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The Evolution of Alternative Cosmologies

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1. Introduction

Cosmology is the subject dealing with the origin, structure and evolution of the universe. Today the studies in the subject are largely driven by the observed facts about the universe and by theories based in physics. Nevertheless cosmology has indeed a long history, since records of most civilizations from the very ancient times indicate that man has always liked to speculate on these questions. While these speculations were based largely on philosophical ideas with very little contribution from facts, there is one trait which the cosmologists of old seem to share with their modern counterparts, viz. their fond wish that the mystery of the nature of the universe would be solved in their lifetime. This trait has often led to categorical views about the state of the universe, that later had to be withdrawn or were quietly forgotten, thus inspiring the caustic comment: "*Cosmologists are always wrong but never in doubt*".

Modern cosmology, really took off in the early decades of the twentieth century. The theoretical inspiration for mainstream cosmology came from the general theory of relativity of Albert Einstein, while its observational foundations rest upon the Hubble law. Different aspects of this cosmology have been described in a historical vein in other talks in this School.

In the present talk we will briefly review the progress of alternative ideas in cosmology, ideas that differed from the mainstream viewpoint which has largely been controlled by the standard big bang cosmology. Alternative ideas have been proposed from time to time by scientists for various reasons, including a desire for better logical structure, fewer assumptions, improved performance on the observational front than the mainstream cosmology. However, before coming to the specific ideas, a few general remarks may be in order.

What is called "mainstream" or "standard" and what is called "alternative" may change with epoch! Two examples will illustrate this truism. Prior to 1900, indeed even during the first decade of the 20th century, the mainstream belief was that the Solar System is at the centre of the Milky Way. Accurate distance measurements of stars and globular clusters in the Galaxy by Harlow Shapley led to the ultimate realization that the alternative view, namely that the Sun and its planets are situated well away from the Galactic Centre, is correct. The distance of the Solar System from the centre of the Galaxy is around 30,000 light years, about two thirds of the visible galactic disc.

The second example relates to the extragalactic nature of diffuse nebulae. Unlike stars which are concentrated sources of light, these nebulae are extended cloud-like structures. Many such nebulae had been seen and many more photographed by the second decade of the 20th century. The majority view was that all these represent objects *within* the Galaxy. Indeed Shapley himself subscribed to this view. As to the alternative view that at least some of these nebulae are extra-galactic, being galaxies in their own right, Shapley (1919) had this to say:

"*...Observation and discussion of the radial velocities, internal motions, and distribution of spiral nebulae, of the real and apparent brightness of novae, of the maximum luminosity of galactic and cluster stars, and finally of the dimensions of our galactic system, all seem definitely to oppose the 'island universe' hypothesis of the spiral nebulae.*"

The island universe hypothesis referred to here originated with Immanuel Kant in the eighteenth century, which stated that there were other galaxies like our own distributed all over the universe and separated by large empty regions of space, like islands in a vast sea. However, by 1925, better estimates of distances became available, thanks to the important work of Hubble and the alternative view became established.

These two examples demonstrate that majority opinions in science do not necessarily guarantee that a given viewpoint is correct. Although the chances of scientists being collectively wrong are rare, they are not negligible. Indeed science prides itself on its self-correcting process wherein new facts can cause a paradigm-shift. As we shall see now, there has been a continuing evolution of ideas and observations in cosmology as part of the process of confirmation of facts about the universe. In the process of this 'mid-course correction', what is considered 'alternative' today, may well become 'standard' tomorrow.

2. The beginning

Modern cosmology may be dated from a theoretical paper written by Einstein (1917) in which he assumed that the universe is homogeneous, isotropic and *static*. This was based on the observational information as available then. No systematic large scale motion of the major components of the universe was noted at the time. [Remember, the existence of external galaxies was still not accepted.] The observations of redshifts from nebulae were few and far between. Thus the standard paradigm was that *the universe is static*.

How strong was this paradigm can be seen from the fact that when Einstein could not obtain a static model from his original field equations, he modified them by adding the cosmological constant term, so that a static solution could be obtained from them.

It was against this paradigm that W. de Sitter (1917), A.Friedmann (1922, 1924) and Abbe' Lemaitre (1927) published their work on non-static models. H.P. Robertson (1928) also deduced a velocity-distance relation for some expanding world models. Initially these works were ignored, largely as mathematical curiosities or esoteric solutions of Einstein's field equations.

Some objected to the de Sitter model because it has an event horizon, which cuts us off from communication with galaxies beyond a certain distance. It was considered peculiar anyway since it is empty...it has motion without matter (as opposed to Einstein's universe with matter without motion).

The expanding models became the standard mainstream models after Hubble's velocity distance relation became established. In this sense the paper by Hubble (1929) marks the watershed in modern cosmology. The paradigm shift generated by it led to the Friedmann models having the status of standard models. Since expanding models could be produced from the original Einstein equations, without the cosmological term, Einstein felt that the addition of that term (in order to obtain the static model) was a mistake and discarded it from his equations. Eddington (and Lemaitre), however, felt that the richer range of cosmological solutions obtained by including this term justifies its existence. I shall return to this term later in this review.

Meanwhile it is worth recalling the work of Robertson (1935) and Walker (1936) who independently showed how rigorous group theoretic arguments lead to the line element commonly used by Friedmann and Lemaitre for a homogeneous and isotropic universe. This line element, is written in the form

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

Here $(r,\ \theta,\ \phi)$ are the constant (comoving) coordinates of a typical galaxy idealized as a *fundamental observer*, and t its proper time. The simplifying assumptions of homogeneity and isotropy of the universe with respect to the fundamental observers, renders the status of 'cosmic time' to the coordinate t. The function $S(t)$ is the scale factor, whose increase with t indicates expansion of the universe, while the parameter k is 0, 1, -1, corresponding to a flat, closed or open universe.

3. Newtonian cosmology

We will now consider our first alternative to the standard Friedmann models, provided by reverting to the Newtonian laws of motion and gravitation. In the mid-1930s, McCrea and Milne (1934), showed that almost exact analogues of the Friedmann models can be obtained from Newtonian physics. These models give the same dynamical behaviour as the Friedmann models, except that the curvature parameter k of the Friedmann models is replaced by a 'total energy' parameter in this cosmology. Thus for positive energy, the model expands to infinity, while for negative energy contraction follows as expansion slows down to a halt. The "zero energy" model is the analogue of the flat $k = 0$ model of relativity: it comes to a halt at infinity.

The Newtonian model can be extended to the hot radiation-dominated phase also (Narlikar 1996). In fact, as shown by Peebles (1971), a lot of the physical cosmology of the early universe can be understood by Newtonian physics. To those who find the general theory heavy going the Newtonian approach is adequate to explain the key features of cosmology.

Newtonian cosmology, however, may generate conceptual difficulties. As is well known, Newtonian physics is valid only in the low-velocity, weak gravitation limit. In cosmology one goes well beyond these limits. Thus the law of addition of velocities becomes suspect, as does the solution of the Poissonian equation with boundary conditions at infinity. The moral is, despite its successes use Newtonian cosmology with caution!

4. Milne's kinematic relativity

E.A. Milne (1935, 1948) was the first to introduce two time scales in a theory of cosmology. He stressed the point that a realistic measurement of distance would be via the 'radar method'. Assume that radar velocity is c. Thus an observer A sends a signal to observer B at time t_1 and the reflected signal from B comes back to A at time t_2. Then A concludes that B's distance from A was $c(t_2 - t_1)/2$, at time $(t_1 + t_2)/2$. This method was criticised by Max Born (1943) as impractical for measuring distances of distant nebulae. However, it has the merit of clarity and singling out light as the prime means of communication. But to get round the ambiguity of moving observers having different time measurements, Milne identified a set of *fundamental observers* for whom the time t is uniquely defined.

The fundamentsl observers may be considered to have emerged from a point O at $R = 0$, at time $T = 0$ with some velocity v (the speed of light c is taken as unity). At time $T > 0$, the observer will be at $R = vT$. The observer's proper time t is given by

$$t = T \times \sqrt{1 - v^2}. \tag{2}$$

Define a radial coordinate r for the observer by

$$r = \frac{v}{\sqrt{1 - v^2}}, \tag{3}$$

so that the line element in terms of the t, r, and the angular coordinates θ, ϕ is given by

$$ds^2 = dt^2 - t^2\left[\frac{dr^2}{1+r^2} + r^2(d\theta^2 + \sin\,\theta dQ^2\right]$$

This line element is none other than that of the empty Friedmann model with $k = -1$. However, here the derivation is purely kinematic and so there is no relationship of the large scale motion to the density of matter in the universe.

The second time scale τ is one in which the fundamental observers appear to be at rest. Choosing τ to be equal to t at $t = t_0$, define

$$t = t_0.\exp[(\tau - t_0)/\, t_0], \tag{4}$$

We find that the line element is conformal to a static line element. Notice that the zero of t corresponds to the epoch of infinite past in the τ time. In this framework, the universe is static, and the redshift is due to the decrease in the frequency of the photon during passage through space owing to the non-linear relation (4) between τ and t.

The Milne theory played an important role in focussing attention on time co-ordinates and their relationships to observations. However, it lacked a dynamical framework, including a theory of gravity which is crucial towards understanding of cosmology. For these reasons it did not get very far.

5. Tired photon models

The idea that redshift arises in a static universe, through the photon losing energy en-route from a distant source of light is a plausible one. Called the 'tired light hypothesis', this idea requires a mechanism for photon energy loss in what appears to be a nearly empty intergalactic space. Nernst in 1937 had developed such a model, assuming that radiation was being absorbed by luminiferous ether.

Finley-Freundliech (1954) took up this idea in order to explain an anomalous redshift found in the Sun and some stars. He postulated a formula giving the frequency decrease $\Delta\nu$ in the frequency ν which is proportional to the fourth power of the temperature of the ambient radiation field, T and to the distance l traversed:

$$\Delta\nu = -A \times \nu \times T^4 \times l, \tag{5}$$

where A is a constant. Although this formula is empirical, it is supposed to apply in a universal way, to stars as well as galaxies. It suggests that photon-photon scattering is involved, a small effect except in a strong radiation field (Born 1954). However, scattering changes direction of the original photon from the source, and this could lead to the source image looking blurred. This has been a main stumbling block of this hypothesis although a solution to this difficulty has been claimed.

6. Matter-antimatter symmetric cosmology

Particle physics tells us that there is complete symmetry between matter and antimatter. While bosons like the photons are their own antiparticles, there are fermions like the electron, proton, neutron, etc., which have distinct antiparticles. However, the large scale studies of the universe show a predominance of matter over antimatter. How does one understand this feature, given the basic symmetry between the two at a fundamental level?

The standard big bang cosmology seeks to answer this question by speculating about the state of the universe very early, when the grand unification of physical interaction was in force. Using suitable scenarios involving breakdown of CP-symmetry, baryon nonconservation and departure from thermodynamic equilbrium, the big bang cosmologists try to generate a slight excess of baryons over antibaryons so as to explain the baryon to photon ratio observed today. A different approach was tried by Alfven and Klein (1963, see also Alfven 1965) in which the universe was initially taken to be made of very low density plasma, symmetric between matter and antimatter. If we consider initially a homogeneous sphere of such material, it will begin to contract, while the matter-antimatter annihilations (which were rare in the low density state), pick up, generating gamma radiation, mesons and neutrinos. The decays of muons and pions generate $e^{\pm}$ pairs. The eventual outcome is a build up of radiation pressure which opposes gravity.

The resultant set of equations describe how the sphere evolves in size. Writing the outward radial velocity of a particle at distance r from the centre as $v = \eta r$, we get

$$\dot{\eta} + \eta^2 = \frac{4\pi}{3}\left[\frac{2\pi\epsilon n_e}{3k_p} - 1\right], \tag{6}$$

and for density ρ of the sphere,

$$\dot{\rho} = -3\eta\rho - \frac{\pi}{2k_p}\rho^2, \tag{7}$$

where n_e is the number density of electrons (and also of positrons) per unit volume. Here the average lifetime of a proton is taken as $(n_p c\sigma_0)^{-1}$, where σ_0 is the classical electron cross-section and k_p is a function of the proton energy, which is of order unity up to relativistic energies. The electron lifetime is similarly related to the parameter k_e. The equation for the time rate of change of n_e is given by

$$\dot{n}_e = -3\eta n_e - \frac{\pi}{k_e} + \frac{\pi\rho^2}{2k_p}. \tag{8}$$

These Newtonian equations were solved by Bonnevier (1965), while their relativistic counterparts were discussed by Laurent and Soderholm (1969). In both cases a bounce from the initial contraction occurs; however, in the latter case there is a maximum mass that can bounce. The mass limit is an order of magnitude less than that observed in the universe and this was a serious limitation to the Alfven-Klein idea.

The other problem with this idea was that no physically satisfactory mechanism could be found which separated matter dominated regions from the antimatter dominated ones. Such separation is essential for us to be able to argue that we live in a matter dominated region in which there is hardly any antimatter.

Although this cosmology lost momentum in the 1970s, some of its ideas deserve to be looked at again in the light of the current ideas on baryogenesis with inputs from GUTs, supersymmetry, strings, etc.

7. Segal's chronometric cosmology

Another kinematical approach to cosmology came from the mathematician I. Segal (1976). The cosmos is taken here as a manifold $\mathcal{M}$ in the form $\mathcal{R} \times \mathcal{S}$, where $\mathcal{R}$ is the real line from $-\infty$ to $+\infty$, denoting the time coordinate, while $\mathcal{S}$ is the space part denoting the hypersurface of a 4-sphere. A mathematical transformation maps the local region around any point on to the Minkowski spacetime that is tangential to $\mathcal{M}$ at that point. The physics at the point is then interpreted with the help of the physics in the tangent space.

A key feature of this cosmology is the Hubble relationship, which is quadratic ($D \propto z^2$) rather than linear. Segal has analyzed the redshift distance relation for the nearby galaxies and claims that it is quadratic rather than linear. This has been debated by observers who have worked on the Hubble law, arguing that Segal's conclusion is vitiated by selection effects.

It should also be stated that the highly mathematical form in which this cosmological model is presented prevents most observational astronomers from appreciating its ideas and predictions. Thus a 'comprehension gap' exists which has led to this approach being ignored.

8. The steady state theory

The cosmology which played a key role in stirring up the subject during the middle of the century was undoubtedly the steady state cosmology put forward by Bondi and Gold (1948) and by Hoyle (1948). This model does not have a singular big bang type epoch; indeed, it does not have either a beginning or an end on the cosmic time axis. What was the motivation that led these scientists to propose the steady state cosmology?

First of all, in 1948 the measured value of $\tau_0 \equiv H_0^{-1}$ was only $\sim 1.8 \times 10^9$ years. Consequently the age of a standard Friedmann model could not exceed τ_0–a value lower than even the geological age of the Earth! Thus a prima facie case existed for doubting the conclusion that the universe began $\sim$ 1 to 1.8 billion years ago.

The second reason was the unsatisfactory nature of the 'beginning' of the universe in a singular event. The big bang singularity prevents a proper discussion of the basic phenomenon of creation of matter. Indeed, it gives the event a mystical flavour. Moreover, one may pose another philosophical question.

Have we any guarantee when we study the past history of the universe, that the physical laws that we use here and now, have always remained the same? We could have assumed this to be the case had the universe itself not changed considerably in the course of time. This, however, was not the case for the Friedmann universes. A typical standard model changes considerably in its physical content and properties from soon after $t = 0$ to the present day. So the assumption that the laws of physics have remained unchanged throughout the history of the standard models is more an article of faith than a verifiable fact. And, if they have not, then the 'guesses' and 'extrapolations' used to talk about the very early universe remain unverifiable hypotheses.

Hoyle's approach to the steady state theory was designed to attack the problem of primary creation of matter. He looked for a field theory for matter creation, a theory which would add extra terms to Einstein's general relativistic field equations to ensure the validity of the law of conservation of matter and energy, despite the creation of matter. His colleagues Bondi and Gold, however, considered the assumption of constancy of physical laws as of paramount importance, as it pertains to the very basics of cosmology.

8.1. The perfect cosmological principle

Bondi and Gold argued that the cosmological principle used in standard cosmology, goes some way towards ensuring that the locally discovered laws of physics have universal validity; but it does not go far enough. This principle tells us that at any given cosmic time t, all fundamental observers see the same large-scale features of the universe. Thus we are justified in assuming no spatial variation in the basic physical laws at any given cosmic time. But there is no justification from the cosmological principle to assume that the laws remain unchanged *with time.*

To provide such a justification Bondi and Gold strengthened and elevated the cosmological principle to what they called the *perfect cosmological principle* (PCP). The PCP states that in addition to the symmetries implicit in the cosmological principle, the universe in the large is unchanging with time. Thus the geometrical and physical properties of the hypersurfaces t = constant do not change with t.

It is important to emphasize the qualification "in the large". On a small enough scale the observed part of the universe *will* change. For example, stars in a galaxy will grow older, a small cluster of galaxies will evolve with time in shape and composition, and so on. However, according to the PCP the statistical properties of the large scale features of the universe do not change.

For example, Hubble's constant should remain the same whether it is measured now or at any time past or present, since its accurate measurement involves the rate of expansion of the universe. This being a property of the large scale structure of the universe, the constancy of H tells us immediately that

$$H = \frac{\dot{S}}{S} = \text{ constant } = H_0, \text{i.e.,} \quad S = \exp(H_0 t). \tag{9}$$

Further, the curvature of a t = constant hypersurface is given by k/S^2. This could in principle be measured at different times and found to be changing unless $k = 0$. Thus the PCP leads us to the unique line element

$$ds^2 = c^2 dt^2 - e^{2H_0 t}[dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)]. \tag{10}$$

Notice that we have arrived at the line element of the steady state universe without having to solve *any* field equations, as we had to do to determine $S(t)$ and k in standard cosmology. Bondi and Gold cited this result as an example of the deductive power of the PCP. Using similar arguments they were able to show that the departure from thermodynamic equilibrium means that the universe is expanding (i.e., $H_0 > 0$). Recall also, that this line element is the same as that obtained by de Sitter (op.cit.) for his model in 1917. However, the steady state universe is not empty: it has a constant density ρ and a constant rate of creation $3H_0\rho$, which for today's values of these parameters works out at

$$J = 2 \times 10^{-46} \left(\frac{\rho_0}{\rho_c}\right) h_0^3 \text{ g cm}^{-3}\text{s}^{-1}, \tag{11}$$

The small value of J shows that there is a very slow but continuous creation of matter going on, in contrast to the one time infinite and explosive creation at $t = 0$ of the standard models.

Attractive though the above deductive approach was, it had its limitations. For example, we do not have a quantitative relation connecting H_0 to say, the mean density ρ_0 as we have in the Friedmann cosmologies. Nor do we have any physical theory for such an important phenomenon as the continuous creation of matter. Is the sacrosanct law of conservation of matter and energy being violated in the process of matter creation? Bondi and Gold apprecieated the fact that questions like these could be answered through a dynamical theory rather than from their deductive approach. However, they felt that the PCP together with local observations already determines the large-scale properties of the universe in a form that can be tested by observations. Therefore they attached greater importance to the empirical approach of testing the PCP by observations than to formulating a dynamic theory that might determine H_0, ρ_0, etc. quantitatively.

8.2. A field theory for creation

Fred Hoyle, on the other hand, took the opposite view. He looked for a field theoretic process that could account for the phenomenon of primary creation of matter. His 1948 paper had included a modification of the Einstein field equations of general relativity in which the right hand side contained an explicit energy momentum tensor for a scalar 'creation field'. However,after several attempts at improving the framework, he finally adopted the formulation suggested by M.H.L. Pryce (1960). This formulation, known as the C-field theory, was used extensively by Hoyle and Narlikar in the early 1960s. The modified Einstein equations look like the following:

$$R^{ik} - \frac{1}{2}g^{ik}R = -\frac{8\pi G}{c^4}\left(T_{(m)}{}^{ik} + T_{(C)}{}^{ik}\right) \tag{12}$$

where $T^{ik}_{(m)}$ is the matter tensor as in the earlier chapters while

$$T_{(C)}{}^{ik} = -f\left(C^iC^k - \frac{1}{2}g^{ik}C^lC_l\right). \tag{13}$$

Again we note that $T^{00}_C < 0$ for $f > 0$. Thus the C-field has negative energy density that produces a repulsive gravitational effect. It is this repulsive force that drives the expansion of the universe. The above effect may resolve one difficulty usually associated with the quantum theory of negative energy fields. Because such fields have no lowest energy state, they normally do not form stable systems. A cascading into lower and lower energy states would inevitably occur if we perturb the field in a given state of negative energy. However, this conclusion is altered if we include the feedback of (13) on spacetime geometry through (12). This feedback results in the expansion of space and in the lowering of the magnitude of field energy. Both these effects tend to work in opposite directions and help stabilize the system.

It is easy to verify that the steady state solution follows from these equations for

$$k = 0, \qquad S = e^{H_0 t}, \qquad \rho = \rho_0 = \frac{3H_0^2}{4\pi G} = fm^2. \tag{14}$$

Notice that both H_0 and ρ_0 are given in terms of the elementary creation process; that is, in terms of the coupling constant f and the mass m of the particle created. Thus the Hoyle approach provides the quantitative information lacking in the deductive approach of the PCP.

8.3. How was the steady state theory received?

The steady state theory encountered stiff opposition on two different grounds. The scientific opposition was because the theory predicted continuous creation of matter, in apparent contradiction of the law of conservation of matter. While this could be a legitimate criticism of the Bondi-Gold deductive approach, it was already answered by Hoyle's approach which by following the action principle and the field equations, automatically ensured compliance with this law. There was some skepticism expressed by theoretical physicists of concepts like nonconservation of baryons and a scalar field with negative stresses. In retrospect, both these concepts were legitimized by developments in particle physics in the late 1970s and 1980s with baryogenesis, inflation, vacuum energy, etc. which are as esoteric as the C−field when judged by the standpoint of the 1950s and 1960s.

The other opposition was cultural! To the western world, the concept of a universe without a beginning and thus lacking a "creation epoch" was strange at best and philosophically unacceptable. The big bang on the other hand was readily appreciated as it gave a scientific legitimacy to the idea of "creation". However, it is somewhat disconcerting that these views were shared by some in the scientific community also and continue to have adherents even today. For a discussion of this attitude see the account of Hoyle, et al (2000). As an example of the hostility, the remarks in the Presidential Address by H. Dingle (1953) to the Royal Astronomical Society, London are worth noting.

Commenting on the perfect cosmological principle, he had this advice for its originators:

...Let our younger cosmologists forget cosmology for the space of three years – the universe is patient – it can wait, and instead read the history of science – I mean the work of great scientists themselves. After asking themselves what meaning it has for the work of today, let them return to cosmology and give their attention again to the great problems into which they have prematurely rushed....

8.4. Observational constraints

Philosophical considerations apart, how did the steady state theory fare in its confrontations with observations? The theory made very definitive predictions and that was one of its attractive features as a scientific theory. Bondi used to emphasize that because of this feature it was vulnarable to disproof, more so than the big bang theory. Indeed there were claims of its disproof from several observational quarters, claims that were later seen to be based on wrong interpretation or uncertain data. Some examples are the Stebbins-Whitford effect, the counts of radio sources, the measurement of the deceleration parameter, etc. For details see Narlikar (2001).

Looking at these episodes, one arrives at a moral, viz., *a theory that makes definitive predictions is more likely to be disproved by uncertain observations at the limits of their capacity, than by its own weaknesses...*

Having said this, we should now look at what turned out to be genuine problems for the steady state theory: (1) the discovery of microwave background by Penzias and Wilson (1965), and (2) the abundances of light nuclei like helium and deuterium. The big bang universe has natural explanations for these observations, which require the universe to have passed through an early but hot era. This type of explanation did not work for the steady state model, as it did not have a high temperature epoch. The model floundered on these two issues and eventually dropped out of contention.

In this context, it is worth recalling an episode reported by Hoyle, et al (2000). In 1955, Bondi, Gold and Hoyle made the following calculation. Given that about 25% of all matter in the universe is in the form of helium, they asked the question: If all this helium were made in stars in a steady state universe, how much stellar energy would be released? The energy density worked out close to 4.4×10^{-13} erg cm^{-3}. At this stage Gold argued that if this were all thermalized, we should have a background temperature of 2.76 K. He wanted to publish this result as a prediction of the steady state theory that it should have a Planckian radiation background of 2.76K. He was, however, overruled by Bondi and Hoyle as they could not see how stars could produce all the helium and what were the thermalizers that converted the stellar radiation to the black body form. Gold's argument had been that any radiation if lying around for sufficiently long time, e.g., $\sim 10^9$ yrs, would be degraded to the black body form by the second law of thermodynamics. It is interesting that the big bang cosmology *cannot* predict the present temperature of the microwave background, and Gamow's own estimates have ranged from 7K to about 50 K (Assis and Neves 1995). Thus, had Gold been allowed to publish the result, the steady state theory would have been in a position to have made the right prediction, *before* the actual discovery by Penzias and Wilson.

8.5. Some positive contributions of the steady state cosmology

Despite the controversy it generated, the steady state theory should be credited with some concepts which, though not apprciated at the time, have been assimilated in present day cosmology. A few examples are given below.

(1) The steady state theory was the first to use inputs from particle physics into cosmology and structure formation. The hot universe version of Gold and Hoyle (1958) used the idea that new matter is created in the form of neutrons and the neutron decay reaction determines the kinetic temperature of the universe. They were able to relate this idea to the size of the typical primary structure in the universe, which was ~ 50 Mpc, and was identified with a supercluster.

(2) The notion of superclusters came naturally in this cosmology as mentioned in (1) and the inhomogeneity on this scale was used by Hoyle and Narlikar (1962) to explain the steep radio source counts reported by Ryle and his collaborators in Cambridge. At the time cosmologists were reluctant to admit inhomogeneity on such a large scale. Today it is accepted for fact.

(3) It underscored the fact that observations of discrete source populations cannot really throw light on cosmological models till their physical properties are understood. The Hoyle-Narlikar radio source count problem demonstrated this fact very clearly.

(4) It is now acknowledged that the cosmological model discussed by Hoyle and Narlikar (1966a) preempted the presently popular inflationary model (see for example Peebles, et al 1991).

(5) Another paper by Hoyle and Narlikar (1966b) was the first to propose that galaxies contain a collapsed massive object at the centres of their nuclei. This may be considered precurser of the currently popular notion that there are black holes in the nuclei of galaxies.

9. Machian Cosmologies

Ernst Mach (1893) had given arguments to suggest that the inertia of matter may owe its origin not just to the matter but also to the background in which it is kept. Indeed Newton had also worried about related issues and the description of his bucket experiment in the *Principia* is very graphic. By noticing that the surface of water in a spinning bucket is curved, with the curvature increasing with the spin of the bucket, Newton could identify a special reference frame as one in which there is no spin and no curvature. Thus an observer in a spinning room will think that a staionary bucket is spinning relative to him; but he can conclude the effect to be illusory by noting that the water surface in that bucket is flat. Newton identified the real 'non-spinning' reference frame with his absolute space.

While being critical of the postulate of absolute space, Mach noticed that this is the reference frame in which the distant stars are non-rotating. He therefore suggested that the local inertial (non-spinning) frame is determined by the distant stars. And, consequently, Newton's laws of motion and the concept of inertia are linked with this frame of distant stars.

An interesting and telling experiment suggesting such a connection is that of the Foucault pendulum. Its plane of oscillation slowly precesses and this allows us to measure the spin of the Earth relative to the local inertial frame. However, we get the same answer if we measure the spin of the Earth relative to the frame of distant stars. Today in this identification the frame of distant stars is replaced by the frame of distant galaxies and the level of accuracy is as high as 0.00025 arcsec/year [see, Barbour and Pfister (1995), p. 364].

Einstein himself was very impressed by Mach's arguments and had hoped that the general theory of relativity would turn out to have these arguments incorporated in it. However, Kurt Gödel (1949) gave a counterexample by producing a cosmological solution of Einstein's field equations which has the distant stars spinning relative to the local inertioal frame. Later Einstein himself lost his interest in Mach's principle largely because he supposed that it was based on action at a distance concept which he thought was unrealistic.

9.1. Spinning universes

Gödel work, while highlighting the non-Machian nature of spinning universes, inspired some cosmologists to think of departing from the postulate of isotropy and the Robertson-Walker line element (1), in an attempt to arrive at non-singular models of the universe. The work of A.K. Raychaudhuri (1955) suggested that spin may help prevent a singularity, although the accompanying shear hastens it. In the end, general results in the 1960s showed that a spacetime singularity is inevitable in general relativity if one assumes positive energy conditions for matter and energy in the universe [for details see Hawking and Ellis (1973)].

Thus the interest in anisotropic cosmologies gradually declined. Certainly, non-Machian models having spin do not prevent the singularity associated with big bang. In an indirect way this result tells us that to avoid spacetime singularity one need not depart from the coincidence of local inertial frame with the cosmological rest frame, which serves as the starting point for Mach's principle.

A few cosmologists have indeed taken Mach's ideas seriously enough to influence developments in gravity theories and cosmology during the 20th Century. It should be emphasized that there is no unique and quantitative way of writing down Mach's principle. People have interpreted it differently when giving quantitative expression to its rather vague and philosophical content. For a discussion of the various approaches to Mach's principle, see Barbour and Pfister (1995). Here we limit ourselves to two cosmological theories that were inspired by Mach's principle.

10. The Brans-Dicke Theory of Gravity

In the early 1960s, C. Brans and R.H. Dicke (1961) provided an interesting alternative to general relativity based on Mach's principle. To understand the reasons leading to their field equations, we first note that Mach's principle would seem to permit the variation of inertia as the particle changed its location relative to the background. The concept of a variable inertial mass itself leads to a problem of interpretation. For, how do we compare masses at two different points in spacetime? Masses are measured in certain units, such as masses of elementary particles, which are themselves subject to change! We need an independent unit of mass against which an increase or decrease of a particle mass can be measured. Such a unit is provided by gravity, by the so called Planck mass :

$$\left(\frac{\hbar c}{G}\right)^{1/2} \cong 2.16 \times 10^{-5}\mathrm{g}. \tag{15}$$

Thus the dimensionless quantity

$$\chi = m\left(\frac{G}{\hbar c}\right)^{1/2} \tag{16}$$

measured at different spacetime points can tell us whether masses m are changing. Or alternatively, if we insist on using mass units that are the same everywhere, a change of χ would tell us that the gravitational constant G is changing. We could of course assume that $\hbar$ and c also change. However, by keeping $\hbar$ and c constant we follow the principle of least modification of existing theories. Thus special relativity and quantum theory are unaffected if we keep $\hbar$ and c fixed. This is the conclusion Brans and Dicke arrived at in their approach to Mach's principle. They looked for a framework in which the gravitational constant G arises from the structure of the universe, so that a changing G could be looked upon as the Machian consequence of a changing universe.

Earlier D.W. Sciama (1953) had given general arguments leading to a relationship between G and the large-scale structure of the universe. We have one example of such a relation in the standard Friedmann cosmologies :

$$\rho_0 = \frac{3H_0^2}{4\pi G} q_0, \quad q_0 \approx \mathcal{O}(1). \tag{17}$$

If we write $R_0 = c/H_0$ as a characteristic length of the universe and $M_0 = 4\pi\rho_0 R_0^3/3$ as the characteristic mass of the universe, then the above relation becomes

$$\frac{1}{G} = \frac{M_0}{R_0 c^2} q_0^{-1} \sim \frac{M_0}{R_0 c^2} \sim \sum \frac{m}{rc^2}. \tag{18}$$

Given a dynamic coupling between the inertia and gravity, a relation of the above type is expected to hold. Brans and Dicke took this relation as one that determines G^{-1} from a linear superposition of inertial contributions m/rc^2, the typical one being from a mass m at a distance r from the point where G is measured. Since m/r is a solution of a scalar wave equation with a point source of strength m, Brans and Dicke postulated that G behaves as the reciprocal of a scalar field ϕ :

$$G \sim \phi^{-1},$$

where ϕ is expected to satisfy a scalar wave equation whose source is all the matter in the universe.

10.1. The action principle

The intuitive concepts are contained in the Brans-Dicke action principle, which may be written in the form

$$\mathcal{A} = \frac{c^3}{16\pi} \int_{\mathcal{V}} (\phi R + \omega \phi^{-1} \phi^k \phi_k) \sqrt{-g} d^4x + \Lambda. \tag{19}$$

Notice first that the coefficent of R is $c^3\phi/16\pi$ instead of $c^3/16\pi G$ as in the Einstein-Hilbert action. The reason for this lies in the anticipated behaviour of $G \sim 1/\phi$ as given above. The second term, with $\phi_k \equiv \partial\phi/\partial x^k$, ensures that ϕ will satisfy a wave equation, while the third term includes, through a Lagrangian density L, all the matter and energy present in the spacetime region $\mathcal{V}$. The energy momentum tensor T^{ik} of matter is related to Λ through the standard variational problem with respect to g_{ik}. ω is a coupling constant.

The variation of $\mathcal{A}$ for small changes of g^{ik} leads to the field equations

$$\begin{aligned} R_{ik} - \frac{1}{2} g_{ik} R = & - \frac{8\pi}{c^4 \phi} T_{ik} - \frac{\omega}{\phi^2} \left(\phi_i \phi_k - \frac{1}{2} g_{ik} \phi^l \phi_l \right) \\ & - \frac{1}{\phi} (\phi_{ik} - g_{ik} \Box \phi). \end{aligned} \tag{20}$$

Similarly, the variation of ϕ leads to the following equation for ϕ. We finally get

$$\Box\phi = \frac{8\pi}{(2\omega + 3)c^4} T. \tag{21}$$

where T is the trace of T^i_k. Thus (21) leads to the anticipated scalar wave equation for ϕ with sources in matter, $\Box$ being the wave operator. Because it contains a scalar field ϕ in addition to the metric tensor g_{ik}, the Brans-Dicke theory is often referred to as the *scalar-tensor theory of gravitation.*

The Brans-Dicke theory prompted several high technology tests of the theory within the solar system, to place limits on the parameter ω. For $\omega = \mathcal{O}(1)$ the theory differs significantly from general relativity. As $\omega \to \infty$, the difference between the two theories disappears. The current lower limit on ω is as high as ~ 3300 (Will 1999). Thus for most practical purposes the theory has ceased to be of interest to gravitational physicists.

The cosmological solutions of this theory have also been discussed extensively, including the inflationary phase as applicable. Again, for most practical purposes, the theory does not give any significantly different conclusion except its predictions about $\mid \dot{G}/G \mid \sim \omega^{-1}H$, H being Hubble's constant. Current limits on $\mid \dot{G}/G \mid H^{-1}$ are $\lesssim 10^{-2}$. Since the solar system tests make ω as high as 3300, there is an overall consistency about this conclusion, but, of course nothing of significant interest to the cosmologist or gravitational physicist.

11. The Hoyle-Narlikar Theory

The second approach to gravitation and cosmology via Mach's principle was by Hoyle and Narlikar (1964, 1966c). In this approach the inertia of a particle was defined by a scalar field arising from other particles in the universe. Let us denote by $a, b, \ldots$ the particles in the universe, m_a, e_a being the mass and charge of the a^{th} particle. As implied by Mach, the mass m_a is not entirely an intrinsic property of particle a; it also owes its origin to the background provided by the rest of the universe. To express this idea quantitatively, write

$$m_a(A) = \lambda_a \sum_{b \neq a} m^{(b)}(A). \tag{22}$$

The above expression means the following. At a typical world point A on the world line of particle a, the mass acquired by a is the net sum of contributions from all other particles $b (\neq a)$ in the universe. The contribution from b at A is given by the scalar function $m^{(b)}(A)$. The coupling constant λ_a is intrinsic to the particle a. Notice, however, that if a were the only particle in the universe $m_a = 0$. The functions $m^{(b)}(X)$ are scalars and the two-point interaction between particles a, b are defined by Green's functions. Thus we write

$$m^{(b)}(X) = \int \lambda_b \tilde{G}(X, B) ds_b \tag{23}$$

and the inertial action as

$$\mathcal{A} = - \sum_{a} \sum_{< b} \int \int \lambda_a \lambda_b \tilde{G}(A, B) ds_a ds_b. \tag{24}$$

What is $\tilde{G}(A, B)$? From symmetry considerations we need $\tilde{G}(A, B) = \tilde{G}(B, A)$. Further we require $\tilde{G}$ to be a Green's function of a scalar wave equation. To fix $\tilde{G}$ completely we use the property of conformal invariance.

Let us consider the transformation

$$\bar{g}_{ik} = \Omega^2 g_{ik} \tag{25}$$

where Ω is a twice-differentiable function of coordinates x^i and lies in the range $0 < \Omega < \infty$. Such a transformation is called *conformal transformation.* Given a spacetime manifold $\mathcal{M}$ with coordinates (x^i) and metric (g_{ik}), we have through (25) generated another spacetime manifold $\bar{\mathcal{M}}$ with the same coordinate system (x^i) but with a different metric $(\Omega^2 g_{ik})$. $\mathcal{M}$ and $\bar{\mathcal{M}}$ are said to be *conformal* to each other. If $\mathcal{M}$ is flat $\bar{\mathcal{M}}$ is said to be *conformally flat.* We fix our Green's function such that our action (24) is conformally invariant. The only scalar linear wave equation that permits this is given by

$$\left[\Box_X + \frac{1}{6}R(X)\right]\tilde{G}(X,B) = [-g(X)]^{-1/2}\delta_4(X,B). \tag{26}$$

$\delta_4(X,B)$ is the four-dimensional Dirac delta function, which vanishes unless $X \equiv B$. The action of HN theory is given by (24), and with the help of definitions (22) and (23) we may write it as

$$\mathcal{A} = -\sum_a \int m_a ds_a. \tag{27}$$

Written in this form $\mathcal{A}$ appears to have only the standard inertial term. How can such an action yield any gravitational equations?

The answer to this question lies in the fact that the m_a*'s* in (27) are not constants but depend on spacetime coordinates *as well as on spacetime geometry.* For they are defined with the help of Green's functions, which in turn are defined in terms of spacetime geometry. Thus if we make a small variation

$$g_{ik} \rightarrow g_{ik} + \delta g_{ik},$$

the wave equation (26) will change and so will its solution. Thus we will have

$$\tilde{G}(A,B) \rightarrow \tilde{G}(A,B) + \delta\tilde{G}(A,B)$$

and hence $\mathcal{A} \rightarrow \mathcal{A} + \delta\mathcal{A}$. We therefore have a nontirivial problem which can be solved to yield the gravitational equations in the following form:

$$R_{ik} - \frac{1}{2}g_{ik}R = -\frac{6}{m^2}\left[T_{ik} + \frac{1}{6}(g_{ik}\Box m^2 - m^2_{;ik}) + \left(m_i m_k - \frac{1}{2}g_{ik}m^l m_l\right)\right] \tag{28}$$

where

$$m(X) = \sum_a m^{(a)}(X). \tag{29}$$

Since the property of conformal invariance was used in the formulation of the theory, we expect the final equations (28) and (29) to exhibit conformal invariance. This expectation is borne out. If (g_{ik}, m) are a solution of these equations, then so are

$$\bar{g}_{ik} = \Omega^2 g_{ik}, \qquad \bar{m} = \Omega^{-1} m. \tag{30}$$

Thus apart from coordinate invariance of general relativity, this theory also shows *conformal invariance.* This circumstance can be turned to our advantage in the following way.

Suppose we are allowed to choose an Ω in the above range that ensures that

$$\bar{m} = \Omega^{-1} m = \text{constant} = m_0. \tag{31}$$

This choice of Ω is possible provided m does not vanish or become infinite. This conformal frame is called the Einstein frame, in which we get a simplified form for (28) :

$$R_{ik} - \frac{1}{2} g_{ik} R = -\kappa T_{ik}, \tag{32}$$

with the constant κ given by

$$\kappa = \frac{6}{m_0^2}. \tag{33}$$

Thus we have arrived at Einstein's equations! At first sight we don't seemed to have gained anything. We have no new theory and hence no new predictions, as in the Brans-Dicke theory. Closer examination, however, reveals several ways in which this theory goes beyond relativity.

1. Our starting point was based on Mach's principle. It is only in the many particle approximation, when the condition (31) is satisfied, that we arrive at the final Einsteinlike field equations. An empty universe in relativity is given by

$$R_{ik} = 0,$$

which can have well-defined spacetimes as solutions. Test particles in such spacetimes will have well-defined trajectories. Such trajectories would not make any sense according to Mach, since we no longer have a material background against which to measure the motion of these particles. In the HN theory an empty universe corresponds to

$$m = 0, \qquad \text{indeterminate } g_{ik},$$

in accord with the Machian conclusion that the spacetime is not determinable.

2. The sign of κ is fixed arbitrarily in general relativity. Neither in the heuristic derivation by Einstein nor in the Hilbert action principle is κ required to be positive. It is only when κ is determined by reference to Newtonian gravity in the weak field approximation that we conclude that $\kappa > 0$. In the HN theory (33) shows that κ must necessarily be positive. (This conclusion does not depend on our assumption of $\lambda_a = 1$; the result follows whatever sign the λ_a are given.)

3. In the direct interparticle approach as described above, it is apparently not possible to accommodate the λ-term of cosmic repulsion. Thus Occam's

razor automatically comes into play. In relativity the λ-term is still possible. However, we will see in §14, that if we relax the condition that the inertial fields m satisfy linear wave equations, and permit non-linearity, then the HN-cosmology also permits a cosmological constant.

4. The transition from (28) to (32) is possible provided $0 < \Omega < \infty$. What happens if we break this rule? Suppose in the solution of (28) we had a hypersurface on which $m = 0$. If we insist on the transformation (31) in a region that contains such a hypersurface, we have to pay the price of $\Omega \to 0$, by admitting spacetime singularities. The work of A.K. Kembhavi (1978) showed that the well-known cases of spacetime singularities of relativity arise because of the occurence of zero mass hypersurfaces in the solution of the equations (28).

The theory was later modified by Hoyle, Burbidge and Narlikar (1995) to include creation of matter. We will return to this approach when we discuss the quasi-steady state cosmology which these authors proposed from the modified equations.

12. The Large Numbers Hypothesis

Physics is riddled with units of various kinds and with experimentally determined quantities of various magnitudes. From this vast collection certain constants emerge as having special significance in the framing of basic physical laws; for example, the constant of gravitation G, the charge of the electron e, and so on. The numbers expressing the magnitudes of G, e, and so on depend on the units used. For example

$$\begin{aligned} e &= 4.80325 \times 10^{-10} \text{electrostatic units} \\ &= 1.60207 \times 10^{-20} \text{electromagnetic units.} \end{aligned}$$

Clearly these numbers by themselves cannot have absolute significance.

However, certain combinations of these physical constants have no units at all. For example, the combination of $\hbar, c$, and e

$$\frac{\hbar c}{e^2} = 137.03602 \tag{34}$$

does not depend on the units used. It must therefore express some physical fact of absolute significance. Indeed, its reciprocal $e^2/\hbar c$, known commonly as the *fine structure constant*, expresses the strength of the electromagnetic interaction, which we believe to be an intrinsic property of nature. A future, more complete, theory may well give a reason why this constant has this particular value.

Given e, G, and the masses of proton and the electron m_p and m_e, we can construct another dimensionless constant (that is, a constant with no units) :

$$\frac{e^2}{Gm_pm_e} = 2.3 \times 10^{39} \sim 10^{40}. \tag{35}$$

This constant measures the relative strength of the electrical and the gravitational forcs between the electron and the proton. Like (34) this constant reflects an intrinsic property of nature. However, unlike (34), the constant in (35) is enormously large! Why such a large number?

Perhaps the appearance of a large dimensionless constant might be dismissed as some quirk on the part of nature. The mystery deepens, however, if we consider another dimensionless number. This is the ratio of the length scale associated with the universe, c/H_0, and the length associated with the electron, $e^2/m_e c^2$. This ratio is

$$\frac{m_e c^3}{e^2 H_0} = 3.7 \times 10^{40} h_0^{-1} \sim 10^{40}. \tag{36}$$

Not only do we have another large dimensionless number in (36), but it is of the same order as in (35).

We can generate another large number of special significance out of particle physics and cosmology. Assuming the closure density ρ_c, let us calculate the number of particles in a Euclidean sphere of radius c/H_0, the mass of each particle being m_p. The answer is

$$\begin{aligned} N &= \frac{4\pi}{3m_p}\left(\frac{c}{H_0}\right)^3 . \frac{3H_0^2}{8\pi G} = \frac{c^3}{2m_p G H_0} \\ &= 4 \times 10^{79} h_0^{-1} \\ &\sim 10^{80}. \end{aligned} \tag{37}$$

Thus taking N as a standard we see that the large dimensionless numbers of (35) and (36) are both of the order of $N^{1/2}$.

Reactions among physicists have varied as to the significance of all these numbers. Some dismiss it as a coincidence with the rejoinder : "So what?" Others have read deep significance in these relationships. The latter class includes such distinguished physicists as A.S. Eddington and P.A.M. Dirac.

Dirac (1937) pointed out that the relationships (36) and (37) contain the Hubble constant H_0, and therefore the magnitudes computed in these formulae vary with the epoch in the standard Friedmann model. If so, the near equality of (35) and (36) has to be coincidence of the present epoch in the universe, unless the constant (35) also varies in such a way as to maintain the state of near equality with (36) at all epochs. With this proviso, the equality of (35) and (36) is not coincidental but is characteristic of the universe *at all epochs.* The proviso also implies that at least one of the so-called constants involved in (35), e, m_p, m_e, and G, must vary with the epoch.

This proviso was generalized by Dirac to what he called the *Large Numbers Hypothesis (LNH).* To understand this hypothesis we rewrite the ratio (36) as that between the time scale associated with the universe, $\tau_0 = H_0^{-1}$, and the time taken by light to travel a distance of the order of the classical electron radius, $t_e = e^2/m_e c^3$. The LNH then states that any large number that at the present epoch is expressible in the form

$$\left(\frac{\tau_o}{t_e}\right)^k.$$

where k is of order unity, varies with the epoch t as $(t/t_e)^k$ with a constant of proportionality of order unity.

Applied to (35), therefore, the LNH implies that the ratio e^2/Gm_pm_e must vary as $(t/t_e)^{-1}$. Dirac made the distinction between e, m_e, m_p on one side and G on the other in the sense that the former are atomic (microscopic quantities) while G has macroscopic significance. In the Machian cosmologies, G is in fact related to the large-scale structure of the universe. Dirac therefore assumed that if we use "atomic units" that always maintain fixed values for atomic quantities, then t_e will be constant and $G \propto t^{-1}$. That is, in terms of atomic time units the gravitational constant must vary with the epoch t, with $|\dot{G}/G| \sim H$.

In 1970s Dirac (1973) returned to his interest in this cosmology. Several detailed models based on the LNH were discussed by him and other authors. However, the interest in them dwindled, as there was no positive evidence for variation of fundamental constants like G. Nevertheless the puzzle of large dimensionless numbers remains.

13. Extrapolations to the very early universe

During the post-1965 period, however, the standard cosmology attracted greater and greater support, largely because it was able to explain two important observations about the universe, namely the abundances of light nuclei and the existence of the microwave background. Although no further observation of comparable significance came up since then, this belief in the validity of the big bang picture led cosmologists to extrapolate the model to very early epochs, going closer and closer to the $t = 0$ epoch. Thus a number of highly speculative elements have entered the so-called standard picture. Hence, although the big bang cosmologists have been accusing of proposers of alternative cosmologists of basing their ideas on physics that is not well established, several ideas have entered the extrapolations to the very early epochs of the standard model, which may also be considered 'nonstandard'. We briefly mention a few.

1. The speculations about the basic physics used for very high energy interactions at, say, 10^{16} GeV, are based on non-established grand unified theory. Particle physicists themselves are not yet certain which of the many approaches to GUTs, string theory, quantum gravity, etc., are correct and relevant. Thus all cosmology based on any such physics is highly speculative.

2. Dark matter is believed to form an important component of the universe. According to most big bang cosmologists the dark matter is mostly nonbaryonic; yet so far we do not have any tangible nonbaryonic particle as candidate for dark matter.

3. How is dark matter distributed ? Does it follow the visible matter? Is it concentrated in selected parts? There is no observational handle on this question so far and all ideas based on it are speculative.

4. How can we 'see' out to those very early epochs, when our observing along the past light cone cannot penetrate the last scattering surface? Thus there can

be no direct observations of the universe prior to the epoch of last scattering and any test of the theory has to be indirect.

In short, the entire exercise is one of showing consistency of *assumed* initial conditions developed under *assumed* physical laws, with modern observations. Thus, so far as speculativeness is concerned, the difference between 'standard' and 'alternative' has steadily eroded.

14. The quasi-steady state cosmology

The quasi-steady state cosmology (QSSC) may be considered the latest in the field of alternative cosmologies. This cosmology was proposed by F. Hoyle, G. Burbidge and J.V. Narlikar (1993) and has been elaborated in detail in subsequent papers, including a book (Hoyle, et al 2000). We begin by briefly describing its basic mathematical foundations (for details see Hoyle, et al 1995, op.cit.). We refer back to the Hoyle-Narlikar theory of gravitation described earlier. There we had reduced the field equations to Einstein-like form by going over to a 'constant mass' conformal frame. If we include the inputs from quantum theory and scale the action in terms of Planck's constant, then we find that the fundamental constants G, $\hbar$ and c, yield a unique mass unit, namely the Planck mass. Indeed if we put the last two constants equal to unity, then the mass arrived at earlier

$$m_0 = (3/4\pi G)^{1/2} \equiv m_P, \tag{38}$$

is the mass of the Planck particle. This suggests that in a gravitational theory without other physical interactions the particles must be of mass (38), which in ordinary practical units is about 10^{-5} gram, the empirically determined value of G being used.

The QSSC enriches the Hoyle-Narlikar theory of gravity with two modifications: (1) the introduction of the cosmological constant and (2) the possibility of creation of matter.

The cosmological constant arises when we modify the conformally invariant scalar wave equation for the mass function (26) by adding a cube term in mass. This is the most general modification of the wave equation while still preserving its conformal invariance. It leads to a λ - term whose magnitude depends on the number of particles in the Hubble-sphere. For $N \sim 2 \times 10^{60}$ Planck particles one gets $\mid \lambda \mid \sim 2 \times 10^{-56}$ cm $^{-2}$, agreeing closely with the magnitude that has observationally been assumed for λ. In the classical big bang cosmology there is no dynamical theory to relate the magnitude of λ to the density or other physical properties of matter. For observational consistency it is assumed that λ today is of the above order. The sign of the cosmological constant derived here is, however, negative. As we shall see shortly, this important difference is responsible for producing bounded oscillations. Although in standard cosmology, λ is taken to be positive, we will see that within the framework of the cosmology discussed here, a negative λ is not inconsistent with observations.

A dynamical derivation of λ within the standard cosmology is possible if one goes into the very early inflationary epochs. However, the values of λ deduced from those calculations are embarrassingly large, being 10^{108} - 10^{120} times the value given by today's observations. The problem then is, how to reduce λ from such high values to the presently acceptable range. By contrast, the QSSC derivation leads to the acceptable range of values with very few theoretical assumptions. Also, we have the satisfaction of seeing its smallness related to the large number N.

The second point of difference in the QSSC comes from the explicit introduction of creation of matter. If we assume a typical particle, the Planck particle to be created at a world point, its worldline has a finite beginning, i.e., it does not stretch with an affine geodetic parameter to $-\infty$. It is short-lasting, however, and decays to lower mass particles like the hadrons, leptons and radiatian in characteristic time $\tau \sim 10^{-43}$s. When we consider the Machian contributions from all these particles to inertia at a point in spacetime, we get the earlier field equations of the Hoyle-Narlikar Cosmology along with extra terms representing creation of matter (- and of course the λ -term). The simplified field equations in a suitably chosen conformal frame, are

$$R_{ik} - \frac{1}{2}g_{ik}R + \lambda g_{ik} = -8\pi G\Big[T_{ik} - f\Big(C_iC_k - \frac{1}{4}g_{ik}C_lC^l\Big)\Big], \tag{39}$$

with the coupling constant f defined as

$$f = \frac{2}{3\tau^2} \tag{40}$$

[We remind the reader that we have taken the speed of light $c = 1$.]

The creation event takes place only where the C-field terms (representing essentially the Machian contributions of the Planck particles) acquire sufficiently high intensity so as to satisfy the condition $\mid C_iC^i \mid = m_P^2$. It can be shown that this is possible only in the vicinity of massive collapsed objects (-almost like black holes!) where the gravitational fields are strong. Such locations give rise to explosive creation of matter. The creation is *non - singular*, however. For, the C-field expands the space by its feedback on geometry and this effect results in ejecting the newly created matter outwards. If such *minibangs* or *minicreation events* occur all over the universe, it expands. The field equations (39) describe solutions of this type. Here we consider the simplest such models briefly.

The spacetime geometry of the quasi-steady state cosmology (QSSC) is described, just as in standard cosmology, by the Robertson-Walkar line element, with the expansion of the universe determined by the scale factor $S(t)$. The difference in our theory is that the equation for the square of the time derivative of S now carries a negative term that decreases like S^{-4}. Thus, in a time-reversed picture, in which the scale factor S grows smaller, a stage will eventually be reached in which this new term will dominate over the *positive* term, due to the material content of the universe, that goes like S^{-3}.

The effect, as one goes backward in time, is to produce an *oscillation* of the scale factor:

$$S(t) = F_Q(t) \cdot \exp(t/P). \tag{41}$$

In the time-dependent scale factor, the parameter Q is the temporal period of the periodic function $F_Q(t)$, which turns out to be 5-10 times longer than the "age of the universe" arrived at in the Big Bang scenario. The other characteristic-time parameter, $P \gg Q$, describes an exponential growth that is very slow on the time scale of the periodic function. P is determined by the rate of matter creation averaged over a large number of minicreation events. Had we no oscillatory part in (41) we would have got the *steady state* solution if Bondi, Gold and Hoyle. The oscillatory part reflects the effect of minicreation events in controlling the expansion of the universe.

The quasi steady-state model also has two dimensionless parameters: the ratio $S_{\text{max}}/S_{\text{min}}$ between the amplitudes of $S(t)$ at its maxima and minima, and the ratio $S(t_0)/S_{\text{min}}$ of the present scale factor to its periodic minimum.

Typical values of these four parameters that best fit the observational data are

$$Q = 4.4 \times 10^{10} \text{ years }, P = 20Q,$$
$$S_{\text{max}}/S_{\text{min}} = 9 \text{ and } S(t_0)/S_{\text{min}} = 6. \tag{42}$$

Among the broad observational data that these parameters must reproduce are (1) the relationship between the redshifts of galaxies and their visual magnitudes, (2) the angular sizes of quasars at different redshifts, (3) the population counts of galaxies and radio sources, (4) the largest observed redshifts, (5) the microwave background and (6) the cosmic abundances of the lightest nuclear isotopes. It would take too much of space to describe how the QSSC manages these challenges. Here we refer the reader to details discussed by Hoyle, et al (2000). Suffice it to say that the QSSC has made a plausible beginning on most observational fronts to match the theory with facts.

Concluding remarks

What are the specific tests that may distinguish the QSSC from standard cosmology? A few are as follows:

(1) If a few light sources like galaxies or clusters are found with modest (~ 0.1) *blueshifts*, they can be identified with those from the previous cycle, lying close to the peak of the scale factor. In standard cosmology there should be no blueshifts.

(2) If low mass stars, say with half a solar mass, are found in red giant stage, they will have to be very old, say $\sim 40 - 50$ Gyr old, and as such they cannot be accommodated in the standard model, but will naturally belong to the previous cycle of the QSSC.

(3) If the dark matter in the galaxies is proved largely to be baryonic, or if other locations like clusters of galaxies turn out to have large quantities of baryonic matter, then the standard cosmology would be in trouble. For, beyond a limit the standard models do not allow for baryonic matter as it drastically cuts down the predicted primordial deuterium and also spoils the scenario for structure formation.

These observations lie just beyond the present frontiers of astronomical observations. So we hope that the cosmological debate will spur observers to scale greater heights and push their observing technology past the present frontiers, as happened fifty years ago with the debate about the original steady state cosmology.

This completes our account of evolution of alternative cosmologies through the twentieth century. There is no doubt that alternatives have contributed valuable ideas to cosmology and have acted as stimulus to new observations. So long as the speculative element in standard cosmology remains significant, alternatives have a role to play.

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