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Cosmologie/*Cosmology*

DÉBAT

DEBATE

Un débat majeur : la cosmologie du « Big Bang »
A major debate: the Big Bang cosmology

III. The case against the Big Bang

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Abstract. This article takes a critical look at the Hot Big Bang Cosmology (*HBBC*). It shows that two of its strongest lines of evidence, viz. the cosmic microwave background and the abundance of light nuclei are capable of being interpreted differently, and in a physically more realistic way. The *HBBC* is shown to have shifted its ground frequently under observational constraints, changing its parameters like Ω_0, Ω_b, Ω_λ and q_0, reinterpreting inflation, hedging options on dark matter, etc. Many of its present deductions are seen to be based on untested physics and unobservable events of the very early Universe, while its beginning in a spacetime singularity indicates its incompleteness as a physical theory. The example of the quasi-steady state cosmology (*QSSC*) is given to demonstrate that an alternative cosmology relying more on the ongoing astrophysical properties of the Universe and directly observable events is possible. The case is therefore made that the *HBBC* does not hold the 'monopoly' to be THE model of the Universe. © Académie des sciences/Elsevier, Paris

Big Bang / galaxies / quasars / cosmological front

Version française abrégée – Contre le « Big Bang »

La cosmologie du « Big Bang » chaud (en anglais : *Hot Big Bang Cosmology*, *HBBC* en abrégé) est considérée comme le modèle standard de l'Univers. Elle décrit l'Univers comme ayant trouvé son origine dans une explosion primordiale (le « Big Bang »), et vise à en décrire l'évolution depuis cette

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origine singulière jusqu'à son état actuel. La cosmologie *HBBC* cherche à associer ses prédictions théoriques aux observations astronomiques et à la théorie physique standard. D'une façon générale, on peut dire que sa force repose sur trois piliers : (1) l'expansion de l'Univers, telle qu'elle ressort des décalages spectraux des galaxies et des quasars ; (2) l'observation d'un rayonnement cosmique planckien de fond de ciel (*Cosmic Background Radiation*, ou *CMB* en anglais), extrêmement homogène sur le ciel ; et (3) les abondances observées des éléments légers. Ces trois phénomènes ont tous été prédits avant d'être observés : (1) par les modèles d'Alexander Friedmann, basés sur la relativité générale d'Einstein, (2) par George Gamow, Ralph Alpher et Robert Herman, par la considération du *CMB* comme un reliquat de l'ère antérieure dominée par le rayonnement, et (3) par Gamow et ses collègues, grâce aux applications de la physique nucléaire à l'Univers primitif.

Alors qu'au premier abord, ces arguments semblent très forts, sinon irréfutables, ils n'apparaissent plus comme tels à un examen plus approfondi. Une faiblesse de l'interprétation du *CMB* est qu'elle ne peut pas prédire la valeur observée réellement de 2,73 K. En ce qui concerne les éléments légers, on se rend compte actuellement que seulement trois ou quatre d'entre eux sont considérés comme ayant été formés au cours de la nucléosynthèse primordiale. En vérité, sur les 320 (ou à peu près) noyaux de la table périodique, ces cas apparaissent comme des exceptions, la règle générale étant que les noyaux sont élaborés au cours du déroulement de processus stellaires et galactiques. Aussi loin que peuvent aller les modèles relativistes, ils passent tous par une époque « singulière », dont on reconnaît qu'elle est « non physique », violant ainsi les hypothèses même de base (celle du principe d'action stationnaire), sur lesquelles ces modèles sont fondés.

La prétention du « Big Bang » à être basée sur la physique standard est aussi moins que précise, puisque les époques très primitives où ont pris place des événements aussi importants que l'inflation, où les germes des inhomogénéités, desquelles les grandes structures observées aujourd'hui sont supposées être issues, où la composition de la matière obscure baryonique ou non baryonique a été déterminée, – ces époques anciennes sont inobservables, et utilisent une physique non vérifiée. De plus, ces événements étant impossibles à répéter, on peut se demander si le « Big Bang » relève de la physique réelle, ou bien d'une chaîne de spéculations se nourrissant l'une de l'autre.

Une question spécifique encore non résolue est celle de l'« âge » de l'Univers du « Big Bang ». Le modèle classique plat, avec une densité de fermeture, naguère rigoureusement exploité par les théoriciens du « Big Bang » est maintenant connu comme impliquant un âge inférieur à celui de quelques-uns des amas globulaires de notre Galaxie. Et l'on a ramené la constante cosmologique dans la discussion, puisque cela permet d'accroître l'âge de l'Univers.

Le développement historique au cours des quatre décennies écoulées montre que les défenseurs du « Big Bang » ont fréquemment changé leur fusil d'épaule lorsqu'ils ont été confrontés aux données, tout en maintenant à chaque occasion qu'ils avaient obtenu la réponse correcte. Ainsi, la constante cosmologique est-elle entrée, et sortie, ainsi l'Univers a-t-il eu la densité critique, puis une densité basse, ainsi a-t-on fermement affirmé le freinage de l'expansion, et maintenant, non moins fermement, son accélération. Ces expériences soulèvent la question de savoir pourquoi nous devrions supposer que ces théoriciens ont raison, – maintenant.

Une affirmation objective doit suggérer par conséquent que le problème cosmologique est loin d'être résolu, et qu'un esprit scientifique se doit de laisser la question ouverte, de telle sorte que les idées alternatives sur la structure et l'évolution de l'Univers soient encore considérées comme méritant l'examen. Une telle alternative est la cosmologie de l'état quasi stationnaire (en anglais : *Quasi-Steady State Cosmology*, ou *QSSC*), proposée en 1993, et selon laquelle la dynamique de l'Univers est commandée par des événements locaux, de petites explosions, limitées et sans singularité aucune, de l'espace-temps. Aussi, contrairement au « Big Bang », la création de matière devient un processus continu, cohérent avec les lois de conservation de la matière et de l'énergie. Cette cosmologie est par conséquent « sans âge » ; elle n'a pas de problèmes du fait de l'existence de très vieilles galaxies. De plus, elle fournit une interprétation entièrement astrophysique du rayonnement de fond de ciel (*CMB*) et de l'origine des noyaux.

Considérons, par exemple, un scénario alternatif, dans lequel tout l'hélium observé est synthétisé par des processus stellaires. Un calcul simple montre que le rayonnement engendré de cette façon, s'il est thermalisé, sera représenté par une courbe de corps noir de température très proche de 2,73 K. On voit aussi que, dès lors que des échelles de temps de l'ordre de 10^{11} années sont disponibles, les autres noyaux légers peuvent aussi être engendrés dans les processus stellaires ou galactiques. La cosmologie *QSSC* permet d'envisager de telles échelles de temps et a suggéré également des processus de thermalisation du rayonnement stellaire, susceptibles de produire le *CMB*. Mais il est clair que de nombreux détails de cette cosmologie exigent encore d'être explorés plus avant.

En résumé, la cosmologie du « Big Bang », contrairement à l'image générale qui en est donnée, n'est pas si fermement installée dans l'évidence ; il y a encore de la place pour des cosmologies alternatives.

1. Introduction

The 'Hot Big Bang Cosmology' (*HBBC* in brief) is the modern paradigm for the origin and evolution of the Universe, from the mythical creation event to the present time, with some prognostications for the future. Over the last three decades the *HBBC* has acquired an aura of certainty and rectitude normally reserved in science for theories whose predictions have been fully confirmed by experiments and observations, such as the Einstein–Newton framework of planetary motion, the understanding of chemistry through the structure of the atom using quantum mechanics or the structure of the DNA in biology.

Prima facie, the following arguments can be made in favour of the *HBBC* paradigm (for details see the above article by Joseph Silk, in this volume).

(1) The *HBBC* predicted the expansion of the Universe (Friedmann, 1922, 1924; Lemaître, 1927) *before* it was discovered by Edwin Hubble (1929). The property of expansion has now been confirmed to much larger distances than originally claimed by Hubble.

(2) The *HBBC* models *predicted* the existence of a low temperature Planckian radiation background at the present epoch as a relic of the early hot post-Big Bang era (Alpher and Herman, 1948). This radiation background was observed by Penzias and Wilson (1965) and its Planckian spectrum fully confirmed by the COBE satellite in 1990 (Mather et al., 1990).

(3) The above prediction of radiation background by the *HBBC* was linked to the idea of synthesis of nuclei in the early Universe by Gamow (1946). Today, it is realized that the early hot era was essential for our understanding of the abundances of light nuclei like ^{4}He, ^{2}H, etc.

These are the main claims in support of the *HBBC* paradigm. Any others are easily seen as arising from the above basic features. The purpose of this article is to examine these claims (and other subsidiary claims) within the framework commonly applied to test the strength of a physical theory.

In section 2 we will outline the basic framework, the 'rules of the game' so to say, and apply it in sections 3–8 to the *HBBC* paradigm. In section 9 we will outline some alternative ideas which may have a useful role to play in our understanding of cosmology, while in the final section 10 we will refer to some anomalous observations that seem to suggest that our present understanding of cosmology, whether through the *HBBC* or otherwise may be grossly oversimplified.

2. Framework for assessing the *HBBC*

Following Karl Popper, one should expect a scientific theory to be subjected to tests which, in principle, can disprove the theory. If the *HBBC* is claimed by its strong adherents to be 'the definitive' statement on the past history of the Universe, then it should propose such tests. We will examine whether the *HBBC* has been subjected to such tests and how it has performed.

It has happened in the past that a scientific theory had to add extra parameters to sustain its predictions when confronted with observational/experimental tests. In itself this need not be a negative mark against the theory, provided an extra parameter so introduced has additional independent observational support for it (apart from the observation it was introduced to account for). A successful example of this approach is Niels Bohr's hypothesis for the *H*-atom, viz., that the angular momentum of an atomic electron is an integral multiple of $\hbar$. This may have appeared rather contrived to explain the discrete energy levels of the *H*-atom; but it subsequently turned out to be a profound statement on the general discrete behaviour of the microscopic world.

History is full of wrong hypotheses that went on adding new additional parameters to prop themselves against the impact of facts. The classic example is of the Philopaus's belief in the existence of a Central Fire around which the Earth revolves. To explain why the Fire is not seen, he had to invent a 'Counter-Earth' moving in such a way that it always came in between the Earth and the Fire. When sceptics asked "Why do we not see the Counter-Earth?", Philopaus had to argue that it was on the 'other' side away from Greece! The epicyclic theory of planetary motion is another example of a wrong approach feeding upon itself through a series of parameters.

Finally, in a causal framework followed in physics, a good theory proceeds from observed initial conditions at time $t = t_1$, say, and makes predictions for the future, say at $t = t_2 > t_1$ which are observationally or experimentally verified. In the case of cosmology, we observe the Universe *today*, at $t = t_0$ (say) and try to relate its present properties to the conditions existing in the past, at $t = t_p << t_0$. This is an inversion of the standard procedure in physics, and is justified, *provided* we can observe or verify the conditions at $t = t_p$. For, the causal cycle is then complete. We shall examine whether the *HBBC* conforms with this discipline.

In this critique of the *HBBC* we will not only reexamine the three claimed strengths of the paradigm referred to in the last section, but will also look at other observations of relevance to the basic issue. Where necessary, we will also look at the historical evolution of evidence vis-a-vis theory, as it provides a better perspective on the issues in the cosmological debate than just their present status.

3. The cosmic microwave background

The general perception that the cosmic microwave background (*CMB*) was discovered by Penzias and Wilson (1965) some seventeen years after its prediction by Alpher and Herman (1948) has been a strong point in the somewhat uncritical acceptance of this radiation as relic radiation. The impression has also been around that this is the *only possible interpretation* of the *CMB*. Taking these impressions together one may ask whether the *HBBC* can predict the present day temperature of the *CMB*.

Clearly, this is not the case, and has been admitted by supporters of the *HBBC* (Rees, 1978; Turner, 1993). Turner (op. cit.) for example, says: "...the CBR (Cosmic Background Radiation) is so fundamental to the standard cosmology that just trying to understand why its temperature is 2.726 K today leads one to discover the most fundamental features of the Universe as well as some of the most pressing cosmological problems – the origin of structure and the nature of the dark matter. In the end we have no firm explanation as to why the Universe even has a temperature; that is, where the fiery radiation came from..."

We will discuss later the difficulties the *HBBC* faces in understanding the origin of structure and the nature of dark matter. Concerning the problem of "where the fiery radiation came from" a very suggestive clue has been consistently ignored by the *HBBC* supporters largely because it does not fit in the standard scenario. The clue is as follows.

The mean density of matter in the form of baryons associated with galaxies is $\rho \sim 3 \times 10^{-31}$ $g{\cdot}cm^{-3}$, with a Hubble constant $H_0 = 60$ km·s^{-1}·Mpc^{-1} to set the extragalactic distance scale. A fraction 0.243 of this matter is believed to be in the form of helium, thus making the helium density to be 7.29×10^{-32} g·cm^{-3}. Now suppose that all of this helium was made in stars. The process $4\,\mathrm{H} \rightarrow {}^4\mathrm{He}$ yields an energy of radiation equal to 6×10^{18} erg for each gramme of ^{4}He produced. Thus a radiation energy density of 4.37×10^{-13} erg·cm^{-3} is produced. If this were thermalized, it would produce a radiation background of temperature 2.76 K. Compare this with the *CMB* temperature of 2.73 K. Given the approximate nature of ρ, the agreement is not bad.

This argument thus has the merit of relating two *presently observed* features of the Universe, viz. the helium abundance and the *CMB* temperature through the well understood astrophysical process of stellar nucleosynthesis of not too distant a past (the *HBBC* requires us to rely on a process that took place when the Universe was 1–200 second old, an era beyond access to present observations). This alternative argument, although attractive, is incomplete on two counts. First, we need to know whether the Universe has had time enough for the process of stellar nucleosynthesis and secondly, what is the process that thermalizes starlight? We will return to these issues later in this article.

4. Light nuclear abundances

One of the strong pillars supporting the *HBBC* is the process of primordial nucleosynthesis that is claimed to yield the correct light nuclear abundances. It is argued that while the heavier nuclei are all made in stars, the stellar scenario is inadequate to account for the light nuclei. Which is where the *HBBC* nucleosynthesis steps in. Since the primordial process is unable to deliver the heavier nuclei like C, O, etc., it is believed that the two processes, stellar and primordial fulfill complementary roles. It is worth reexaming this argument.

There are more than 320 isotopes in the periodic table. Almost all of them, with the possible exception of a few light isotopes, are now understood to be of stellar origin. The exceptions include D, He, Li, Be and B, of which we have already discussed a possible stellar scenario for making ^{4}He, to which we will return in section 9. In their paper on stellar nucleosynthesis Burbidge et al. (1957) had denoted by 'X-process' the then unknown process that may produce light isotopes in a stellar framework. Recently Burbidge and Hoyle (1998) have outlined a possible alternative approach, that of making even the light nuclei in stars.

First consider the *HBBC* claim that the synthesis of light nuclei is naturally possible in the primordial era. It has been well known for many years, (see, for example, Wagoner et al., 1967) that the primordial nucleosynthesis process gives abundances of D, ^{3}He, ^{4}He and ^{7}Li in satisfactory agreement with astronomical observations if the average density of baryons ρ_b was related to the radiation temperature T_9 in units of 10^9 K by the relation $\rho_b \cong 10^{-5}\,T_9^3$. According to the *HBBC*, the ratio has remained unchanged since the nucleosynthesis epoch. Inserting therefore the present value of $T_9 = 2.73 \times 10^{-9}$, we get ρ_b at present as 2×10^{-31} g·cm^{-3}. This is some two orders of magnitude below the closure density. (We continue to take $H_0 \approx 60$ km·s^{-1}·Mpc^{-1}).

The above result is a rather severe constraint for the *HBBC*, especially since the predicted abundance of D drops sharply if the baryonic density increases significantly above this value. We have already noted the observed density of galactic matter at 3×10^{-31} g·cm^{-3}. This estimate, within its observational errors, is consistent with the above density. However, if we include dark matter in the halos of galaxies and clusters of galaxies, in addition to this value, there is obvious problem with the deuterium abundance. Hence the *HBBC* has to *assume* that this additional dark matter is *non-baryonic*.

The proportion of non-baryonic to baryonic dark matter is even higher (more than ten times) if the *HBBC* theories driven by inflation demand that the density is equal to the closure density ($\Omega_0 \approx 1$). Inflation was once the most popular option for the *HBBC*, although during the 1990s it began to lose its sheen at least for cosmologists driven by observational considerations.

Returning to light nuclei, Burbidge and Hoyle (op. cit.) have pointed out that spallation reactions of high energy cosmic ray protons on ^{12}C and ^{16}O nuclei can produce the isotopes ^{6}Li, ^{9}Be, ^{10}B and ^{11}B. Modern work shows that high energy C and O can also bombard protons and α-particles to produce these nuclei (see for example, Vangioni-Flam et al., 1996). Stellar winds from massive stars and ejections from supernovae can produce such high energy nuclei. Concerning ^{7}Li, apart from the *HBBC* nucleosynthesis, process of galactic production has also been suggested by the recent observations of stellar abundances (Rebolo et al., 1988; Balchandran, 1990; Lemoine et al., 1995).

Burbidge and Hoyle have also argued that ^{3}He is produced in large quantities in dwarf stars. There are several other stars which show that most of the helium in their atmosphere is in the form of ^{3}He. A longer time scale for stellar processing is capable of yielding an ^{3}He/H ratio $\approx 2 \times 10^{-5}$ as observed. Likewise there is growing evidence of processes that can generate deuterium in stars, e.g. in stellar flares and given a time scale of the order of 10^{11} yr, (see section 9) it would not be difficult to enrich the interstellar gas with D to the extent observed. More measurements of the D/H ratio will throw light on the process of deuterium production.

Thus it appears that primordial (*HBBC*) nycleosynthesis can at best deliver only a few light nuclei provided it severely constrains the baryonic matter density. The alternative scenario of stellar nucleosynthesis can in principle deliver *all* of the 320 or so isotopes, provided, in some cases, longer than the *HBBC* time scales are allowed. We will show how these time scales are possible in an alternative cosmology outlined in section 9.

5. Inflation and the age problem

In the euphoria following the idea of inflation in the 1980s, many *HBBC* theoreticians converged on $\Omega_0 = 1$ as the right Friedmann model. Inflation offered remedies for a number of weaknesses of the *classical HBBC*, such as the horizon problem, the flatness problem, the entropy problem, etc. It also offered solutions to problems newly acquired from astroparticle physics, such as the magnetic monopole problem, the domain wall problem, etc. The earlier set of problems were of course known before. But following the dictum: “Acknowledge the weaknesses of your theory only when you have found cures for them”, these had not received much publicity. With the arrival of inflation these problems were duly recognized and used to justify *why* inflationary era was essential in the *HBBC*. However, even till today there is no agreement amongst the Big Bang proponents as to the basic physical theory that drives inflation.

On the contrary, inflation also brought with it some constraints. By doing away with fine-tuning of density, it led to $\Omega_0 = 1$. This, however, constrained the Universe to an age of 2/3 H_0. For $H_0 \leq 50$ km·s^{-1}·Mpc^{-1}, this age was ≥ 13 Gyr, not inconsistent, although not quite comfortable with the ages of some old globular clusters in the range 12–18 Gyr. The revised measurements of H_0 by the HST, however, pushed its value higher, in the range of 60–80 km·s^{-1}·Mpc^{-1}, thereby bringing the age of the Universe down to range $\sim$ 8–10 Gyr. Thus there was a conflict between the stellar ages and the age of the Universe.

In the 1990s therefore there began a change over from the clear inflationary prediction $\Omega_0 = 1$ to $\Omega_0 + \Omega_\lambda = 1$, where Ω_λ was the contribution of the cosmological constant. A lowering of Ω_0 and raising of Ω_λ *increases* the theoretical age of the Universe and one can raise it to accommodate the uncomfortably large stellar ages. For a discussion of this constraint see a review by Bagla et al. (1996). Thus inflation survives but with a heavily tarnished reputation. Many Big Bang theoreticians no longer wish to refer to inflation, although if it is banished altogether, the acknowledged weaknesses of the *HBBC* will resurface.

6. The problem of the cosmological constant

There is another theoretical difficulty arising from the legacy of inflation, namely the cosmological constant. This has been pointed out by several theoreticians (see, for example, Weinberg, 1989). However, first let us look at the observational situation.

The cosmological constant (λ) has had a mixed history. It was first proposed by Einstein in 1917, who needed it to balance the force of gravity in order to have a static model of the Universe. He abandoned it, when in the post 1929-cosmology the Universe was generally believed to be non-static and expanding.

Since then λ has been in and out of favour in the *HBBC*. It is invoked whenever observations constrain the theory, since its inclusion widens the parameter space of the *HBBC* models. It is quietly buried when the constraining observations turn out to be inconclusive. It is a safe bet today that if future observations lead to $H_0 \leq 50$ km·s^{-1}·Mpc^{-1} and if stellar ages are revised downwards to < 12 Gyr, the cosmological constant will be put back in the mothballs. Whether it is in or out, the *HBBC* proponents justify its status with equal conviction.

Bagla et al. (1996) had concluded that the present observational constraints force one to $\lambda > 0$, and that too into a relatively narrow window. The parameter $\Omega_\lambda = \lambda c^2 / 3 H_0^2$ is believed to be in the range (0.4-0.7). If it is lower than 0.4, there is problem with the age of the Universe (see section 5) and the m–z relation using supernovae. If it is higher than $\sim$ 0.7, there is conflict with the frequency of gravitationally lensed objects. Recent observations of supernovae in galaxies of redshifts upto ~ 1 show that the $\Omega_\lambda = 0$ models are ruled out, that the Universe is accelerating. Thus in the current phase of the *HBBC* opinion the λ is riding high. In c.g.s. units its value is of the order 10^{-56} cm^{-2}.

Let us go back to the theoretical problem of having a λ-term of this order, *if* one believes in the existence of the inflationary phase. For, during that phase, when the characteristic time scale of expansion was $\sim 10^{-36}$ s, the vacuum energy had generated a cosmological constant of order $\sim 10^{52}$ cm^{-2}. In the original version of inflation, the constant dropped to zero after the transition from the old vacuum to the new vacuum took place. Thus there should be no cosmological constant today. This clear-cut prediction now has to be replaced by another which says that a small residual λ was left behind *after* the transition was over, its value being $\sim 10^{-56}$ cm^{-2}. Thus, a fraction $\sim 10^{-108}$ of the original (inflationary) value is left as a relic.

This is an example of the kind of fine turning that inflation was proposed to do away with! For, if the fraction were different (say, 10^{-107} or 10^{-109}), it would drastically alter the present day λ, making it ten times larger or ten times smaller. Considering the presently permitted window of values of λ, it means that the post-inflationary Universe was fine-tuned to meet the exact requirements of today.

7. The Big Bang singularity

The very event of 'Big Bang' is mathematically identified as a spacetime singularity. At a singularity the mathematical description of spacetime geometry breaks down, e.g. through the divergence of curvature invariants like R, $R_{ik}R^{ik}$, $R_{ijkl}R^{ijkl}$, etc. Physical notions likewise become undefinable, e.g., through the divergence of density, temperature etc.

It is not difficult to show that the appearance of Big Bang is paradoxical and demonstrates some internal inconsistency of classical relativistic cosmology. For, here we begin with the classical action principle including the Hilbert action term

$$-\frac{c^4}{16\pi G}\int_{\mathcal{V}} R\sqrt{-g}\,\mathrm{d}^4x$$

where $\mathcal{V}$ is any four-dimensional spacetime volume. The variation of the metric tensor is $\mathcal{V}$ then leads to the classical Einstein equations of relativity, the rational being that the volume $\mathcal{V}$ as well as the variations of the metric are chosen *arbitrarily*. Next the equations are solved under symmetry assumptions of Weyl's postulate and the cosmological principle, leading to the Friedmann–Lemaître solutions. These in turn take us to the Big Bang epoch. Being a singular epoch, however, it would not and could not be included in the region $\mathcal{V}$ where the variation of action was performed. [The Euler–Lagrange variational process demands a certain degree of smoothness in the form of continuity and differentiability of spacetime geometry which is violated by the existence of a spacetime singularity.] Thus the very framework on which the deduction of Big Bang rests is nullified.

In the 1950s and the early 1960s, there were serious attempts to look for nonsingular cosmological models through the introduction of spin and shear [for a review, see Narlikar and Kembhavi, 1980]. These did not succeed and the reason became clear a few years later through the singularity theorems of Penrose, Hawking and Geroch (for a review, see Hawking and Ellis, 1973). So long as the stress energy tensors satisfy certain 'physically reasonable' energy conditions, and a few other generic conditions are assumed, the theorems led to the result that a spacetime singularity is unavoidable.

The existence of a singularity that breaks the very rules on which the theory is based points to a defect or incompleteness of the theory. In this case, a natural deduction should have been to look upon the relativistic framework in that light, and to look for its modification or augmentation, e.g. through an appeal to a quantum theory of gravity. Instead, the singularity theorems were used as a ex-post-facto justification of the Big Bang.

More recently the study of gravity in the quantum domain has generated more interest through approaches like loops, strings, path integrals etc. Whether these techniques succeed in eliminating the spacetime singularity remains to be seen. In the meantime works like that by Senovilla (1991) have inspired efforts to look for singularity-free solutions within the classical relativity by relaxing some of the conditions of the singularity theorems. The C-field cosmology that gave the nonsingular steady state model in the 1960s has demonstrated that by relaxing the energy conditions singularity can be averted (Hoyle and Narlikar, 1964). Again, it is ironical that the C-field approach which was criticized on the grounds of breaking the energy conditions found popular support when it reappeared in the 1980s under the garb of inflation. Linde's (1987) nonsingular eternally self-reproducing Universe is in principle no different from the much-maligned steady state Universe of Bondi and Gold (1948) and Hoyle (1948); but this fact is never acknowledged by those who work in the inflationary paradigm.

8. The dark matter problem

There is considerable observational evidence of dark matter. The flat rotation curves of spiral galaxies and the relaxed velocity distribution in a few clusters indicate the existence of unseen gravitating matter far in excess of the observed matter. However, a note of caution is advised: do not apply virial theorem to clusters which are manifestly *not relaxed*, as this would lead to an over-estimation of dark matter. There are many highly irregular clusters which are clearly unstable, and are either just forming or coming apart. As Victor Ambartsumian put it, they are systems of positive energy. To apply virial theorem to them would lead to an over-estimation of dark matter.

There are two reasons why too high a density of ordinary matter is as embarrassment to the *HBBC*. We have already discussed one, namely the limit on baryonic density by the requirement of primordial deuterium production. The other comes from structure formation and is briefly as follows. The *HBBC* envisages the present-day large scale structure as evolving out of primordial seeds of density fluctuation. The one major advantage of the inflationary phase is claimed to be the evolution of a scale invariant spectrum, originally discussed in the context of galaxy distributions by Harrison (1970) and Zel'dovich (1972). Nevertheless, if all matter were baryonic it would interact with primordial radiation, thus leaving fairly major imprints on the radiation background in the form of temperature fluctuations $\Delta T/T$. The theories of the 1970s and 1980s predicted $\Delta T/T$ in the range of 10^{-4} to 10^{-3} but these were not found. To reduce $\Delta T/T$ to low enough values therefore non-baryonic matter had to be involved. If the dominant part of the matter were non-baryonic, it would gravitationally control the evolution of large scale structure without disturbing the radiation background.

The COBE finding of $\Delta T/T$ of the order of a few times 10^{-6} in 1992 has been claimed as a great success for the *HBBC*. The discovery has to be seen against the background of null results by successive searches during the 1970s and 1980s at the higher levels then predicted by the *HBBC* theorists. These earlier results had forced the *HBBC* structure formation scenarios to go in search for esoteric dark matter of the non-baryonic kind.

Despite the COBE findings, and more detections of $\Delta T/T$ by other surveys, the structure formation scenario is still far from clear. Assumptions about hot/cold/mixed non-baryonic dark matter, biasing, epoch dependent biasing, the Hubble Constant, the density parameter, the cosmological constant, etc. have to be folded in along with the initial conditions to see how large scale structure developed. The evolution of structure is being tried with the Zel'dovich approximation, percolation, genus, N-body simulations with various algorithms, etc.

The basic question a sceptic may ask is: "Is this physics?" In a physical theory one starts with observed initial conditions, puts in the various assumptions of the theory, makes predictions which are tested with final results. In the *HBBC* there is no independent information available about the initial fluctuation spectrum, although the present-day observations of large scale structure provide the information about the final state. Instead we have one set of assumptions feeding upon another in order to build up a self-consistent process whose starting point is untestable. Discoveries by future *CMB* projects like *PLANCK* or *MAP* are expected to provide further epicycles to the current scenario.

Meanwhile there is no evidence whatsoever for the species of non-baryonic dark matter on which all these scenarios are based. One may make a safe prediction as follows. Should the high energy particle accelerators find evidence for a non-baryonic particle, it will be hailed as confirmation of one or other of the existing scenarios, even though it is a far cry from artificial production in a terrestrial accelerator to a continued existence in the intergalactic space.

9. The quasi-steady state cosmology

The above objections to the *HBBC* range from the theoretical to the observational and carry different degrees of emphasis. At worst the theory is incomplete and in conflict with observations, being propped up by epicycles. At best it is a mutually consistent set of assumptions not all of which are supported by independent observations. But in no case is it a strong enough physical theory to be entitled to the monopolistic status it currently enjoyes.

At this stage the *HBBC* supporters might argue that as this is the only theory worked out to any depth and detail, the best bet is to work on it till all its anomalies are cleared. This is easily seen to be a circular argument since it does not allow alternative theories to be developed in detail to be compared to the *HBBC* and reality.

In the 1950s and till the mid-1960s the Steady State Cosmology (*SCC*) had played the role of an alternative cosmology. The discovery of the *CMB* in 1965 and its interpretation as relic radiation together with the growing belief that light nuclei cannot be made in stars, led to the *SSC* dropping out of contention and the *HBBC* assuming the role of the unique standard model.

In this article we have seen that over the last three decades the unique status enjoyed by the relic interpretation has eroded. Indeed making the *CMB* by thermalization of starlight explains its present temperature while making the light isotopes in stellar/galactic setting will bring the creation of all 320-odd isotopes under one scenario. The question is, can a new cosmological theory be built which allows long enough time scales for the above alternative processes? Here we will briefly outline the Quasi-Steady State Cosmology (*QSSC*) to show how such a theory might be constructed. For a recent technical review of the *QSSC* see Narlikar (1999).

The *QSSC* describes the Universe as an entity without a beginning and without an end, but in which matter is created in 'mini-creation events'. The creation is at the expense of a cosmological field C with *negative energy and stresses.* Both the creation process and the interaction of the C-field and the created matter with gravitation is described through field equations derived from an action principle. The action is Machian in the sense that the inertia of a typical particle is linked to the existence of other particles in the Universe through a long range conformally invariant scalar interaction.

The resulting field equations also are conformally invariant and in a specific conformal frame look like Einstein's equations with a cosmological constant while their right hand side has matter energy tensor and the energy tensor for the C-field. The creation process causes matter to be created at the expense of the C-field. Thus it preserves the law of conservation of matter and energy, with the condition C_i (the gradient of the C-field) equalling the four-momentum of the created particle. The rest mass of the created particle is none other than the Planck mass $m_p = (3\hbar c/4\pi G)$. (The Machian way of interpreting this relation is to argue that G is determined by the mass m_p of the created particle). Likewise the cosmological constant is given by $\lambda \sim \mathcal{N}^{-2}$, where $\mathcal{N}$ is the number of particles in the observable Universe. With $\mathcal{N} \sim 10^{60}$ the value of $\lambda \sim 10^{-56}\,\mathrm{cm}^{-2}$.

The creation process typically takes place around a collapsed massive object whose strong gravitational field lifts the strength of the C-field to a level where the creation condition $C_i C^i = M_o^2 c^4$ is satisfied in its neighbourhood. The presence of the created C-field exerts a negative pressure causing the spacetime in the neighbourhood of the collapsed massive object to expand rapidly, thus ejecting the created matter. In some cases the growth of the C-field in the massive object may cause a break up of the object leading to coherent chunks being ejected. If the object is spinning, then the ejection would be preferentially along its axis of spin. The explosions in active galactic nuclei, quasars, the jets from radio sources, the gamma ray bursts, etc. could be examples of such mini-creation events. Notice that unlike the big bang, the mini-creation events are non-singular and consistent with established conservation laws.

The overall effect of the *C*-field cosmologically is to make the Universe expand. However, the long term expansion with a scale factor $\alpha \exp(t/P)$ as in the old *SSC*, with time scale *P* is superposed with short term oscillations with time scale $Q \approx P/20$. The oscillations correspond to phases when the mini-creation events are switched on and off. Since the cosmological level of the *C*-field strength rises and falls, a typical mini-creation event works well when the above level is high and is switched off when the level of the *C*-field strength falls too low.

The *QSSC* is able to explain all present cosmological observations of discrete sources with $P \sim 10^{12}$ yr, $Q \sim 5 \times 10^{9}$ yr. These include the present value of H_0 ($\approx 60 - 65$ km·s^{-1}·Mpc^{-1}), the m–z (magnitude-redshift) relation by using Type IA supernovae, the radio source count, the θ (angular diameter)–z relation for ultra-compact sources, the surface brightness–z relation, etc. Also, in an infinitely old Universe there is no problem of very old galaxies.

The *QSSC* oscillations are finite with the maximum redshift observable in the present cycle at $\sim$ 5–6. Thus each cycle is matter-dominated. The radiation background is, however, maintained from one cycle to the next one. Thus from the minimum scale phase of one cycle to next, its energy density is expected to fall by a factor $\exp(-4\,Q/P)$. This drop is made up by the thermalization of starlight produced during the cycle. This if ϵ is the energy density of starlight generated in a cycle and u_m is the energy density of the *CMB* at the start of a cycle, then $\epsilon \cong 4u_m\,Q/P$. If the cycle minimum occurred at redshirt z_m, then the present *CMB* energy density would be $P\epsilon/4Q(1 + z_m)$. Substituting the values of ϵ, P, z_m and Q we can extimate the present-day energy density of *CMB* and the result agrees well with the observed value of $\sim 4 \times 10^{-13}$ erg·cm^{-3} corresponding to temperature ~ 2.7 K. This calculation is, of course a minor variation on the calculation of section 3, which provided an astrophysical explanation of the *CMB*.

How is the starlight thermalized? Consider the following scenario. The cooling of metallic vapours including carbon produces whisker-like particles of lengths $\sim$ 0.5–1.0 mm, which convert optical radiation into millimetre one. Such whiskers typically form in the neighbourhood of supernovae (which eject metals), and subsequently pushed out of the galaxy through pressures of shock waves. It can be shown that a density of $\sim 10^{-35}$ g·cm^{-3} of such whiskers close to the minimum of the oscillatory phase would suffice for thermalization of starlight. Narlikar et al. (1997) have discussed evidence for such whiskers in different astrophysical settings.

In section 4 we had shown that light nuclear abundances can be explained in a stellar framework, provided we have time scales of the right order ($\sim 10^{11}$ yr). The *QSSC* does provide such time scales with *P* as large as 10^{12} yr, $Q \sim 5 \times 10^{10}$ yr. Certainly with the *QSSC* providing an alternative cosmology this possibility deserves serious consideration.

The preliminary investigations of structure formation in the *QSSC* have yielded promising results (Ali et al., 1999). The large scale structure may develop through minicreation events ejecting coherent objects some of which may act as centres of future creation. An N-body simulation using this algorithm shows how filaments and voids emerge through iteration of the creation process. The two-point correlation function for a 3D simulation has the observed index ~ -1.8.

Finally, the *QSSC* does not place any limit on the density of baryonic matter either from the nucleosynthesis point of view or from considerations of large scale structure. Thus the dark matter in galaxies could be baryonic, being burnt out old stars, white dwarfs, etc. as well as low mass 'failed' stars.

There are several possible tests distinguishing the *QSSC* from the big bang. The former predicts, for example, the existence of galaxies with modest blueshifts, seen at the peak of the scale of the last cycle. Such galaxies will be very faint, $m \sim 27$. Further, a half solar mass star, may take as long as

$\sim$ 50 Gyr to evolve off the main sequence. If such stars are found on the giant branch, it will be almost impossible to explain their existence in the *HBBC*, whereas, they could be accommodated in the *QSSC* without difficulty.

10. Concluding remarks

In this article we have shown that the acknowledged strength of the *HBBC*, viz. the predictions of the expansion of the Universe, the cosmic microwave background and the abundances of light nuclei can no longer be considered arguments powerful enough to justify its claim as the one and only viable theory of the real Universe. The microwave background and light nuclear abundances can be explained by an alternative, purely astrophysical scenario. We have also seen how, to understand the emerging details of the Universe the *HBBC* has to make many epicyclic assumptions which have no basis in direct observation. Nor can it make the claim to be the only viable cosmological theory, since alternative cosmologies like the *QSSC* have made considerable progress in understanding the real Universe.

Because of limitations of space we have not discussed an important set of observations that hit at the very basis of cosmology, viz. the Hubble law. These observations relate to anomalous redshifts of extragalactic objects, falling into several categories. For details we refer the reader to Arp (1987, 1998) and Hoyle et al. (1999). These observations indicate that the redshift of an extragalactic object may not necessarily depend on its distance. If confirmed, these findings will require new ideas to understand them.

The *C*-field of the *QSSC* or the redshift anomalies referred to above are often criticized by the proponents of *HBBC* on the grounds that they demand new untested physics. However, the *HBBC* concepts of the very early Universe such as the big bang itself, high energy physics of basic interactions at $\geq 10^{16}$ GeV, events like inflation lasting no longer than 10^{-36} s, the assumption of cold dark matter, etc. are open to the same criticism, perhaps at an even stronger level. For, many of these concepts involve unobservable and unrepeatable events, and thus raise the question, as to whether we are following here the standard practice of science of dealing with repeatable experiments.

Considering the vast input of data coming from various observing instruments, it is premature to freeze one's option in favour of the hot big bang cosmology as the only theory of the Universe. Perhaps one should heed Landau's cautionary dictum: "Cosmologists are always wrong, but never in doubt." As it has done in the past on so many occasions, the Universe may once again and before long, prove the majority conviction wrong.

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