving peaks and periodicities in the redshift distribution, are present, and these are not expected in normal cosmological models.

On the other side, there is also some evidence, particularly for low-redshift QSOs, that some of these may be the nuclei of galaxies with the same redshifts. These cases support the idea that these objects have cosmological redshifts. Thus, it appears that QSOs can have a wide range of values of z_i, from very small values, close to zero, to values such that they are the dominant quantity in the observed redshift.

7.2. Galaxies

In the early 1970s, Tifft [see Arp (1987) for many references] showed that the differential redshifts of galaxies in some well-known clusters appeared to be quantized with the quantum unit equal to $c\ \Delta\lambda/\lambda =$

72.5 km sec^{-1}. Later, he found the same effect in the differential redshifts of pairs of galaxies (Tifft, 1982*a,b*), and Arp and Sulentic (1985) have shown that the same effect is present in small groups of galaxies when differences are taken between the brightest galaxy in the group and each satellite system.

Arp (1987) has found a number of cases of galaxies with very different redshifts, apparently physically connected with luminous bridges, the most famous of these being NGC 7619 and its companion, where the redshift difference is $c\ \Delta\lambda/\lambda \approx 8000$ km sec^{-1}. In addition, he has described other evidence of physical associations of comparatively nearby spirals with very different redshifts.

Thus, it appears that some galaxies may also have intrinsic redshift components. However, in the cases in which the evidence is the strongest, z_c is small and may amount to hundreds or thousands of km sec^{-1} measured in units of cz_i. This result may have tremendous repercussions. For example, if appropriate parts of the redshift of galaxies in the extensive surveys were reinterpreted in this way, the large-scale structure would disappear, and the galaxy distribution could really be structureless.

8. CONCLUSION

Sixty years after Hubble's original demonstration of expansion, and more than 20 years after the discovery of the microwave background radiation, these are still the strongest pieces of evidence which support the view that we live in a Friedmann universe. In zeroth order the hot big-bang model looks good, but after many attempts, we still have no really good observational evidence concerning the true value of q_0, whether the universe is open or closed, or whether or not the cosmological constant is zero. There is a great deal of theoretical belief, but no solid results.

There is another major problem. While it appears very likely that the redshifts of normal galaxies are due to the expansion of the universe, the redshifts of many of the QSOs and some parts of the redshifts of normal galaxies may very well not have this origin.

These two major conclusions—that we live in a Friedmann universe, but that some objects in it have noncosmological redshifts—are not necessarily in conflict. What it does mean, of course, is that discussions of the universe at high redshifts which are based on observations of QSOs and related objects cannot be taken seriously. However, we must try to understand the nature of this new redshift phenomenon. This may lead us to open Pandora's box. This in turn might lead to new cosmological models. Only the future will tell.

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