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Nonconservation of Baryons in Cosmology—Revisited

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Abstract. The concept of the steady-state universe discussed by Hoyle & Narlikar two decades ago is revived in the light of the present discussions of the phase transition in the early big-bang universe. It is shown that with suitable scaling the bubble universe solution bears a striking similarity to the inflationary scenarios being discussed today. The currently discussed idea of cosmic baldness was also anticipated in the *C*-field cosmology of the steady-state universe.

Key words: Cosmology—steady-state universe—inflationary universe

1. Introduction

The de Sitter model of the universe was the second cosmological model to come out of general relativity. Although first proposed in 1917, it has been found to be of relevance in different cosmological scenarios. Thus it featured as the line element of the steady-state universe in 1948 (Bondi & Gold 1948; Hoyle 1948) and more recently, it has been invoked to describe the inflationary phase of the early big-bang universe (Guth 1981).

The physical motivation in each case has been different. The original de Sitter universe was supposed to be empty but had the feature of expansion based on trajectories of test particles (‘motion without matter’). The steady-state theory arrived at this space-time either from the perfect cosmological principle or from a dynamical field theory while in inflationary scenarios a phase transition generates this solution. The purpose of this paper is to highlight the extraordinary similarity of ideas in the *C*-field theory of steady-state cosmology and the main features of the presently popular inflationary models.

In the mid-1960s Hoyle & Narlikar published a series of three papers (1966a, b, c; hereafter Papers 1, 2 and 3 respectively) on cosmology and cosmogony, based on the *C*-field theory of matter creation (Hoyle & Narlikar 1963). Paper 1 dealt with the concept that the strong gravitational fields of collapsed objects (black holes were still to gain currency in those days) would facilitate the creation of baryons in their vicinity. The de Sitter line element

$$ds^2 = c^2dt^2 - e^{2Ht}\,[dr^2 + r^2\,(d\theta^2 + \sin^2\theta\, d\phi^2)] \tag{1}$$

was thus seen as describing the large-scale space-time of the steady-state universe in which, on an average, matter creation in a large region keeps pace with its expansion. The overall Hubble constant H was seen to be related to the baryon mass m and the constant f, coupling the C-field to the newly created matter:

$$H^2 = \frac{4\pi}{3} Gfm^2. \tag{2}$$

Here G is the gravitational constant.

In Paper 2 Hoyle & Narlikar considered the possibility of departures for the steady state, when Equation (2) does not hold. We showed that if baryon creation was 'switched off' in a given region of space-time, that region would expand essentially as the standard Friedmann model. This steadily rarefying region would therefore appear as a 'bubble' in a denser medium, and it was argued that we live in one such bubble. In a radical departure from the steady-state assumption of Paper 2 we then argued that the coupling constant f was considerably higher (by $\sim 10^{20}$) than that given by Equation (2); that is, the Hubble constant of the denser medium outside the bubble was higher (by $\sim 10^{10}$) than that estimated at present.

The same phenomenon on a smaller scale led us to the formation of elliptical galaxies around dense massive nuclei. This was discussed in Paper 3 where it was argued that because of the observed absence of rotation in ellipticals it was hard to imagine their formation through a condensation process.

It is interesting that the ideas outlined in these three papers are now finding currency. The difficulty of low angular momentum in ellipticals is being realized as a major difficulty of the theory which seeks to form them by condensation of a gas cloud (Efstathiou &Jones 1979).The discovery of a massive collapsed object in M87 (Sargent *et al.* 1978; Young *et al.* 1978) has emphasized the possible dynamical importance of massive galactic nuclei. Recently Carr & Rees (1984) have argued that supermassive pregalactic objects might nucleate galaxies around them. It would appear that the objections of 18 years ago to the ideas of Paper 3 seem to have disappeared in the meantime.

However, it is the ideas in the first two papers that I wish to discuss here. Although the *C*-field cosmology worked within the framework of general relativity and thus ensured the conservation of energy and momentum, its notion of baryon nonconservation was anathema to theoretical physicists of the 1960s. Not so now! Under the grand unification programme the creation or annihilation of baryons is considered not only possible but also probable. Further, the inflationary phase in the universe makes use of the de Sitter expansion (1), coupled with the idea that our observable universe is a tiny bubble in the cosmological substratum (Guth 1981). Although the basic motivation may be different in the two cases, the striking similarity of the two cosmological models warrants taking a second look at the *C*-field cosmology.

In the following section the basic formalism of the *C*-field theory is described. In Section 3 the bubble solution is discussed with new boundary conditions relevant to the present calculations of the early universe. In the final section we compare the bubble universe with the inflationary universe and highlight the features of the latter which were anticipated by the former.

2. The *C*-field cosmology

2.1 *The Basic Formalism*

Although in his first and subsequent papers on the discussion of continuous creation of matter Hoyle (1948, 1949) had used scalar field theories, a simple and elegant formulation was given in 1960 by the late M. H. L. Pryce (personal communication).

Following the principle of Occam's razor, Pryce assumed the field to be scalar, with zero mass and zero charge, and derived its properties from an action principle. In our discussions of matter creation Hoyle & Narlikar adopted the Pryce formulation.

In the following discussion we will use the Hilbert action principle and assume that the space-time contains a set of particles *a*, *b*, . . . with masses m_a, m_b, . . . which do not interact except via gravity and the scalar *C*-field of Pryce. Accordingly, the action is given by

$$\mathcal{A} = \frac{1}{16\pi G}\int R\sqrt{-g}\,\mathrm{d}^4x - \sum_a \int m_a \mathrm{d}s_a - \frac{1}{2}f\int C_i C^i \sqrt{-g}\,\mathrm{d}^4x + \sum_a \int C_i \mathrm{d}x_a^i, \tag{3}$$

where we have taken the speed of light = 1. In Equation (3) C_i stands for the derivative $\partial/\partial x^i \equiv C_{,i}$, x_a^i and s_a are the coordinates ($i = 0, 1, 2, 3$) and proper time along the world line of particle *a*, while *f* is a coupling constant.

The apparently simple form (3) conceals the non-trivial aspect of matter creation which becomes clear when we examine the last term in $\mathcal{A}$. If there were no matter creation, this term would be path-independent and make no contribution to the action. If, however, the world line of *a* has end points at A_- (annihilation) and A_+ (creation) then it contributes to $\mathcal{A}$ through the last term, an amount

$$\int_{A_+}^{A_-} C_i \mathrm{d}x_a^i = C(A_-) - C(A_+). \tag{4}$$

In other words, the *C*-field does not interact with matter except when it is created or annihilated.

Thus the variation $\mathcal{A} \to \mathcal{A} + \delta\mathcal{A}$ which is caused by varying the world line of particle *a* gives for $\delta\mathcal{A} = 0$ the geodetic equation

$$\frac{\mathrm{d}^2 x_a^i}{\mathrm{d}s_a} + \Gamma^i_{kl}\frac{\mathrm{d}x_a^k}{\mathrm{d}s_a}\frac{\mathrm{d}x_a^l}{\mathrm{d}s_a} = 0 \tag{5}$$

together with the end-point conditions

$$m_a \frac{\mathrm{d}x_a^i}{\mathrm{d}s_a} = C^i, \qquad C^i C_i = m_a^2. \tag{6}$$

The variation of *C* gives, for $\delta\mathcal{A} = 0$,

$$\Box C \equiv C^k{}_{;k} = \frac{1}{f}n \tag{7}$$

where n = net number of creation events in unit proper 4-volume. Each point of A_+ type contributes + 1 to *n* while each point of A_- type contributes – 1.

The variation of the metric gives the modified Einstein field equations

$$R^{ik} - \frac{1}{2}g^{ik}R = -8\pi G\left\{\underset{(\mathrm{m})}{T^{ik}} + \underset{(\mathrm{c})}{T^{ik}}\right\} \tag{8}$$

where $\underset{(\mathrm{m})}{T^{ik}}$ is the matter energy tensor for the system of particles *a*, *b*, . . . and $\underset{(\mathrm{c})}{T^{ik}}$ is given by

$$\underset{(c)}{T^{ik}} = -f\left\{C^iC^k - \frac{1}{2}g^{ik}C^lC_l\right\}. \tag{9}$$

Although $\underset{(c)}{T^{ik}}$ has the familiar form for a scalar field it is different in one important aspect: it has a minus sign in front which (for $f > 0$) implies that the C-field has negative energy density. Under normal circumstances this would be a cause for concern from the quantization point of view. However, here the situation is somewhat different. As part of Einstein's equations the C-field is coupled to gravity and any quantum cascading down the negative energy states would result in a rapid expansion of space which acts as a control on the cascading process. In the 'steady state' the expansion of the universe just balances the cascading tendency so that $\underset{(c)}{T^{ik}}$ is finitely negative.

The divergence of Equation (8) gives

$$\underset{(m)}{T^{ik}}{}_{;k} = fC^iC^k{}_{;k}. \tag{10}$$

This is the modified conservation law of energy. If there is net creation of matter then the left hand side of Equation (10) is nonzero. From Equation (7) we see that the right-hand side is also nonzero. On the other, hand we can also get solutions with *no* net creation (or annihilation) for which

$$\Box C = 0. \tag{11}$$

As we shall see in Section 2.2 below, these solutions are analogous to the Friedmann models.

2.2 *Cosmological Solutions*

We now consider applications of this formalism to cosmology and will first discuss the steady-state solution and the bubble universe. Accordingly we take the space-time to be given by the Robertson-Walker line element

$$ds^2 = dt^2 - S^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\right] \tag{12}$$

where $k = 0$, $+ 1$ or $- 1$. The field equations in the case of a dust universe with density ρ become

$$\frac{\dot{S}^2 + k}{S^2} = \frac{8\pi G}{3}\left(\rho - \frac{1}{2}f\dot{C}^2\right) \tag{13}$$

$$2\frac{\ddot{S}}{S} + \frac{\dot{S}^2 + k}{S^2} = 4\pi G f\dot{C}^2. \tag{14}$$

Here, in the homogeneous isotropic case C depends on t only.

Equation (7) takes the form

$$\frac{f}{S^3}\frac{d}{dt}(\dot{C}S^3) = n(t), \tag{15}$$

where $n(t)$ is the rate of creation of particles of mass m per unit proper 3-volume. Thus we get from 7

$$\dot{\rho} + \frac{3\dot{S}}{S}\rho = nm. \tag{16}$$

Assuming that particles of mass *m* are created at rest in the cosmological substratum we get from (6)

$$\dot{C} = m, \tag{17}$$

If, however, *no* particles are created then from (15) we get

$$\dot{C} = S^{-3}. \tag{18}$$

Equations (17) and (18) represent the two different classes of solutions possible in the *C*-field cosmology.

The steady-state solution given by the de Sitter line element

$$ds^2 = dt^2 - e^{2Ht}[dr^2 + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)] \tag{19}$$

belongs to the first of the two classes with

$$\rho = fm^2 = \frac{3H^2}{4\pi G} \ (= \text{constant}). \tag{20}$$

Notice that the characteristic parameter of the de Sitter space-time—the Hubble constant *H*—is related to the *C*-field coupling constant *f* and the mass *m* of the particle created.

If *m* is the typical baryonic mass (= mass of the proton, say) then we can express *f* in terms of the present value of Hubble constant, with the help of Equation (20):

$$f \simeq 1.6 \times 10^{19}\, h_0^2\, g^{-1}\, \text{cm}^{-3}. \tag{21}$$

Although we obtained the value of *f* above using the observed value $H = 100\ h_0$ km s^{-1} Mpc^{-1}, the actual cosmological reasoning is the reverse: it is the value of *f* that determines how fast the steady-state universe should expand.

It is also worth pointing out the difference of interpretation of the energy tensor in this solution and in the de Sitter model as obtained by de Sitter, and in the inflationary models. In de Sitter's version the space-time was considered empty but the Einstein equations contained the λ-term. In the inflationary scenario the phase transition gives rise to a λ-term. However, it appears on the right-hand side of the equations

$$R_{ik} - \frac{1}{2}g_{ik}R = -\lambda g_{ik}. \tag{22}$$

This right hand side describes the energy tensor of a cosmic fluid with density $\rho = \lambda/8\pi G$ and negative pressure $p = -\rho$. It is interesting to recall that W. H. McCrea. (1951) gave a similar interpretation to cosmic fluid in the steady-state universe.

In the second class of solutions with no creation we get the following equation for the scale factor *S:*

$$\dot{S}^2 = -k + \frac{A}{S} - \frac{B^2}{S^4} \tag{23}$$

where A and B are constants related to ρ and $\dot{C}$ by

$$S^3\rho = \frac{3A}{8\pi G}, \qquad S^3\dot{C} = \frac{B}{(4\pi Gf)^{1/2}}. \tag{24}$$

Notice that Equation (23) describes a non-singular universe. For $k = 0$, it has the explicit solution

$$S = (\alpha t^2 + \beta)^{1/3}, \qquad \alpha = \frac{9}{4}A, \qquad \beta = \frac{B^2}{A}. \tag{25}$$

At large t this behaves like the Einstein-de Sitter solution.

In an earlier paper, Narlikar (1974) had discussed this solution as arising from explosive creation at a single epoch t_0 so that $n(t) \propto \delta\,(t - t_0)$. This model thus provided a nonsingular discussion of the big-bang event.

In Paper 2, however, Equation (23) was supposed to arise when creation was spontaneously 'switched off' in a given space-time region. The switch-off would occur if the creation condition (6) failed to be satisfied in a finite region due to local fluctuations. In that event the region would expand according to Equation (23) in a de Sitter background given by Equation (19), somewhat like a low-density air-bubble in a denser liquid. For a reason outlined below, it was suggested, however, that the outer steady state background corresponded to a Hubble constant several orders of magnitude smaller than the currently estimated value 100 h_0 kms^{-1} Mpc^{-1}.

In Paper 1 it was argued that for the creation of particles of mass m_a the condition (6) must be satisfied. In a universe containing a uniform distribution of massive objects the possibility emerges that in the vicinity ofa massive body the magnitude of $C^i\,C_i$ is raised above the average cosmological value. Hence, if the average value of $C_i\,C^i$ is below the required threshold m_a^2, but rises above it near a typical massive body then creation of particles would take place only near the body. Thus according to Paper 1, the steady state is maintained by creation of matter around existing masses.

However, the value of f given by Equation (21) was found to be too small to explain explosive outpouring of particles near active galactic nuclei. In order to explain such events as the origin of high-energy cosmic rays it was necessary to raise f by a factor $\sim 10^{20}$ above the value given by Equation (21). The relation (20) then implied that the Hubble constant must be larger than its presently observed value by a factor $\sim 10^{10}$. In other words, the characteristic cosmological timescale of the steady-state model turned out to be ~ 1 yr rather than $\sim 10^{10}$ yr.

It is in such a universe that the bubble is formed by the spontaneous cut-off of the creation process. The present Hubble constant of 100 h_0 km s^{-1} Mpc^{-1} corresponds not to the steady-state solution but to the Friedmann-like solution (25). The steady state solution only provides the initial conditions for the formation of the bubble to which our direct observations of the universe have so far been confined.

3. The early universe

3.1 *The Creation of Relativistic Particles*

We now consider certain modifications in the above picture to take into account the radiation-dominated early universe. We will consider epochs at which baryons as well as leptons obey the relativistic approximation (Narlikar 1983). Following the cosmological principle we assume, as before that C depends on t only. We will, however, modify the single-particle creation scenario which led to conditions (6) and assume that two particles of equal and opposite 3-momenta $\pm P$ are created at each point A_+. Then the action principle gives

$$\dot{C} = 2\sqrt{P^2 + m^2} \equiv 2E. \tag{26}$$

Here m is the rest-mass of each particle created and E its energy. In the relativistic approximation

$$E \simeq P \gg m. \tag{27}$$

In the formalism to be described below, condition (27) is assumed to hold although it is not difficult to develop a similar theory for the nonrelativistic case.

If CP is conserved in the creation process, the two created products will form a particle antiparticle pair. If CP is broken both particles could be of the same type. Equation (26) ensures, however, that the total energy and momentum are conserved between the C-field and the two created particles. Since C is a scalar field the spin is conserved by ensuring that the created particles carry opposite spins.

In the two-particle creation at a given place the symmetry of isotropy is spontaneously broken. However, since the directions of motion of the created pair are random, the symmetry is hidden. It is therefore correct to assume that on a macroscopic scale C still depends on t only.

It is convenient to write $\dot{C}$ as a function of the scale factor S, Thus we will write Equation (26) in the form

$$\dot{C} \equiv g(S) = 2P \tag{28}$$

so that at the epoch of scale factor S the created particles have momentum $g(S)/2$. After creation, the momentum decreases according to the law

$$P \propto 1/S. \tag{29}$$

Let $N(P, S)\,\mathrm{d}P$ denote the number density of particles at epoch of scale factor S with momenta in the range P and $P + \mathrm{d}P$. The pressure $p(S)$ and energy density $\varepsilon(S)$ of the cosmological material are then given by

$$p(S) = \frac{1}{3}\varepsilon(S) = \frac{1}{3}\int_0^\infty PN(P, S)\mathrm{d}P. \tag{30}$$

Because of the relation (29), the function $N(P, S)$ satisfies the equation

$$\frac{\partial N}{\partial P}\cdot\frac{P}{S} = \frac{\partial N}{\partial S} + \frac{2N}{S} \tag{31}$$

which integrates to

$$N(P, S) = \frac{1}{S^2}F(PS). \tag{32}$$

The arbitrary function $F(PS)$ is related to how the particles are created. In general we expect it to have a step-function type discontinuity at $P = g(S)/2$ to take into account the injection of new particles according to Equation (28). Because of the relation (29), if in an expanding universe

$$\frac{\mathrm{d}}{\mathrm{d}S}[Sg(S)] < 0, \tag{33}$$

then the particles which are already in existence at epoch S will have momenta greater than $g(S)/2$. Hence

$$N(P, S) = \frac{1}{S^2} F(PS)\theta\left[P - \frac{1}{2}g(S)\right]. \tag{34}$$

Here θ is the Heaviside function.

Likewise, if

$$\frac{\mathrm{d}}{\mathrm{d}S}[Sg(S)] > 0, \tag{35}$$

then

$$N(P, S) = \frac{1}{S^2} F(PS)\theta\left[\frac{1}{2}g(S) - P\right]. \tag{36}$$

We will refer to the two cases leading to Equations (34) and (36) as Cases 1 and 2 respectively.

Consider now the relation (10). This becomes in the present case

$$\frac{\mathrm{d}}{\mathrm{d}S}(\varepsilon S^3) + 3pS^2 = f\dot{C}\frac{\mathrm{d}}{\mathrm{d}S}(\dot{C}S^3). \tag{37}$$

Using Equations (30) and (34) we get for Case 1

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}S}(\varepsilon S^3) + 3pS^2 &= \frac{\mathrm{d}}{\mathrm{d}S}\int_{\frac{1}{2}g(S)}^{\infty} PSF(PS)\mathrm{d}P + \int_{\frac{1}{2}g(S)}^{\infty} PF(PS)\mathrm{d}P \\ &= -\frac{1}{2}g(S)F\left\{\frac{1}{2}Sg(S)\right\}\frac{\mathrm{d}}{\mathrm{d}S}\left[\frac{1}{2}Sg(S)\right].\end{aligned}$$

The right hand side of Equation (37) is simplified by using Equation (28). Case 2 can be similarly handled and we get in the two cases the final result

$$F\left\{\frac{1}{2}Sg(S)\right\} = \pm 4fS^2\frac{3g(S) + Sg'(S)}{g(S) + Sg'(S)}. \tag{38}$$

This minus sign on the right-hand side corresponds to Case 1 and the plus sign to Case 2. In either case, the particle distribution function is determined if $g(S)$ is specified, or vice versa. Once $g(S)$ is determined the function $S(t)$ is fixed by the Equations (13) and (14).

3.2 *The Steady-State Solution*

Consider the simple example where $F(x) \propto x^2$, say,

$$F(x) = \lambda x^2, \qquad \lambda = \text{constant} > 0. \tag{39}$$

Here, F is proportional to the geometrical volume of the momentum space. Then

Equation (38) gives (taking the positive sign) after simple integration,

$$g(S) = \text{constant} = \sqrt{48f/\lambda} = 2P_0 \text{ (say)}. \tag{40}$$

This leads us to the steady-state line element with

$$\frac{1}{3}\varepsilon = p = \frac{12f^2}{\lambda} = fP_0^2, \qquad N = 4fP_0 \tag{41}$$

$$H^2 = \frac{8\pi Gf}{3} P_0^2, \tag{42}$$

where P_0 is the momentum of the particle created. At any given epoch the momentum distribution of the created particles follows the distribution function

$$N(P, S) = \lambda P^2, \qquad \lambda P \leqslant P_0. \tag{43}$$

This distribution function presupposes that particles are created at random at relativistic speeds, but once they are created they do not collide and alter their momenta. Thus the relation (29) denotes the way in which each particle loses its momentum with expansion.

In the actual situation prevalent in a high-density universe, the no-collision condition will be satisfied provided the collision rate Γ_C of various particles is less than the rate of expansion of the universe, *viz.*, H. We will assume that $\Gamma_C \ll H$.

What should be the value of H? From Equation (20) H is determined by f and m. However, rather than specify f and m first, we will proceed in an empirical manner, and use Occam's razor.

First we note that the only constants at the disposal of a gravity theory like general relativity are G and c. We may also add $\hbar$ to the list if we wish to include the effects of quantum theory. From G, $\hbar$ and c a time-scale emerges which is given by

$$\tau_P = \sqrt{G\hbar/c^5}. \tag{44}$$

For $\tau \lesssim \tau_P$ the discussion of various phenomena must proceed via quantum rather than classical gravity.

Work by several authors (see for example Atkatz & Pagels 1982; Brout *et al.* 1980, Vilenkin 1982; Padmanabhan 1983) has shown that empty flat space-time is unstable to quantum fluctuations and that dynamical discussions of such fluctuations lead inevitably to matter creation and C-field like (negative energy) terms in the T^{ik}. Therefore we could argue that if our steady-state solution evolved this way, the resulting H would be comparable to τ_P^{-1}. Accordingly we set

$$H = \beta\tau_P^{-1}, \qquad \beta \lesssim 1. \tag{45}$$

The condition $\beta < 1$ is necessary to ensure that our classical description has some validity.

Next we will conjecture about the created mass m, again in a heuristic way. The present ideas in grand unification theories (GUTs) suggest that the massive X-boson plays a crucial role in baryon-nonconservation. We therefore identify its mass m_x with m and write Equation (20) as

$$H^2 = \frac{4\pi G}{3} f m_x^2. \tag{46}$$

From Equations (45) and (46) we are able to determine *f*:

$$f = \frac{3c^5\beta^2}{4\pi m_x^2 G^2 \hbar} = \frac{3}{4\pi}\frac{c^4\beta^2}{G\hbar^2}\frac{m_P^2}{m_x^2}, \tag{47}$$

where

$$m_P = \sqrt{\frac{c\hbar}{G}} \tag{48}$$

is called the Planck mass. We will consider the numerical values of f, m_x, m_p *etc.* later.

3.3 *The Growth of a Bubble*

In this highly dense steady-state universe we next consider the idea that creation is switched off in a finite region which subsequently expands as a bubble. To estimate the physical size of such a bubble we proceed as follows.

How long does an X-boson survive after creation? Its lifetime may be estimated on dimensional arguments to be $\tau_x = \Gamma_x^{-1}$ where

$$\Gamma_X = \gamma \frac{m_X c^2}{\hbar} \tag{49}$$

and γ is a dimensionless constant. To estimate γ we suppose that there are altogether g effective degrees of freedom in the cosmological mixture of particles. This quantity g is determined in the usual way by

$$g = g_b + \frac{7}{8} g_f \tag{50}$$

where g_b = total number of boson spin states and g_f = total number of fermion spin states. Then we expect that

$$\gamma = \alpha g \tag{51}$$

where α is a constant estimated by some GUTs in the range 10^{-2} to 10^{-5}.

The 'switching off' of creation may be linked to the disappearance of X-bosons. Thus, during the lifetime τ_x of the created X-boson a characteristic cosmological 3-volume of linear size c/H will expand to

$$L = \frac{c}{H}\exp(\tau_X H) = \frac{c}{H}\exp\left(\frac{\beta\tau_X}{\tau_P}\right). \tag{52}$$

This is the size of the bubble at the onset of its expansion as a Friedmann universe. To estimate its present size we use the fact that during expansion the scale-factor increases inversely as temperature. The radiation temperature at the Planck epoch was

$$T_P = \frac{m_P c^2}{k} \tag{53}$$

where k = Boltzmann's constant. If the present temperature is given by T_0, the present size is given by

$$L_0 \simeq \frac{c}{H}\exp\left(\frac{\beta\tau_X}{\tau_P}\right)\frac{T_P}{T_0} = \frac{c}{H}\cdot\frac{T_P}{T_0}\cdot\exp\Sigma, \tag{54}$$

say.

In Equation (54) the quantities T_p, τ_p, c, H are determined in terms of elementary constants c, G, $\hbar$, k *etc.*, while $T_0 \simeq 3K$ is given by observations. Using Equations (49) and (51) we write

$$\Sigma = \frac{\beta \tau_X}{\tau_P} = \frac{\beta}{\gamma} \frac{m_P}{m_X} \simeq \frac{\beta}{\alpha g} \frac{m_P}{m_X}. \tag{55}$$

We will first estimate Σ from Equation (54) by using $L_0 = 10^{28}\ h_0^{-1}$ cm· Then we have

$$\Sigma = \ln\left[\frac{L_0 H}{c} \frac{T_0}{T_P}\right] \simeq 67 - \ln h_0 \tag{56}$$

where the current uncertainty of the value of Hubble constant suggests that | In h_0 | < 1. We will therefore ignore it.

In Equation (55) set $\beta \simeq 1$ and $g \simeq 200$ as the approximate numbers of degrees of freedom of all particle species in the early universe. Then we get

$$m_X \simeq 7.5 \times 10^{-5}\, \alpha^{-1}\, m_P \simeq 7.5 \times 10^{14}\, \alpha^{-1}\ \text{GeV}. \tag{57}$$

Note that this limit is consistent with the present lower bounds on the proton lifetime.

If all the GUT parameters were fully determinable, we could have had more reliable estimates of m_x, g, α *etc.* Also, the relation (51) could then be stated more accurately. The current work suggests that since $\alpha < 1$ in Equation (57) the mass of the X-boson is expected to be higher than 7.5×10^{14} GeV. Also, since we expect $m_p > m_x$, α should not be lower than $\sim 10^{-4}$. This requirement comes from the consistency of the overall cosmological scheme presented here and could be compared with the values of α given by various GUTs.

4. A comparison with the inflationary scenarios

The exponential term exp Σ in Equation (54) is analogous to the inflationary term in the big-bang cosmology. That the value of Σ is the same (within small calculational uncertainties) in the two pictures may come as a surprise; but on closer examination this is to be expected. The reason is as follows.

In our bubble picture as in the standard Friedmann cosmology the rate of expansion $\sim t^{2/3}$ is comparatively slow. As a result, the present observable universe of linear dimension $\sim 10^{28}$ cm has to come out of a relatively large region of the early universe. In the inflationary scenarios this largeness is achieved by a temporary de Sitter like phase which is associated with phase transition. In the present model the background universe is always in de Sitter (steady-state) form but the growth of a bubble is associated with the switching off of the creation process. The timescale for switch-off is linked with the disappearance of X-bosons in a given volume. A volume of cosmological dimension c/H inflates during this time to a linear size c/H exp Σ. At this stage the bubble formation is complete and the bubble expands as the Einstein-de Sitter model would.

The picture presented here is still phenomenological since it does not discuss the dynamical aspects of how the creation is switched off. The constant Σ is in principle calculable if a fully developed grand unified theory and C-field theory is available. The numerical estimates given in Section 3.3 suggest that a self-consistent detailed theory may be possible.

The above weakness apart, the present scheme offers certain advantages over the standard inflationary scenario. The background universe is singularity free and the bubble itself starts from a well-defined initial state. The background de Sitter space-time is free from particle horizons and there is thus no impediment towards its achieving a highly homogeneous state. In fact, as discussed within the old *C*-field theory (Hoyle & Narlikar 1963), the newly created matter serves to homogenize the universe and to wipe out any earlier 'memories' of inhomogeneities. This idea has been suggested anew recently by Barrow & Stein Schabes (1983) under the concept of "cosmic no-hair conjecture".

Since the de Sitter space-time is flat in the spatial sense ($k = 0$), the emerging bubble is also spatially flat. Thus the density parameter

$$\Omega = \frac{8\pi G\rho S^2}{3\dot{S}^2} \tag{58}$$

will be very close to unity. The departure from unity is given by the last term of Equation (23) for the case $k = 0$. This term carries the rapidly diminishing negative *C*-field energy and is negligible by the present epoch. Thus this model would predict $\Omega = 1$ to a high degree of accuracy.

Finally, because of its nonsingular beginning this model holds out hopes of relating the behaviour of the background steady model to investigations of quantum cosmology.

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