Pramāṇa Vol. 2, No. 3, 1974, pp 158–170. Printed in India.

Mini-bangs in cosmology and astrophysics

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MS received 12 January 1974

Abstract. The ideas originally proposed to discuss continuous creation of matter are reconsidered in the context of the big bang cosmological models. It is shown that singularity-free big bang models are possible under the modified field equations of general relativity. However, the case is made out that matter creation takes place in several mini-bangs at different epochs rather than in one big bang. The implications of this idea for high energy astrophysics and for gravitational radiation are discussed.

Keywords. Cosmology; matter creation; high energy astrophysics; gravitational radiation.

1. Introduction

Primary creation of matter and radiation is *the* most fundamental event in cosmology. Compared to this the behaviour of matter and radiation subsequent to creation is of secondary importance. Yet, a survey of the current cosmological literature reveals that very little attention has been paid to the creation event (or events) by the observational and theoretical astronomers. This neglect is due to a number of reasons. Many cosmologists consider the creation problem to be so fundamental as to be beyond the reach of physics. To some creation represents a violation of the sacrosanct conservation laws of theoretical physics, and therefore to be avoided as far as possible. Others hesitate to tackle it on the ground that there is no observational evidence for it. Nevertheless matter and radiation do exist and pose the tantalizing question: "Where did they come from in the first place?"

The creation problem has been explicitly discussed by those interested in the steady state cosmology (Hoyle 1948, McCrea 1951, Hoyle and Narlikar 1962, Bondi and Lyttleton 1959, Gold and Hoyle 1960). One of the characteristics of a steady expanding nonempty universe is the continuous creation of matter. If ρ is the density of the universe and H the Hubble constant, the rate of creation of matter per unit volume is given by

$$K = 3\rho H \tag{1}$$

With existing estimates of ρ and H, K is in the region of 10^{-47} gm cm^{-3} sec^{-1}. Small though it is, K represents an apparent violation of the law of conservation of matter and energy, and is mainly responsible for the suspicion with which the steady state theory is viewed by the common astronomer or physicist. Yet, ironically, the classical Friedmann models which are considered less radical in outlook, require a violation of the above conservation law in a more dramatic form. In such models, all the present contents of the universe must be created at once, thus giving an infinite value of K!

To argue that the creation event is beyond the scope of physical enquiry and that one should restrict one's discussion to events subsequent to creation represents a departure from the traditionally held views on the scope of scientific enquiry. Indeed some cosmologists (*see* Harrison 1972 for a review) are willing to consider the state of the universe at the age of 10^{-43} seconds but they hesitate to consider the case of zero age.

The sharp contrast which existed between the steady state and the big bang models twenty years ago has softened somewhat at present. Creation in discrete events and local evolution in times comparable to H^{-1} has been considered in the steady state framework by Hoyle and Narlikar (1966 a, b) while some physicists like Neéman (1965) have removed the uniqueness of the big bang by postulating 'delayed' big bangs.

The purpose of this paper is to show that once creation of matter is admitted as a part of physical enquiry, the difference between the two types of cosmological models is considerably reduced. The same formalism which led to the steady state theory can be made to give big bang type solutions but without singularity.

Finally, the question 'Is creation taking place now?' will be considered in the light of available astrophysical evidence. This comes largely from high energy astrophysics, galactic structure and the nature of the intergalactic medium. However, the recent interest in the possible existence of gravitational radiation has added another dimension to this problem. It will be shown that creation events are possible sources of gravitational radiation.

2. Creation: a mathematical formalism

It is well known that Einstein's equations can be derived from a variational principle

$$\delta S/\delta g_{ik} = 0 \tag{2}$$

where g_{ik} is the space-time metric and S is the action functional

$$S = \frac{1}{16\pi G}\int R\sqrt{-g}\,\mathrm{d}^4x - \sum_a \int m_a \mathrm{d}a \tag{3}$$

Throughout this paper, except when putting in numbers, we will take the velocity of light $c = 1$. In (3) R is the scalar curvature, g the determinant of g_{ik} and G the constant of gravitation. The second term of (3) represents a collection of particles, m_a being the mass of the a-th particle and da the element of its proper time.

Application of (2) to (3) leads to the field equations

$$R^{ik} - \tfrac{1}{2} g^{ik} R = -8\pi G \underset{(m)}{T^{ik}} \tag{4}$$

where $\underset{(m)}{T^{ik}}$ is the usual energy momentum tensor of matter arising from the second term of (3). In the 'smooth dust' approximation commonly considered in cosmology (4) becomes simplified because

$$\underset{(m)}{T^{ik}} = \rho u^i u^k \tag{5}$$

where ρ is the density and u^i the flow vector of dust.

The conservation law for matter and energy follows from (4) by taking divergence. Because of this, the Einstein equations cannot describe matter creation. Can we modify (4) in some way so as to permit the possibility of

$$\underset{(m)}{T}{}^{ik}{}_{;k} \neq 0? \tag{6}$$

Hoyle's idea was to introduce such a modification and he did write modified field equations to take account of matter creation. However, a simple modification using the action principle was suggested by M H L Pryce (private communication), and was subsequently adopted by Hoyle. In this paper we shall be mainly concerned with this formulation. Only towards the end we shall point out a more satisfactory alternative.

The modified action is now given by

$$S = \frac{1}{16\pi G}\int R\sqrt{-g}\,\mathrm{d}^4x - \sum_a \int m_a\,\mathrm{d}a + \tfrac{1}{2}f\int C_i C^i\sqrt{-g}\,\mathrm{d}^4x - \sum_a \int C_i\,\mathrm{d}a^i \tag{7}$$

where C is a new scalar field and $C_i = \partial C/\partial x^i$ its gradient. f is a coupling constant.

At first the last term of (7) seems ineffective in a variational problem. This is because it is path-independent, and seems to depend only on the end points where the variations are zero anyway. However a new subtlety is introduced at this stage. Since the theory talks about creation (or annihilation) of matter, it must admit the possibility of a world line beginning or ending at a spacetime point. Suppose particle a is created at spacetime point A_1 and is annihilated at point A_2. Then we have

$$\int C_i\,\mathrm{d}a^i = C(A_2) - C(A_1) \tag{8}$$

In a variational problem we must vary not only the particle worldlines but also their ends. If therefore A_1 or A_2 (or both) lie in a spacetime region where variations are taking place we get a non-zero contribution from (8). Explicitly we have at A_1

$$m_a\,\mathrm{d}a^i/\mathrm{d}a = C^i(A_1) \tag{9}$$

and at A_2

$$m_a\,\mathrm{d}a^i/\mathrm{d}a = C^i(A_2) \tag{10}$$

Between A_1 and A_2 the worldline satisfies the usual geodesic equation

$$\frac{\mathrm{d}^2a^i}{\mathrm{d}a^2} + \Gamma_{kl}^{\ i}\frac{\mathrm{d}a^k}{\mathrm{d}a}\frac{\mathrm{d}a^l}{\mathrm{d}a} = 0 \tag{11}$$

Thus the C-field does not affect the motion of an existing particle. It comes into play at the instant of its creation or annihilation. (9) and (10) represent the law of conservation of momentum. At the time of creation the momentum generated comes out of the field momentum of the C-field.

The sources of the C-field are the ends of worldlines. The variation of C in the action principle leads to

$$fC^k{}_{;k} = \left\{\frac{\delta_4(X, A_1)}{\sqrt{-g(A_1)}} - \frac{\delta_4(X, A_2)}{\sqrt{-g(A_2)}}\right\} \tag{12}$$

That is, a world point where creation occurs acts as a positive source and a world point where annihilation occurs acts as a negative source.

The gravitational equations are obtained by the variation of g_{ik} and are given by

$$R^{ik} - \tfrac{1}{2} g^{ik} R = -8\pi G \left[\underset{(m)}{T^{ik}} + \underset{(c)}{T^{ik}} \right] \tag{13}$$

where $\underset{(m)}{T^{ik}}$ is the usual matter tensor and

$$\underset{(c)}{T^{ik}} = -f\{C^i C^k - \tfrac{1}{2} g^{ik} C^l C_l\} \tag{14}$$

It is easy to see that

$$\underset{(m)}{T^{ik}}_{;k} = -\underset{(c)}{T}_{;k}{}^{ik} = fC^i C^k{}_{;k} \tag{15}$$

We have already seen that $C^k{}_{;k} = 0$ except where particles are created or annihilated. Thus at such world points the conservation law for $\underset{(m)}{T^{ik}}$ breaks down. *However, the combined energy in matter and the C-field is always conserved.*

This concludes the discussion of the basic laws governing the C-field. It is possible to describe the same ideas somewhat better in the form of a direct particle theory instead of a field theory [Hoyle and Narlikar 1964]. For the present purpose the more familiar field formulation is sufficient.

3. Cosmological solutions

To obtain the simplest cosmological solutions of the modified field equations we make use of the Robertson–Walker line element

$$ds^2 = dt^2 - Q^2(t) \left[\frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \sin^2\theta \, d\phi^2) \right] \tag{16}$$

where $k = 0, \pm 1$ and r, θ, ϕ represent a typical fundamental observer in the sense of the Weyl postulate. t denotes the cosmic time so that the spaces $t =$ constant are homogeneous and isotropic. In the smooth dust approximation, ρ is a function of t only while u^i has only the time-component. The C-field in this case can be at most a function of t.

These assumptions considerably simplify the field equations which reduce to

$$2 \frac{\ddot{Q}}{Q} + \frac{\dot{Q}^2 + k}{Q^2} = 4\pi G f \dot{C}^2 \tag{17}$$

$$3 \frac{\dot{Q}^2 + k}{Q^2} = 8\pi G \rho - 4\pi G f \dot{C}^2 \tag{18}$$

Because $f > 0$, the C-field has negative pressure and energy. The source equation for the C-field (12) takes the form

$$f \cdot \frac{1}{Q^3} \frac{d}{dt} (\dot{C} Q^3) = n(t) \tag{19}$$

where $n(t)$ is the net rate of creation of particles per unit proper volume. If $N(t)$ is the number density of particles at time t, then clearly we have

$$\frac{1}{Q^3} \frac{d}{dt} (NQ^3) = n \tag{20}$$

Finally, if m is the average mass of the particles in the universe, the matter density is given by

$$\rho = mN \tag{21}$$

With these equations we now proceed to examine the cosmological solutions.

(i) *The steady state model*—In this model ρ, N and n are constant in time. Denoting their values by ρ_0, N_0 and n_0 respectively, we get from (20)

$$\dot{Q}/Q = n_0/3N_0 = \text{constant} = H \text{ (say)} \tag{22}$$

where H is the Hubble constant. Integrating (22) we get

$$Q(t) = \exp Ht \tag{23}$$

the constant of integration being absorbed in the scale factor. Then (19) leads to

$$\dot{C} = N_0/f + Ae^{-3Ht}, \qquad A = \text{constant}. \tag{24}$$

Next we substitute (24) and (23) into (17) and find that

$$k = 0, \; A = 0 \tag{25}$$

and

$$\rho_0 = fm^2 = 3H^2/4\pi G, \quad N_0 = fm, \quad n_0 = 3Hfm. \tag{26}$$

Notice that the steady state solution has been obtained simply by requiring $N(t)$ and $n(t)$ constant. The above relations tell us how the density of matter is related to Hubble's constant, *i.e.*, to the rate of expansion of the universe. Both ρ_0 and H are in fact given by the coupling constant f and the mass of the particle created.

(ii) *The big bang models*—Originally it was thought that the big bang models cannot be described in the above framework, except trivially by assuming $C = 0$. We now show that explosive rather than continuous creation does lead to big bang cosmologies.

For this we consider creation to take place at a unique epoch $t = 0$ (say), so that

$$n(t) = N_0 \delta(t) \tag{27}$$

According to (27) N_0 particles are suddenly created at time $t = 0$. We may assume that prior to this event there were no particles in the universe. Then (20) integrates to

$$N = \frac{N_0 Q_0^3}{Q^3}, \qquad t > 0 \tag{28}$$

where $Q_0 = Q(0)$. Similarly (19) integrates to

$$\dot{C} = \frac{N_0 Q_0^3}{f Q^3} \theta(t) \tag{29}$$

where $\theta(t)$ is the Heaviside function suggesting that $\dot{C} = 0$ for $t < 0$. Substitution of (29) into (18) gives for $t > 0$

$$3\frac{\dot{Q}^2 + k}{Q^2} = \frac{8\pi G N_0 Q_0^3}{Q^3}\left\{m - \frac{N_0 Q_0^3}{2fQ^3}\right\} \tag{30}$$

where m is the mass of a typical particle.

The usual Friedmann equations are modified in two respects. First the density term is determined absolutely by the creation event. Second, the creation event leads to generation of the C-field which contributes an important term to the right hand side of (30). This term is dominant in the early stages when Q is small.

The equation (30) is similar to that obtained earlier by Hoyle and Narlikar (1966 *a*) except that in the earlier analysis the equation was not used to describe a creation process. Rather it was obtained as a mathematical solution of source free *C*-field equations. This left undetermined constants in the equation. All quantities in (30), on the other hand, are determined by the creation event. Writing

$$A = \frac{8\pi}{3} GmN_0Q_0^3, \qquad B = \frac{4\pi}{3f} GN_0^2 Q_0^6 \tag{31}$$

we get from (30)

$$\dot{Q}^2 = -k + \frac{A}{Q} - \frac{B}{Q^4} \tag{32}$$

The *C*-field term thus prevents the case $Q = 0$. If $k = 0$ or -1, Q will continually increase from Q_0 to infinity. If $k = +1$, Q will oscillate between finite limits, Q_1, Q_2, say. Since these models differ from the Friedmann models only for small Q, we shall consider the behaviour of these models in some detail for such values of Q. Since the models with $k = \pm 1$ behave in this range of Q in essentially the same way as the $k = 0$ model, we shall confine our attention to this latter case.

For $k = 0$, the equation (32) can be integrated explicitly and we get

$$Q(t) = \bar{Q}\left\{1 + \frac{(t-t_1)^2}{t_0^2}\right\}^{\frac{1}{3}} \tag{33}$$

where

$$\bar{Q} = \left(\frac{N_0}{3fm}\right)^{\frac{1}{3}} Q_0, \qquad t_0 = (12\pi Gfm^2)^{-\frac{1}{2}} \tag{34}$$

and t_1 is the constant of integration.

To determine t_1 we have to take into account the creation condition (9). Since particles of mass m are being created at $t = 0$, at rest in the Robertson-Walker coordinate system, this condition becomes

$$\dot{C} = m \quad \text{at} \quad t = 0 \tag{35}$$

However, some ambiguity arises at this stage because of the discontinuity of $\dot{C}$ at $t = 0$, as shown by (29). For $t = 0, -\dot{C}$ was zero whereas for $t = 0+$ it has the value

$$2mt_0^2/(t_0^2 + t_1^2) \tag{36}$$

in the above solution. Which value should one adopt in (35)?

If we take $\dot{C} = 0$, obviously (35) cannot be satisfied and no matter creation will take place. This represents one possible course of events. If on the other hand we take (36) for the value of $\dot{C}$ we get a self-consistent solution with

$$t_1^2 = t_0^2, \qquad i.e., \quad t_1 = -t_0 \tag{37}$$

The reason for taking the minus sign for t_1 follows from the fact that at $t = 0$ the universe is expanding because of the negative energy repulsion generated through the *C*-field. Thus at $t = 0$ Hubble constant must be positive. From (33) the Hubble constant at $t = 0$ is given by

$$-\tfrac{2}{3}\, t_1/(t_0^2 + t_1^2) \tag{38}$$

For $t_1 = -t_0$, we will get the positive value of Hubble constant. We therefore take

$$Q(t) = \bar{Q}\left\{1 + \frac{(t+t_0)^2}{t_0^2}\right\}^{\frac{1}{3}} \tag{39}$$

with t_0 given by (34) as the complete solution. The maximum density occurs at $t = 0$ and is given by

$$\rho_{max} = fm^2 \tag{40}$$

We shall return to the choice between these two alternatives at $t = 0$ towards the end of this section when we discuss the question of the onset of creation.

It is clear from the above discussion that if we want to apply the C-field theory to big bang models, we must raise the value of the coupling constant by several orders of magnitude over that required for the steady state model, in order to have a high density and high temperature phase close to the creation event. It is easy to estimate the order of magnitude required by comparing with the standard Friedmann models. From the point of view of nucleosynthesis the density and expansion rate required is that operating at approximately 1 second after the big bang. Since the Hubble constant is inversely proportional to the epoch of the Einstein-de Sitter or the radiation model, the value of Hubble constant at 1 sec is $\sim 3 \cdot 10^{17}$ times higher than that at present. This means f must be raised by $\sim 10^{35}$, above the value required for the steady state model.

In the above discussion we have ignored the radiation terms in the energy momentum tensor. Strictly speaking they are more important than the matter terms for small Q. However, inclusion of these does not alter the singularity issue discussed above. The equation (32) is modified to

$$\dot{Q}^2 = -k + \frac{A}{Q} + \frac{D}{Q^2} - \frac{B}{Q^3} \tag{41}$$

where D is a constant relating to the density of radiation. Clearly the creation terms still dominate the picture close to $Q = 0$ which is never attained.

We conclude this section with a few remarks on the question: 'What sets off the creation process?' We have already seen in (9) the necessary condition for the creation of a particle of mass m_a. However, (9) does not guarantee that creation will take place. Indeed in classical physics it is not possible to answer the above question at all; we must look to quantum physics for the solution. In quantum electrodynamics we have an analogous situation. For example, an atomic electron in a higher energy state has two alternatives available. The first is to stay put in the same state and the second to jump down to a state of lower energy. In the absence of an external electromagnetic field, the electron jumps down with a certain probability. This problem is solved [*see* Hoyle and Narlikar 1969, for details] by considering the different possibilities available to the electron. According to quantum mechanics, a particle does not follow a unique path but can follow any path with a certain probability. The probability for a typical path Γ is proportional to

$$\exp\{iS(\Gamma)/\hbar\}, \tag{42}$$

where S is the action functional computed for the path Γ and $\hbar$ is the usual Planck constant The atomic eletcron accordingly neither stays put nor definitely jumps down, but adopts either course with a certain probability.

In the same way in the creation problem, we have different possibilities: (i) no particle is created, (ii) a particle of certain mass m_a is created. These are the alternatives encountered at $t = 0$ in the above solution. In a full quantum mechanical solution of the problem we should be able to calculate the probability and hence the rate of creation. Such a calculation will yield the value of fm^2 which, at present has to be fixed on phenomenological grounds. At present we do not know in (ii) what type of particle can be created. There may be selection rules operating which could rule out many possibilities, *e.g.*, the creation of charged particles. Only when our knowledge of particle physics is more advanced can we answer this question in detail.

4. Creation in finite regions

Nevertheless the concept of creation of the entire universe at one single instant as discussed above is somewhat artificial. Already, we have seen that in the quantum world the transition from a state of $C = 0$ to a state of $C \neq 0$ can take place in a variety of ways. It is therefore unrealistic to expect this transition to take place at a unique instant. Rather we would expect matter to appear in a series of such transitions at all possible epochs. At first this might suggest that continuous creation of matter as required by the steady state theory is the more realistic idea. However, even in that theory, the concept of a uniform rate of creation is equally artificial. The most realistic idea seems to be intermediate between the two solutions discussed in the previous sections. In this we have creation in the form of 'mini-bangs' at various instants between $t = -\infty$ to $t = +\infty$. The possibility that there may be delayed big bangs has previously been considered (Neéman, 1965) although such discussions have still attached significance to the primary big bang. The present suggestion attaches no such significance to any particular creation event. All creation events are mini-bangs which are confined to *finite* regions of space.

Creation of matter in finite regions has been considered before (McCrea 1964, Hoyle and Narlikar 1966 *a*). In the second of these references creation was assumed to take place in the neighbourhood of finite massive objects. The argument was based on the assumption that the overall threshold of C-field energy in the universe was just a little lower than that necessary for the creation of a particle of mass m_a. That is,

$$C_i C^i < m_a^2 \tag{43}$$

where the difference between the two sides of (43) was small. In a strong gravitational field surrounding a massive object, $C_i C^i$ is raised so that it equals m_a^2. This induces creation in the neighbourhood of already existing massive objects. However, the creation in such cases was assumed to be at a steady rate, like the first solution of section 3. What we are now proposing is that the creation is in the form of a mini-bang as discussed in the second solution of section 3.

The solution discussed in the previous section is now taken to apply over a limited region, $r \leqslant r_b$, say, for a spherical region centred on $r = 0$. For $r > r_b$ a different solution will apply, corresponding to zero matter density and no creation. The C-field, however is nonzero even outside $r = r_b$ since it is radiative in characters Also, at $r = r_b$, C must be continuous. That an exterior solution with these conditions exists can be proved but an explicit analytical solution of this exterior problem is not yet available. Our succeeding remarks will therefore be of a qualitative nature.

The idea of creation in finite regions at various instants of time finds application in various branches of astrophysics. We will discuss briefly some of the more important ones.

(i) *Galaxy formation*—This has always posed a problem to the cosmologists, largely because like star formation, galaxy formation is considered a case of condensation from the intergalactic medium. In an expanding universe gravitational forces alone are not enough to induce condensation. Moreover, the distribution of matter within a galaxy does not appear as if it has condensed from a large cloud. Many elliptical galaxies have dense concentrations of matter in the nuclear regions and some nuclei exhibit violent activity in which matter has *outward* motion. This outpouring of matter is consistent with the idea of creation in a sporadic outburst rather than with condensation. Moreover, if we adopt the present point of view we only require one generation of massive objects to produce the next. Since the universe is as a whole without a beginning, it is not necessary to postulate initial conditions.

(ii) *High energy astrophysics*—In a mini-bang it is possible to produce particles of very high energy. Althouhg we do not yet have a quantized theory of particle creation, we can see qualitatively that particles of high energy will be produced with smaller probability compared to particles of low energy. This leads to the interesting possibility that the energy spectrum of cosmic ray particles may be due to the primary process of creation.

The parts of astrophysics which normally require enormous reservoirs of energy, *e.g.*, strong radio sources, QSOs, sources of x-rays and γ-rays, are likely places for violent mini-bangs. In principle there is no limit to the amount of energy that can be generated in a creation process, since an output of positive energy matter is accompanied by the generation of equal amount of negative energy C-field.

(iii) *Black holes*—Besides avoiding singularity of the gravitational equations, the C-field may also prevent the collapse of a massive object into its Schwarzschild radius. Thus black holes need not exist. However, objects with large gravitational redshifts will exist. This is seen as follows. The contraction of a uniform finite massive object is given by an equation similar to (32) for $k = +1$. This equation suggests that the object will continue to oscillate between two finite radii. Although a contracting phase is the time reversed version of the expanding phase, the two phases do not appear so symmetrical to an outside observer. Light from a contracting object is redshifted because of Doppler effect and gravitation, whereas light from an expanding object is blue-shifted by Doppler effect and redshifted by gravitation. Thus blueshift may or may not be seen, but redshift will always be there (Faulkner, Hoyle and Narlikar 1964).

(iv) *The microwave background*—According to the present point of view, the observed microwave background is not of universal origin but relates to the creation process in a finite but very large region. The remarkable isotropy of this radiation requires the region to be large. Since the mini-bang contemplated here is of non-singular nature, it should be possible to investigate the behaviour of matter and radiation in the early stages in a more realistic way than in the case of singular big-bang models. In particular it would be interesting to find if the 'coincidence' between the energy densities of microwave background, the cosmic rays, star light and the magnetic field, is capable of further explanation. It is proposed to investigate this problem in a future paper.

Apart from these applications, the possibility has emerged lately of linking the creation process to observations of gravitational radiation. We shall investigate this possibility in the following section. Since the results on gravitational radiation so far are in an ambiguous state we shall not go into great quantitative details in exploring the theoretical predictions.

5. Gravitational radiation

Weber (1969, 1970) has, after extensive efforts at detecting gravitational radiation, reported positive results. His observations indicate a flux of gravitational radiation coming from the centre of the galaxy. Using the conventional theory of first order gravitational radiation as given by general relativity one can estimate the loss of matter from the galactic centre. The estimates range from 10–10^3 solar masses per year. Even the lower limit of this range over the entire life of the galaxy, places severe strains on its structure, unless one can show that the radiation is of a comparatively short life time. The purpose of the present work is to look for alternative explanation which places no strain on the overall dynamics and astrophysics of the galaxy.

Analysis of Weber's results shows that he measures, not the flux of radiation, but certain components of R_{ijkl} through the principle of geodesic deviation. In the following analysis we shall investigate the amount of creation of matter needed at the centre of the galaxy in order to produce the observed magnitude of R_{ijkl}. To fix ideas we shall choose a spherically symmetric outburst at the centre $r = 0$. Since the overall gravitational field within the galaxy is not large, we shall choose a flat-space background (as is done in the first order theory of gravitational radiation). We shall also assume that there is enough C-field background of cosmological origin so that the creation condition (9) is met.

Suppose $\dot{\mathscr{N}}(t)$ represents the number of particles created per unit time in the galactic centre. The C-field which arises from this satisfies the wave equation

$$fC^k{}_{;k} = \dot{\mathscr{N}}(t)\,\delta_3(r) \tag{44}$$

The retarded solution of (44) is

$$C(r, t) = \dot{\mathscr{N}}(t-r)/4\pi fr \tag{45}$$

A field of this order will produce a small modification of spacetime geometry, and hence a non-zero R_{ijkl}. In general we expect the non-zero R_{ijkl} to be of the same order of magnitude as the non-zero R_{ij}. The latter can be estimated by the field equations (13). An order of magnitude calculation gives

$$|R_{ij}| \sim |8\pi G f C_i C_j| \sim 8\pi G f \left|\frac{\ddot{\mathscr{N}}(t-r)}{4\pi f r}\right|^2 \tag{46}$$

For comparison with observations it is advisable to introduce the velocity of light c. Then (46) gives for R_{ijkl}

$$|R_{ijkl}| \sim \frac{G\ddot{\mathscr{N}}^2}{2\pi f r^2 c^6} \tag{47}$$

Weber quotes an energy density $\mathscr{E} \sim 10^{-32}$ gm cm^{-3} in the waves detected by him. In a plane gravitational wave the magnitude R say, of a typical non-zero R_{ijkl} is related to the energy density by

$$\mathscr{E} \sim c^6 R^2/8\pi G\omega^2 \tag{48}$$

where ω is the circular frequency of the wave. In Weber's case $\omega \sim 10^4$. Hence

$$R \sim (8\pi G\mathscr{E})^{\frac{1}{2}} \omega/c^3 \sim 10^{-38} \text{ cm}^{-2} \tag{49}$$

If we substitute (49) for the left hand side of (47), we get an estimate of $\ddot{\mathscr{N}}$. If m is the mass of a typical particle created, then the rate of mass creation in the galaxy is given by

$$\dot{M} = m\dot{\mathscr{N}} \tag{50}$$

Since $\rho = fm^2$ has the dimensions of density, (47) can be rewritten in the form

$$\ddot{M} \sim \left(\frac{2\pi R\rho}{G}\right)^{\frac{1}{2}} rc^3 \tag{51}$$

Setting $r \sim 3 \cdot 10^{22}$ cm, $R \sim 10^{-38}$ cm^{-2}, we get

$$\ddot{M} \simeq 10^{39} \rho^{\frac{1}{2}} \text{ gm sec}^{-2} \tag{52}$$

where ρ is expressed in gm cm^{-3}. To get $\dot{M}$, we divide (52) by ω, since Weber's apparatus responds to this frequency. Setting $\rho \sim 10^{-29}$ gm cm^{-3}, the steady state value, we get the average value of $\dot{M}$ as

$$\langle\dot{M}\rangle \sim 3 \cdot 10^{20} \text{ gm sec}^{-1} \sim 5 \cdot 10^{-6}\, M_\odot/\text{year} \tag{53}$$

This is the creation rate required over the bandwidth observed by Weber. The net rate required may well be higher than this by 2–3 orders of magnitude. Even so, it will be much less than that required by the conventional theory (where it is mass loss that occurs).

Also, allowance must be made in the above calculation for the fact that Weber observes sharp pulses rather than continuous radiation. The pulsed nature of radiation would imply, in this picture a discrete creation of small lumps of matter averaging to the rate given by (53). However, more elaborate calculations must await further positive results from gravitational radiation experiments.

A remark is necessary as to why we have used the steady state value of ρ. This is because we are visualizing a steady creation rate in the centre of the galaxy as in the steady state model. We could instead consider the big-bang type creation in which case we have huge amount of matter created for a very short duration. Then we have to substitute a much larger value of ρ as mentioned in the earlier section. But although this raises $\dot{M}$ it does not increase total overall creation since it lasts for a short time. The galactic centre does not show signs of any violent activity, and hence we prefer the steady state solution in this case.

At the time of writing this paper, there is considerable disagreement between Weber and other observers who have set up experiments to detect gravitational radiation. Experiments other than Weber's continue to yield null results, and so it may be premature to take the above numbers too seriously. Our main object here is to point out that mini-bangs are possible sources of gravitational radiation.

6. Concluding remarks

The C-field theory described above represents a simple attempt at understanding the basic phenomenon of creation of matter. The main drawback of the theory so far presented is its incompleteness so far as quantum phenomena are concerned. Further work in that direction is necessary in order to understand the nature and magnitude of the coupling constant f. In the classical theory presented so far f represents creation rate in a statistical sense. A quantum theory should be able to tell how f is made up of a basic interaction constant and the probability of creation.

Perhaps the C-field theory is a crude version of a more sophisticated theory of inertia. This was suggested in earlier work by Hoyle and Narlikar (1972) on the conformal theory of gravitation. In this theory mass of a particle is defined in terms of the rest of the universe in a Machian way. The description of the theory is conformally invariant, although in a specific conformal frame the theory resembles general relativity. In this theory if we take explicit account of *finite* world lines, as was done in the reference cited above, it is possible to arrive at the steady state model *without recourse to the* C*-field.* Such an approach is intellectually more satisfactory since we do not require an extra field just to take account of the ends of particle world lines.

In a recent paper (Narlikar 1973), it was conjectured that if proper account is taken of creation of matter, the singularity of many cosmological models would disappear. This conjecture was based on the type of solutions discussed in section 3, and it could serve as a guiding principle in looking for a theory which explicitly takes account of the creation phenomenon. It is hoped to investigate this problem in a future paper.

Acknowledgement

The work described in this paper is supported by a Fellowship from the Jawaharlal Nehru Fund.

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