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A QUASI-STEADY STATE COSMOLOGICAL MODEL WITH CREATION OF MATTER

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ABSTRACT

A detailed account is given of a quasi-steady state cosmological model which was originally briefly described by Arp et al. We show that this model will explain the 2.73 K microwave background and the abundances of the light isotopes D, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, and ^{11}B.

The model is based on the idea that creation takes place in little big bangs each involving about $10^{16}\ M_\odot$ distributed over all space and time, the universe itself being without a beginning. We then show that an attractive feature of this idea is that we can explain in a natural way the general outpouring of mass and energy from a wide range of extragalactic objects, ranging from protogalaxies through to high-energy events (radio galaxies and QSOs) down to small scales in the nucleus of our Galaxy.

Following the introduction and discussion of earlier ideas, in § 3 we discuss the physics of creation. It is shown that unless creation of matter is included in the physical laws, the laws lack universality. Creation of matter is governed by a conservation law which operates to prevent spacetime singularities which otherwise occur in general relativity. In contrast to the classical steady state model, creation takes place only in strong gravitational fields associated with dense aggregates of already existing matter. Also unlike the classical steady state, the expansion rate $H = \dot{S}/S$ of the universe is not a constant but can vary secularly, corresponding to changes in the number and masses of the creation centers which drive the expansion. The model fits the observational facts of cosmology best when intermittent bursts of creation, occurring at intervals generally of order H_0^{-1}, are interspersed with longer periods of comparatively weak creation, but with the possibility that, viewed over long time intervals, the expansion is an approximately steady process with a generation length $\sim H_0^{-1}$.

If such mass-creation events have slight anisotropy, they can be detected by the laser interferometric gravity wave detectors being planned now. The gravity wave background produced by them should also be detectable by the timing measurements of millisecond pulsars.

Development of the theory indicates that newly created particles have a mass $(3\hbar c/4\pi G)^{1/2}$. Such Planck particles are unstable over a time scale of $\sim 10^{-43}$ s. An equipartition between radiation and matter in the decay leads to a production of $\sim 5 \times 10^{18}$ baryons per Planck particle, with the square of this number, 2.5×10^{37}, the source of the large dimensionless numbers of physics and cosmology. Although most of the radiative energy goes into the kinetic energies of expansion of the particles of a Planck fireball, thereby supplying the starting point of high-energy astrophysics, the radiation field causes a decaying Planck particle to expand as a cloud of particles in which nuclear reactions take place. It is as a consequence of such reactions that the light elements are produced. Unlike the situation in big bang cosmology, beryllium and boron are synthesized as well as lithium and helium, and all with relative abundances that agree very well with solar system values (§ 6).

Provided that the most important creation centers have masses of order $10^{16}\ M_\odot$, agreeing with the masses of individual cells in the honeycomb structure of the observed distribution of galaxies, the random thermal energy associated with the expanding material from creation centers is in good agreement with that required to explain the genesis of the microwave background. A thermalizing agent such as metallic whiskers, with an optical depth of 10 or more at the last major creation episode, is adequate to explain the observed smoothness of the resulting background, without interfering with extragalactic astronomy at the radio and optical wavelengths. This leads to a required present-day average intergalactic density of $\sim 10^{-35}$ g cm^{-3} for such particles, only a modest requirement.

Although the last major creation episode occurred at a time $\sim H_0^{-1}$ ago, creation continues at the present day in the form of a cascade which passes from larger masses to smaller masses.

In § 8 we discuss the likelihood that creation events can give rise to the observed properties of radio galaxies, QSOs, etc. We take as an example the properties of the well-known galaxy M87.

Finally, in § 9 we give a summary of our theory and make comparisons between these new ideas and the currently favored views.

Subject headings: cosmic microwave background — cosmology: theory — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

In an earlier paper (Arp et al. 1990) and in a brief letter (Arp et al. 1992), we have proposed a quasi-steady state cosmological model (QSSC). In this paper we give a more detailed account of the way in which this model explains the key cosmological observations, including the microwave background radiation and the fluctuations in it and the production of the light elements.

Our model is based on the idea that creation takes place primarily in little big bangs each involving about 10^{16} $M_{\odot}$, distributed over all space and time, the universe itself being without a beginning.

A very attractive feature of this idea is that the physics behind the cosmology may also explain in a natural way the general outpouring of mass and energy from a wide range of individual objects which are observed at all redshifts, ranging downward in energy from ejection of objects (protogalaxies) from galaxies as was first proposed by Ambartsumian (1958, 1965), through ejection from powerful radio galaxies, QSOs, Seyfert galaxies, and the like, to small-scale effects in the nucleus of our own Galaxy. That is, we are proposing a cosmogony which fits naturally in the QSSC in which galaxies and clusters are formed by ejection from the little big bangs involving $\sim 10^{16}$ $M_{\odot}$, and then subsequently ejection takes place in the subunits in a kind of a cascade process. Thus creation takes place over a wide range of energies and mass-creation rates as part of an ongoing process in space and time.

The plan of the paper is as follows. In § 2 we discuss the earlier history of the problem of active nuclei and give a critical assessment of the present black hole accretion disk paradigm. In § 3 we discuss what is sometimes described, often with a derogatory connotation, as "new physics"—the creation of mass in centers of very high gravitational potential. In § 4 we describe a possible way of detecting such creation events through the gravity waves they may emit. In § 5 we return to the cosmological problem and explain in some detail how these ideas can account for the microwave background. In § 6 we show how the light isotopes were formed. In § 7 we discuss the case for the existence of galactic objects with a wide range of evolutionary ages ranging from $\sim 10^8$ to $\sim 10^{11}$ yr. Such a distribution is expected in an ongoing universe. In § 8 we return to the galactic nuclei and give an account of how they may be understood in terms of mass-creation events in the nuclei. In § 9 we summarize our ideas and compare and contrast them with the current popular view of cosmology and cosmogony.

2. EARLIER VIEWS OF ENERGY GENERATION IN GALACTIC NUCLEI

Two of us were involved at the outset with what was termed "high-energy astrophysics" (Hoyle et al. 1964a). We were in no doubt then, and are in no doubt now, that a wide range of phenomena are related to situations involving strong gravitational fields. Over the years since this work of the 1960s, the range of phenomena has broadened from its earlier emphasis on sources of strong radio emission and Seyfert nuclei to include compact γ-ray and X-ray sources. Most of the phenomena are associated with galactic nuclei, and the general term "active galactic nuclei" (AGN) is frequently used to cover them all.

The big problem as it was seen at the outset (cf. Hoyle et al. 1964a) was how to get potentially available gravitational energy out of a highly condensed system. An attractive idea, also suggested at an early stage (cf. Salpeter 1964) was for a large compact mass approaching a relativistic event horizon to acquire material from far outside itself. The acquired material possesses angular momentum about the central object and so forms a disk rotating about the object instead of falling directly into it, a disk which then acts as a target for further infalling material. Since infalling material attains speeds approaching that of light, the postulated situation is analogous to a laboratory experiment in which a high-speed beam of particles is made to hit some target, the outcome being high-energy phenomena with obvious analogies to the astrophysical case. Over the years this *black hole with accretion disk* picture has become a widely accepted paradigm, despite the lack of any clear-cut evidence in favor of it. The evidence is all circumstantial, never direct. Nor is the term *black hole* a valid one. There is no evidence that the central compact object has crossed an event horizon, certainly not in our coordinate system and not even in a comoving coordinate system, as we shall show in this paper (§ 3). It should be realized that when it is reported that black holes of large mass in the centers of galaxies are being looked for, what the authors of such reports really mean is that they are trying to find evidence of compact objects producing strong gravitational fields. This point is important because the relation of a compact object to an associated event horizon will later be seen to be of critical relevance.

Although we ourselves were in a position to adopt the paradigm already in 1964–1965 (Hoyle et al. 1964a), we were always reluctant to do so, or at any rate hesitant to do so. Our reason was the insistence by Ambartsumian and others (Ambartsumian 1958, 1965) that the evidence was always of outward motion. There was no evidence of the infall of material such as the paradigm requires. The evidence is all of outflow.

When all of the mechanisms of energy release were reviewed by one of us in 1970 (Burbidge 1970), we were mindful of these issues and quoted the prophetic remark made by Jeans (1929) that "The type of conjecture which presents itself somewhat insistently is that the centers of the nebulae are of the nature of 'singular points' at which matter is pouring into our universe from some other, and entirely extraneous dimension, so that, to a denizen of our universe, they appear as points at which matter is being continuously created." It is exactly this conjecture of Jeans that we shall take up in detail in § 3 and the subsequent discussion.

Another argument which had been used still earlier against accretion by ordinary stars also had some weight with us. This was to the effect that the energy output from the surfaces of stars, whether as radiation or as particle emission, had the ability to push back the interstellar gas and to prevent the gas from approaching at all closely to the stars. The same situation seemed to hold, and to an enhanced degree, for material approaching at a distance toward a compact object. While still moving slowly, the material would be easily pressed back and so prevented from falling in. It remains hard for us to see how the paradigm copes with this difficulty. Material moving inward only at speeds of ~ 100 km s^{-1} would very readily be reversed and blown away by violet events that are required to release energy at rates upward of 10^{45} ergs s^{-1} in many cases. An explicit solution in relativity showing the relevance of exploding objects to high-energy astrophysics was considered first by Hoyle, Narlikar, & Faulkner (1964b) and later elaborated on by Narlikar & Apparao (1975).

The point appears more forcibly when energies per unit mass are considered. Thus material approaching a compact object at ~ 100 km s^{-1} has $\sim 10^{14}$ ergs g^{-1}, a million times smaller than the relativistic energy release $\sim 10^{20}$ ergs g^{-1} which the same material falling into a strong gravitational field could release. Only a small fraction of the latter, absorbed in material at a distance, is sufficient to blow away the former. [1]

It is also important to stress that the nonthermal processes then known in the 1960s were not taking place in high-density regions and so were not happening in or immediately around an accretion disk close to a compact object. The processes in question were radio emission and the excitation sources for QSOs and for various forms of optical emission from active galactic nuclei, the spectra of all of which clearly come from diffuse gas with particle densities typically in the range 10^6–10^{10} cm^{-3}. While it was true that such nonthermal processes could be seen as tertiary phenomena contingent on secondary emissions from an accretion disk, we felt that this further removal of the evidence from the primary situation of the compact object itself did not help to strengthen our belief in the model. Indeed, one now had three epicycles on what was supposed to be the prime mover. The accretion disk around the compact object was the first epicycle. The infall of fast-moving infalling material onto the accretion disk was the second epicycle, and the need for resulting emissions from the disk, whether particulate or radiative, to excite phenomena such as radio emissions at distances of some parsecs or greater from the object was the third epicycle. It is our impression that current versions of the paradigm, which seek also to explain γ-ray and X-ray emission, have added still further epicycles (cf. Holt, Neff, & Urry 1992).

It is generally accepted that theoretical ideas in order to be worthwhile should be falsifiable through observations and experiments. However, as is the case for most paradigms, the black hole accretion disk proposal contains so many epicycles and parameters that it appears not to fulfill this requirement. This is not to say that it is not correct, but it gives further justification for our attempt to find an alternative. This is what we shall do in the succeeding sections.

We therefore turn next to the fundamental issue in developing this new cosmogony, namely, the physics associated with the creation of mass.

3. THE CREATION OF MATTER AND ITS CONSEQUENCES

It appears to us that to overcome serious difficulties which the study of cosmology presents, it is necessary that matter be created. Creation occurs when certain conservation equations are satisfied. It is the purpose of this section to discuss these issues and also to explain why it seems likely that particles at creation are Planck particles, which is to say particles with mass

$$\left(\frac{3\hbar c}{4\pi G}\right)^{1/2} \simeq 10^{-5}\ \text{g}\ . \tag{1}$$

[1] This process may, at first sight, appear to be related to the well-known Eddington limit. However, the derivation of the Eddington limit requires outward momentum to be carried by radiation, whereas a powerful source of energy—whether radiative or particle emission—can blow away an approaching cloud of gas through absorption, leading to the development of an explosive pressure internally within the cloud. This process is more effective than the Eddington process by the ratio of the speed of light to the velocity of approach of the cloud to the energy source, in this case a factor of 1000 or more.

With respect to a Riemannian metric, consider a finite volume V of spacetime. In general there are infinitely many ways in which the situation within V can be specified subject to boundary conditions prescribed on the three-dimensional surface of V. For each such configuration a finite dimensionless number known as the action, say $\mathscr{A}$, is calculated by a stated mathematical rule, with the interpretation that $\exp i\mathscr{A}$ is to be proportional to the quantum probability amplitude for the occurrence of the configuration in question. When V is large enough that the paths of many particles traverse V, the action is a large number, and in general $\exp i\mathscr{A}$ changes considerably for even a very slight variation of the configuration. When summations such as

$$\sum_{\text{configurations in } V} \exp i\mathscr{A} \tag{2}$$

are considered, in order to determine the expectation value of some physical quantity, there is an essentially complete cancellation of terms, with the exception of configurations close to the one for which

$$\delta\mathscr{A} = 0\ . \tag{3}$$

Thus the situation when V is large is determined by equation (3). This principle of stationary action holds with respect to all the parameters specifying the configurations. It is from this condition that the equations of classical physics are derived. Quantum physics arises, on the other hand, when V is small enough for $\mathscr{A}$ not to be a large number, when summations like expression (2) have to be evaluated explicitly. For an extensive discussion of the latter problem see Feynman & Hibbs (1965).

It is an essential requirement of physics that V must be arbitrary—no restrictions must be involved in its choice. It is this freedom to choose V anywhere which gives physical laws their universality. Yet it is this deep-rooted and essential requirement that is flouted in big bang cosmology, and the manner of it defies normal scientific logic, giving rise in our view to the conviction that big bang cosmology cannot possibly be correct.

In Riemannian space time the element of proper length for the coordinate displacement dx^i $(i = 1, 2, 3, 4)$ at the point X is given by

$$ds^2 = g_{ik}(x)dx^i dx^k\ , \tag{4}$$

with various choices for the metric tensor $g_{ik}(x)$ representing possible configurations within V, subject to boundary conditions imposed on g_{ik} at the surface of V. Calculating $\mathscr{A}$ as a functional of g_{ik}, $\mathscr{A}[g_{ik}]$, say, the condition

$$\mathscr{A}[g_{ik} + \delta g_{ik}] = \mathscr{A}[g_{ik}] \tag{5}$$

evaluated to the first order in δg_{ik} yields the gravitational equations, where $\delta g_{ik}(x)$ are arbitrary small variations of g_{ik} inside V, subject to $\delta g_{ik} = 0$ on the boundary of V. The gravitational equations are nonlinear partial differential equations with the spacetime coordinates as independent variables.

The metric (4) is approximated in cosmology by assumptions of homogeneity and isotropy, in such a way that a synchronous time coordinate t can be defined, and so that the general partial differential equations become ordinary equations which can be solved. It is then shown that in all such approximated situations the universe was in a singular state at a time of order H_0^{-1} in the past, H_0 being the present-day measured expansion rate of the galaxies. For convenience, the zero of the time coordinate is taken at the singular state, the big bang, in which case the present-day value of t is the "age of the universe," no more than about 10 billion years, about twice the age of the Earth.

What is now done is in our view improper. It is argued that the volume V used to obtain the physical laws as outlined above must be chosen so that all its interior points have $t > 0$, thereby losing the most essential feature of physics, namely, that V is to be arbitrary so that the resulting physical laws are universal. According to big bang cosmology, universality is lost. This situation has no precedent in science. Special cases of general theories have often been used to test the theories. Should a special case not agree with observation or experiment, it is valid to argue that something must be amiss with the general situation. But a special case cannot be used to decide what it is that needs changing in the basic theory.

Improvements in understanding of basic theory have never been achieved that way. They have always come from the perceptions of individuals who, while being motivated by special situations, go outside them in taking the crucial steps. While being strongly motivated by the special situations investigated by Faraday, Maxwell went outside them in his concept of the so-called displacement current, and it was this concept which gave real life to the electromagnetic theory. It is to be expected, we think, that something similar should apply in cosmology.

The explicit formula for $\mathscr{A}$, applicable to a set of particles $a, b, \ldots$ is usually written in the form

$$\mathscr{A} = -\sum_a \int m_a \, da \,, \tag{6}$$

where da is an element of proper length along the assigned path of particle a and m_a is the particle mass. Subject to certain improvements in the interpretation of equation (6), it can be shown (cf. Hoyle 1992) that equation (6) contains the following:

1. The equations of classical dynamics.
2. Schrödinger's equation.
3. The dynamical equations of special relativity.
4. Scale-invariant gravitational equations which reduce to those of general relativity for a particular choice of scale (Hoyle & Narlikar 1964, 1966c).

These successes are sufficiently impressive for one to be able to say that there is something deeply correct about equation (6), with the implication that further successes may be expected from improvements in the sophistication with which equation (6) is interpreted.

Now according to big bang cosmology the unrestricted choice of the particle paths, extending backward in time infinitely in a Riemannian space, is to be truncated to

$$\mathscr{A} = -\sum_a \int_{t=0} m_a \, da \,. \tag{7}$$

That is to say, with coordinates chosen so that the synchronous time t can be used, the paths of the particles are restricted to begin at or near $t = 0$. One now easily sees that the lack of generality in equation (7) and the objections discussed above are overcome by studying configurations in which the end-points $A_0, B_0, \ldots$ of particles $a, b, \ldots$ can be freely chosen, in which case, for a configuration with particular choices of A_0, $B_0, \ldots$, the action is to be calculated from

$$\mathscr{A} = -\int_{A_0} m_a \, da - \int_{B_0} m_b \, db - \cdots, \tag{8}$$

with the line integrals evaluated along paths emanating from $A_0, B_0, \ldots$, i.e., from the points at which the particles originate. The situation is now general, and there is no restriction on the spacetime volume V to which the theory is to be applied. Once again the physical laws obtained from equation (8), and from increased sophistication in the meaning of $m_a, m_b, \ldots$, are genuinely universal. This is the argument for accepting the creation of matter as a necessary physical process. Without it, physics is greatly maimed. The word "creation" is to be interpreted in the same sense as in "pair creation," as a process to which clear-cut mathematical laws are to be applied. These will next be considered.

The introduction of a scalar field $C(X)$ marks the step to the quasi-steady state cosmology, a step first taken in 1948 by one of the present authors (Hoyle 1948). The field $C(X)$ is related to the points $A_0, B_0, \ldots$ by the wave equation

$$\Box_X C(X) + \frac{1}{6} R(X)C(X) = f^{-1} \sum_{A_0} \frac{\delta_4(X - A_0)}{[-g(A_0)]^{1/2}} \,, \tag{9}$$

where f is a positive coupling constant and $R(X)$ is the Riemannian scalar curvature at the spacetime point X. The field $C(X)$ is a particular solution of equation (9) such that the field is everywhere zero should all the terms on the right-hand side of equation (9) be zero, i.e., $C(X)$ is the so-called fundamental solution of equation (9). The term $\frac{1}{6}RC$ is required by considerations of scale invariance. It is needed to obtain scale-invariant gravitational equations.

The action formula is next upgraded to

$$\mathscr{A} = -\int_{A_0} m_a(A) da - \int_{B_0} m_b(B) db \cdots - C(A_0) - C(B_0) \cdots \,. \tag{10}$$

As was first shown by Hoyle & Narlikar (1964), a Machian interpretation of inertia makes it necessary to include the possibility of $m_a, m_b, \ldots$ being variable along the particle paths, thereby leading to general relativity as in item 4 above. The details of the procedure for obtaining general relativity have been repeatedly discussed (e.g., Hoyle & Narlikar 1964). Interpreting equation (10) quantum mechanically, $\exp i\mathscr{A}$ is the amplitude for particle a to be created at A_0, b at B_0, etc. Or when many particles are involved, with $\mathscr{A}$ a very large number and with the stationary action condition (3) holding with respect to variations of $A_0, B_0, \ldots$, an easy calculation shows that the following conservation conditions must be satisfied at these points:

$$C_i(A_0) = m_a(A_0) \frac{da_i}{da} \,,$$
$$C_i(B_0) = m_b(B_0) \frac{db_i}{db} \,, \tag{11}$$
$$\text{etc.}\,,$$

where

$$C_i(A_0) = \left[\frac{\partial C(X)}{\partial x^i}\right]_{A_0}, \quad C_i(B_0) = \left[\frac{\partial C(X)}{\partial x^i}\right]_{B_0}, \quad \text{etc}\,. \tag{12}$$

It is also easy to show from equations (11) that

$$(C_i C^i)_{A_0} = m_a^2(A_0) \,, \tag{13}$$

with similar equations for $b, \ldots$. That is to say, the length of the vector obtained by taking the gradient of the scalar field is the mass of the created particle. When this condition is satisfied, particles are created at a rate to be determined by standard quantum mechanical methods. Indeed, a closer investigation than is necessary here shows that the calculation is of a form similar to stimulated emission in a photon field, but with the important detail that the δ_+ and δ_- propagators of the photon field are inverted.

The essential difference between the classical steady state theory (Bondi & Gold 1948; Hoyle 1948) and what we have recently proposed (Arp et al. 1990, 1992) can now be appreciated. In the classical steady state the gradient of the C-field taken on a cosmological scale was considered to be large enough for equation (13) to be satisfied everywhere, so that creation could occur everywhere, but with quantum matrix elements that were very small, the rate of creation being everywhere nonzero but supposed small. Here, on the other hand, we regard the energies of bosons of the C-field taken cosmologically to be far too low for creation to occur homogeneously throughout spacetime. Hoyle & Narlikar (1966a, b) had considered the possibility of lifting the threshold of the C-field energy near a massive object. Particularly, such bosons falling into strong gravitational fields pick up energy, which becomes unlimited as the matter distribution producing a strong gravitational field approaches an event horizon. Thus, for the Schwarzschild metric (with $c = 1$),

$$ds^2 = \left(1 - \frac{2GM}{r}\right)dt^2 - \frac{dr^2}{1 - 2GM/r} - r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\,, \tag{14}$$

the left-hand side of equation (13) can be shown to increase according to the factor $(1 - 2GM/r)^{-1}$, whence it is seen that for a local object going close enough to an event horizon at radius $2GM$, C-field bosons that happen to fall close to the surface of the object will inevitably satisfy equation (13), and the creation process will be switched on. Also in contrast to the classical steady state theory, we do not consider the matrix elements for the creation process to be small. We regard the process, when it is switched on, as being effectively explosive, akin to the discharge of an exceedingly powerful laser.

The buildup of the C-field energy near the event horizon has a dynamical feedback on the equilibrium of a massive object. Because of the divergent negative pressure of the C-field at the event horizon, an object undergoing gravitational collapse is not able to surge through the event horizon. Instead it experiences a bounce that prevents its becoming a black hole even in the comoving frame.

Applying these ideas to cosmology, which is to say using the Robertson-Walker metric with an expansion scale factor $S(t)$, and obtaining the gravitational equations from scale-invariant considerations (Hoyle & Narlikar 1966a, b) the ordinary differential equations for $S(t)$ reduce to

$$\frac{\ddot{S}}{S} = -\frac{4\pi G}{3}\bar{\rho} + \frac{8\pi}{3} Gf\overline{\dot{C}^2}\,, \tag{15}$$

$$\frac{\dot{S}^2 + k}{S^2} = \frac{8\pi G}{3}\bar{\rho} - \frac{4\pi G}{3} f\overline{\dot{C}^2}\,. \tag{16}$$

Just as $\bar{\rho}$ is the smoothed cosmological mass density, $\overline{\dot{C}^2}$ is the cosmologically smoothed value of $\dot{C}^2$ contributed from the right-hand side of the wave equation (9) by many creation centers. One can now contemplate several possibilities according to the averaged properties of the creation centers:

1. It happens that the many creation centers maintain a steady value of $\overline{\dot{C}^2}$. With the k term in equation (16) becoming negligible with continuing expansion of the universe, there is then a steady state solution of equations (15) and (16),

$$S(t) = \exp Ht\,, \quad \frac{3H^2}{4\pi G} = f\overline{\dot{C}^2} = \bar{\rho}\,. \tag{17}$$

The big bang claim that $S(t) \to 0$ at some finite t, *whatever the model*, is disproved by this case, which served in the historic role of a counterexample. Models of chaotic inflation, also contingent on the introduction of a scalar field, have provided similar examples more recently (Linde 1983, 1987).

2. The creation centers are such that $\overline{\dot{C}^2}$ varies, but not much, in the time scale for the expansion of the universe. Then there is a steady state solution with equation (17) holding secularly.

3. $\overline{\dot{C}^2}$ is dominated by large creation centers with masses $\sim 10^{16}\, M_\odot$ as obtained in the next section. The activities of the creation centers are explosive and are correlated in episodes of comparatively short duration. During such episodes $\overline{\dot{C}^2}$ increases essentially impulsively, causing a sudden increase in the expansion rate of the universe with the parameter q defined by

$$q = -\frac{S\ddot{S}}{\dot{S}^2} \tag{18}$$

becoming sharply negative. Then, until the next impulsive episode occurs, the $\overline{\dot{C}^2}$ terms in equations (15) and (16) die away in comparison with the $\bar{\rho}$ terms (S^{-3} for $\bar{\rho}$, S^{-6} for $\overline{\dot{C}^2}$) and the universe expands for a while as in a Friedmann model with q positive.

The third of these possibilities accords best with the facts of observational cosmology, and it is this case that we will have in mind throughout the rest of this paper. The structure of equation (15) also points in this direction. Equations like (15) and (16) apply locally within a creation center, but of course with the terms much larger than their smoothed cosmological values. In equation (15) the $\dot{C}^2$ term can be seen to act as a negative pressure, the essential characteristic of an inflationary theory. It is for this reason that creation centers are inherently explosive. As they explode, causing the universe to expand rapidly, conditions become unfavorable for new large centers to be formed. Then, as the expansion of the universe weakens, perhaps with $\ddot{S}$ even becoming negative for a while, conditions for new centers to form become increasingly favorable and a further cycle is established. Hence possibility 3 can be seen as a potentially cyclic phenomenon, with short-lived creation episodes interspersed by lengthy periods of free expansion, rather like the model of operation of a car engine. We refer to this model as the quasi-steady state model (QSSC) with the abovementioned large-scale fluctuations in space and time.

Our picture is of a universe having oscillations superposed on a general expansion, the currently available astronomical data referring to the situation in an expansionary half-cycle of the oscillations. The time required for a creation event to fall close enough to its event horizon for breakout to occur is determined by an expression of the form

$$\frac{2GM}{c^3} \times \frac{\text{Mass of newly created particle}}{\text{Cosmological boson energy}}\,. \tag{19}$$

In an expanding phase of the oscillations, the second factor in expression (19) increases as S^3, limiting more and more the values of M for which expression (19) is less than $(\dot{S}/S)^{-1}$. Thus, in expansionary half-cycles of the universal oscillations the masses of creation events decline, while the opposite occurs during contractionary half-cycles. In the latter, creation masses increase, until the resulting negative pressure effects reverse the universal contraction. The value of M for which expression (19) is then of the order of the time of reversal determines the scale of the largest creation events, those shortly to be discussed in § 5. The largest creation events occur at oscillatory minima, and they are therefore cophased, a property that is important in the later discussion of the origin of the microwave background.

Using the Compton wavelength of newly created particles as the unit of length, and choosing the scale such that $m_a(A_0) = m_b(B_0) = \cdots = m_p$, say, it can be shown (Hoyle & Narlikar 1964) that the gravitational constant G is related to m_p by

$$G = \frac{3}{4\pi m_p^2} . \tag{20}$$

This demonstrates that gravitation is necessarily an attractive phenomenon, a deduction which cannot be made in the usual form of general relativity where G can be positive or negative according to how one chooses it to be. Since the units specified above require $\hbar = 1$, $c = 1$, it follows from equation (20) that m_p is related to G as in equation (1). Thus newly created particles are Planck particles, a situation that has two important consequences. One is that it explains why gravitation between ordinary atomic particles is such a weak force, a weakness that is often expressed by

$$\frac{\text{Gravitational force between two protons}}{\text{Electrical force between two protons}} = 8 \times 10^{-37} . \tag{21}$$

Taking Planck particles to bear the elementary charge, this ratio for them is not small at all, however. Indeed, it is about 30. All the very small dimensionless numbers which have for long been considered to haunt physics and cosmology arise because of the circumstance that Planck particles decay into large numbers of baryons.

Decay into a large number of secondaries prevents the inverse process of particle annihilation from having much importance. Particle annihilation would require a large number of secondaries to be brought together into a spatial volume with a dimension of the order of the Compton wavelength of the Planck particle, $\sim 10^{-33}$ cm, and there are few, if any, places in the universe where this happens. This makes for a one-way property of the creation-annihilation process which can be taken as defining an arrow of time for the universe. An arrow was already implied in equation (10), by setting the points $A_0, B_0, \ldots$ as the lower limits of the time integrals. With the arrow set in this sense, the universe expands, i.e., the C^2 terms in equations (15) and (16) act with the coupling constant f positive. Then, according to the extension of the Wheeler-Feynman absorber theory given by Hoyle & Narlikar (1974), the future universe acts as a perfect absorber and electromagnetic propagation takes place in the same sense as the universe expands. So goes thermodynamics, and with it the metabolic processes of animals like ourselves. Of course in a purely formal sense, $-t$ can always be written for t. Mathematically $A_0, B_0, \ldots$ then appear as upper limits of the line integrals, the sign of $\dot{S}$ is inverted and the universe contracts, radiation propagates from future to past, and thermodynamics and metabolic rates go backward. Everything appears subjectively the same, however, because we then live our lives backward with respect to t. The essential point is that we age in the same time sense as Planck particles decay and as the universe expands. All this follows from the circumstance that the relation of Planck particles to their secondaries is not reversible with respect to time, in the universe as it happens to be.

4. POSSIBLE DETECTION OF GRAVITY WAVES FROM MINI–CREATION EVENTS

In this section we briefly describe a novel way in which the hypothesis of minibangs might be testable in the near future. Narlikar & DasGupta (1993) have discussed the possibility of detecting gravity waves from a mini–creation event, provided that the created mass expands anisotropically, thus having a time-dependent quadrupole moment. The basic idea is as follows.

As we have seen here, an isotropic expansion after creation in a local region simulates the Friedmann model with $q_0 > 0$. The simplest case ($k = 0$) has the expansion factor varying as $t^{2/3}$. In an anisotropic expansion this asymptotic expansion state is described by the Bianchi type I model with the line element

$$ds^2 = c^2 dt^2 - X^2(t)dx^2 - Y^2(t)dy^2 - Z^2(t)dz^2 , \tag{22}$$

with (x, y, z) the principal Cartesian axes for the anisotropic expansion. The expansion functions are given (in the matter-dominated stage) for arbitary angle α by

$$\begin{aligned} X(t) &= S(t)[F(t)]^{2 \sin \alpha} , \\ Y(t) &= S(t)[F(t)]^{2 \sin (\alpha + 2\pi/3)} , \\ Z(t) &= S(t)[F(t)]^{2 \sin (\alpha + 4\pi/3)} , \end{aligned} \tag{23}$$

where $S(t)$ and $F(t)$ are related to the total expanding mass M by

$$\begin{aligned} S^3 &\equiv XYZ = \tfrac{9}{2} GM(t + \Sigma) = \text{constant} , \\ F^3 &= \frac{GMt^2}{S^3} . \end{aligned} \tag{24}$$

The S function is the overall expansion factor with the matter density falling as

$$\rho = \frac{3M}{4\pi S^3} . \tag{25}$$

The parameter α indicates the anisotropy of expansion. Although equation (24) suggests that $S \to 0$ as $t \to 0$, this is misleading. As in the isotropic case, the C-field steps in to prevent a singularity outside the radius $2GM/c^2$, and the above solution only describes the asymptotic state when the expansion has reduced the influence of the C-field to negligible proportions.

With such objects as sources, Narlikar & DasGupta (1993) have argued that gravity waves emerging from them should be detectable with Laser Interferometric Gravity Observatory (LIGO) type detectors directly or through the effect the gravity wave background has on the timing mechanisms of millisecond pulsars. Provided that there is anisotropy of expansion (denoted by α in the above solution), masses of the order of $10^3\ M_\odot$ or above located at cosmological distances should be detectable by the LIGO within a few years of its operation. The background measurements affecting millisecond pulsars likewise should become precise enough in the coming years to place upper limits on sizes of minibang masses and also to distinguish between the present theory and the big bang theory in which a gravity wave background may arise from some version of the inflationary models.

5. THE ORIGIN OF THE MICROWAVE BACKGROUND

In § 3 we described the creation process in the QSSC and showed how large masses could appear. Thus we start here with a mass of condensed material producing a strong gravitational field. This requires the radius R of a spherically symmetric distribution to be larger, but not much larger, than the event horizon value $2GM/c^2$, where M is the total mass and G the gravitational constant. The reason for this starting point was discussed in § 3, where it was explained how the material comes to be in a state of outward expansion from its initial state at

$$R \simeq \frac{2GM}{c^2} . \tag{26}$$

It is easy to show that the initial mean density ρ_i at the stage where equation (26) holds, is given by

$$\rho_i \simeq 2 \times 10^{16}\left(\frac{M_\odot}{M}\right)^2 \text{ g cm}^{-3} . \tag{27}$$

It is often stated that big bang cosmology explains the microwave background. It does no such thing, of course. Big bang cosmology assumes the microwave background, and it does so in a quite arbitrary way, requiring the baryon-to-photon ratio to be close to 3×10^{-10}, without offering a convincing explanation of this number, which could just as well be anything at all. Rather than choosing such an arbitrarily small number for this ratio, we believe that it is more reasonable to assume the equipartition condition:

$$\text{Energy density of matter} \approx \text{Energy density of radiation} . \tag{28}$$

This is at the stage when equations (26) and (27) hold. In § 6 below we attempt to show how equation (28) comes about. From equation (28) the initial temperature T_i of the radiation is given by equating aT_i^4 to $\rho_i c^2$, i.e., by

$$T_i \simeq 7 \times 10^{12}\left(\frac{M_\odot}{M}\right)^{1/2} \text{ K} . \tag{29}$$

As the system expands, the opacity of the material will at first be sufficient to prevent radiation from escaping from the interior of the object into the space outside. But a stage will eventually be reached at which this is no longer the case, a stage at which radiation does indeed escape. In Appendix A at the end of this paper, we show that the density of matter at the stage where radiation escapes is given by

$$\rho \simeq \left[3 \times 10^{-9}\left(\frac{M_\odot}{M}\right)^{2/3} \kappa^{-1}\right]^{6/5} \text{ g cm}^{-3} , \tag{30}$$

where κ is the mass absorption coefficient of the material expressed in $\text{cm}^2 \text{ g}^{-1}$. In the early stages of expansion, when the material is hot enough to be ionized, opacity from electron scattering is important, but for large $M/M_\odot$, implying an eventual low temperature with the material largely un-ionized, opacity by dust becomes dominant. Metallic needles of small diameter are highly absorbent of microwave radiation and of radiation in the far-infrared, as is shown in Figure 1 (Wickramasinghe, Wickramasinghe, & Hoyle 1992). Note, however, that the κ-values in Figure 1 must be multiplied by the concentration of needles in the material in order to obtain the opacity to be used in equation (30). Thus, for a concentration by mass of 10^{-5}, the value of the opacity to be used in equation (30) is $\sim 10^2 \text{ cm}^{-3} \text{ g}^{-1}$ in the far-infrared and microwave regions, rather than the $10^7 \text{ cm}^{-3} \text{ g}^{-1}$ of Figure 1, which refers to needles alone.

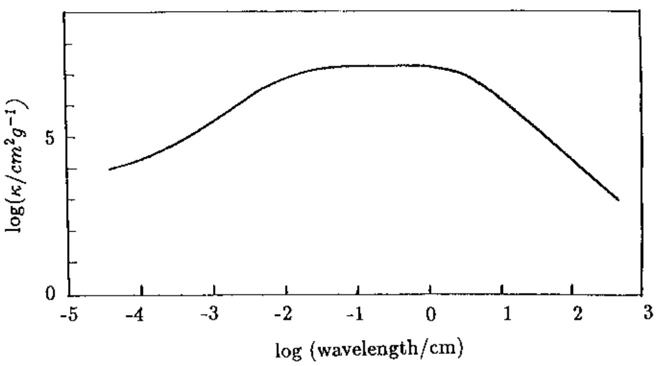

FIG. 1.—Plot of the mass absorption coefficient for iron whiskers with low-frequency, low temperature conductivity 10^{18} s^{-1}, the whiskers being of length 1 mm and diameter 0.02 μm, taken from Wickramasinghe, Wickramasinghe, & Hoyle (1992).

The dimensions of the needles used in Figure 1 are those found in laboratory studies of condensing metallic vapors (Sears 1957; Nabarro & Jackson 1958). Similarly condensing particles would be expected from metallic vapors in the ejecta of supernovae, and supernovae are adequate to supply the required cosmic quantity of such particles. Thus the total mass of galactic material in the visible universe is $\sim 10^{21} M_\odot$, requiring a total mass of $\sim 10^{16} M_\odot$ as iron particles in order to give a concentration of 10^{-5}. With $\sim 10^9$ galaxies in the visible universe, the required production rate over 10^{10} yr is therefore $\sim 10^{-3} M_\odot \text{ galaxy}^{-1} \text{ yr}^{-1}$, satisfactorily close to standard estimates of the average iron production rate.

Supernova ejecta tend to be expelled from the disks of galaxies, the reason being that the dynamical relaxation times of disks are longer than the evolution times of early-type stars. Thus the 10–100 supernovae derived from rich associations of early type stars act coherently in expanding their products out and away from their parent galaxies, and so into extragalactic space on account of the high ejection speeds of supernova material.

If the object were alone, escaping radiation would simply continue out into space, but if we are concerned with an epoch in the universe at which there are many similar objects, radiation from a particular object will eventually overlap that from other objects. And material from neighboring objects will also tend to overlap, at some density, say ρ(overlap), which should be about $10^{-27} \text{ g cm}^{-3}$, the density found typically in major clusters of galaxies; the time scale of the overlap process will be $\sim 10^{16}$ s, in which time radiation, after escaping from its parent object, experiences $\sim 10^{16} \rho\kappa c$ further absorptions and emissions. With $\rho(\text{overlap}) = 10^{-27} \text{ g cm}^{-3}$, $\kappa = 10^2 \text{ cm}^3 \text{ g}^{-1}$, this amounts to about 30 absorptions and reemissions, more than ample to thermalize and smooth the radiation field; only a few absorptions and reemissions are sufficient to remove fine-scale irregularities in the radiation field, while ~ 10 absorptions and reemissions will largely remove deviations from large-scale isotropy. Once thermalized, a radiation field carries no information concerning the distribution of the thermalizing agent. Only to the extent that the field is not thermalized can the thermalizing agent be "seen." Our view of the recently claimed deviations from strict isotropy found by *COBE* (Smoot et al. 1992; Wright et al. 1992) is that they result from slight variations from strict thermalization, either at the episode of overlap we are now discussing or perhaps from the more recent production of infrared radiation by galaxies.

It is important to notice that, whereas material from creation centers has spread out at the present universal epoch so as to overlap on a scale of $\sim 10^{26}$ cm, radiation because of its much higher speed of travel has spread out from its centers of origin by $\sim 10^{27}$ cm or more. To the extent that one region of dimension $\sim 10^{27}$ cm differs from another, there could be a difference in the associated radiation field, and several such regions projected together against the sky could differ slightly on angular scales $\sim 10°$. But since each region contains $\sim 10^6$ galaxies, such effects must necessarily be very small and are readily containable within permitted fluctuations of the background.

What determines the value of ρ(overlap)? Simply the number of objects associated with the universal episode in question. Each object can be regarded as having a sphere of influence in which its material may expand freely without impinging on material from neighboring objects. Filling the sphere of influence determines ρ(overlap). Taking the number of objects to be such that

$$\rho(\text{overlap}) \simeq 10^{-27}\ \text{g cm}^{-3}\ , \tag{31}$$

the lookback redshift to the episode in question is about $z = 4$. Subsequent to this episode, the universe has expanded as in a Friedmann cosmology with the density falling as $(1 + z)^{-3}$ and the temperature of the radiation field falling as $(1 + z)^{-1}$. At present we have

$$\rho(\text{present}) \simeq \frac{3H_0^2}{8\pi G} \simeq 10^{-29}\ \text{g cm}^{-3}\ , \tag{32}$$

which, together with equation (31), gives $(1 + z)^3 \simeq 100$, i.e., $z \simeq 4$. This is an important result for astrophysics, since it implies that the episode of overlap in this cosmological model is not back in some remote, inherently unobservable relic state of the universe but is within the range of the latest generation of telescopes. In our view, this is a positive feature for our cosmological model, since it suggests that the model is susceptible to observational test, a situation which is not the case for the corresponding phase in the big bang theory. To illustrate this point, the gross difference in the energy ratio of thermal radiation to matter between the present universe and the supposed relic universe of big bang cosmology is worth noticing. The present ratio is $\sim 10^{-4}$. Even at the center of a nuclear weapon or in a supernova, it is no larger than $\sim 10^{-3}$. Yet at the supposed stage of helium formation in big bang cosmology, the ratio is $\sim 10^7$, and at still earlier stages it is $\sim 10^9$. It needs more faith than we possess to believe that physical laws obtained for our tremendously different world can be taken to apply in fine detail to such grossly different conditions.

Except while the density falls from the escape value given by equation (30) to the overlap value of $\sim 10^{-27}$ g cm^{-3}, the temperature of the radiation field declines as the cube root of the density. But during the fall from the value given by equation (30) to 10^{-27} g cm^{-3}, a fall by a factor p, say, the temperature descends as the fourth root of the density. Thus the present temperature T(present) is given by

$$T(\text{present}) = T_i\left[\frac{\rho(\text{present})}{\rho_i}\right]^{1/3} p^{1/12}\ , \tag{33}$$

a result that is easily obtained from the above remarks. Using equation (27) for ρ_i and equation (29) for T_i, we therefore have

$$T(\text{present}) = 2.6 \times 10^7\left(\frac{M}{M_\odot}\right)^{1/6} p^{1/12}\rho(\text{present})^{1/3}\ . \tag{34}$$

With T(present) = 2.73 K, ρ(present) = 10^{-29} g cm^{-3}, we get

$$\frac{M}{M_\odot} = 1.4 \times 10^{16} p^{-1/2}\ . \tag{35}$$

The result in equation (35) relates to the real world, for it gives the masses of the units of which the observed honeycomb-like structure of galaxies is composed, i.e., the scale of superclusters of galaxies. As regards the values of p, put $M/M_\odot \simeq 3 \times 10^{15}$, $\kappa = 10^2$ cm^3 g^{-1} in equation (30). The density in the expanding objects at which radiation escapes is then found to be $\sim 10^{-25}$ g cm^{-3}. With ρ(overlap) = 10^{-27} g cm^{-3}, the value of p is about 10^2, and the supercluster mass is a little above 10^{15} $M_\odot$, a good number for the entire Virgo complex of galaxies, for example.

If we care to add that after escape of radiation the object expands at parabolic speed against its own gravitational field, as is done in big bang cosmology, the speed at overlap is

$$\sim 4 \times 10^7\left(\frac{M}{M_\odot}\right)^{1/3} \rho(\text{overlap})^{1/6}\ \text{cm s}^{-1}\ , \tag{36}$$

which, for $M/M_\odot \simeq 10^{15}$, ρ(overlap) = 10^{-27} g cm^{-3}, is about 1000 km s^{-1}. Strict closure would require that this expansion speed agree with that needed to match the expansion of the whole universe. However, strict closure would be a counsel of perfection. We expect there to be excesses and deficits, also of ~ 1000 km s^{-1}, with respect to the expansion of the universe. This leads to the following general considerations:

1. The density of $\sim 10^{-25}$ g cm^{-3} at the escape of radiation is a good value for that of material at the inception of the formation of galaxies, while 10^{-27} g cm^{-3} is a good value for an average density in clusters of galaxies. Indeed, these density values suggest that galaxy formation and cluster formation occur during the expansion of material, after the escape of radiation but before overlap.
2. Where there is a deficit of expansion energy to match the expansion of the universe, the galaxy clusters obtained under item 1 above subsequently remain bound. Where there is an excess of expansion energy, the galaxies and clusters continue to move apart.
3. Where there is an excess of expansion energy, uncondensed gas impacts uncondensed gas from neighboring objects at speeds ~ 1000 km s^{-1}, generating kinetic temperatures $\sim 5 \times 10^7$ K. The Jeans mass for this temperature and for the overlap density of 10^{-27} g cm^{-3} is typically that of a small cluster of galaxies. Thus galaxies can also be formed by cooling processes in such impacting gas (cf. Gold & Hoyle 1959).

Some years ago, Ostriker, Peebles, & Yahil (1974) strongly made the case that for systems of galaxies ranging from binaries up to rich clusters, it appeared that the total mass was proportional to the scale R of the system. This was one of the results which led to much of the excitement concerning "missing mass." However, one of us (Burbidge 1975) pointed out at that time that the relation $M \propto R$ was a direct result of assuming that all of the systems are bound, since M is the virial mass. That, together with the fact that the characteristic velocity differences in systems of very different sizes ($M \approx v^2R/G$) show only a very small range of values from ~ 300 to about 1000 km s^{-1} when we go from small groups up to rich clusters, leads directly to $M \propto R$. Thus it was argued (Burbidge 1975) that the really important parameter was the value of the temperature corresponding to these velocities. This is just the temperature $\sim 5 \times 10^7$ K discussed above.

4. Bremsstrahlung in hot gas at temperatures upward of $\sim 10^8$ K generates an X-ray background. Allowing for a present-day weakening by the factor

$$[\rho(\text{present})/10^{-27}]^{4/3} \approx 2 \times 10^{-3} , \quad (37)$$

the present-day energy density of such a background, produced by exceptionally high impact speeds, is $\sim 3 \times 10^{-17}$ ergs cm^{-3}, consistent with the observed X-ray background energy density.

Comparison of this conclusion with the modern interpretation of the observations of the X-ray background leads to an interesting result. As Setti (1992) has pointed out, Cowsik & Kobetich (1972) showed that the observed spectrum in the energy range 3–100 keV is well fitted by a bremsstrahlung spectrum with $T \simeq 40$ keV. However, others (cf. Giacconi & Zamorani 1987) showed that the subtraction of known discrete source contributions would distort the thermal shape. On the other hand, the existence of a very precise blackbody spectrum for the cosmic microwave background (CMB) (Mather et al. 1990) requires that there be an upper limit to the size of the Compton effect involving the scattering of the hot electrons on the photons of the CMB (Field & Perrenod 1977; Guilbert & Fabian 1986). This appears to limit the contribution to the X-ray background by hot gas to only a few percent. Thus it may simply be that only a few percent of the X-ray background can be explained by the creation process.

However, the latter part of this argument is predicated on the assumption that the microwave background has not been subject to smoothing and thermalization subsequent to X-ray production. This assumption is not satisfied here, with ~ 10 or more absorptions and reemissions by iron whiskers occurring *after* X-ray production. This raises the possibility that the observed X-ray spectrum has a bremsstrahlung form because it really was generated by bremsstrahlung, rather than by a concatenation of sources which just happened to imitate a bremsstrahlung spectrum. In that case the contribution from creative galactic nuclei would have to be less than it is sometimes represented to be.

5. For bound systems of galaxies, motions relative to the Hubble flow up to ~ 1000 km s^{-1} are to be expected. These are maintained despite the expansion of the universe.

It is not our purpose here to discuss in detail these several processes. Our main conclusion here is that this model not only will explain the microwave background and the honeycomb structure and scale of the distribution of galaxies, but it has the possibility of many connections with astrophysics, something which big bang cosmology lacks.

Finally, we stress again that the observed smoothness and blackbody character of the CMB is due to the many absorptions and reemissions taking place in the radiation field. The process is taking place at comparatively small redshifts. As was discussed by Arp et al. (1992), this is a different process from that described by Peebles et al. (1991), who showed that in the classical steady state model, there are departures from a pure blackbody curve.

6. THE SYNTHESIS OF THE LIGHT ELEMENTS

By extending the adiabatic proportionality $\rho \propto T^3$ backward to times *before* the initial situation for the density and temperature values given in equations (27) and (29), i.e.,

$$\rho = \frac{\rho_i}{T_i^3} T^3 = 5.8 \times 10^{-23} \left(\frac{M_\odot}{M}\right)^{1/2} T^3 , \quad (38)$$

the synthesis of the light elements can be explained in much the same way as in big bang cosmology. With $M/M_\odot = 10^{15}$ this procedure gives

$$\rho = 1.8 \times 10^{-30} T^3 , \quad (39)$$

to be compared with the requirement that the baryonic density be $10^{-32}T^3$, or $10^{-5}T_9^3$ (with T_9 in units of 10^9 K), for synthesizing D, ^{3}He, ^{4}He, and ^{7}Li satisfactorily. The hundred-fold discrepancy here can be overcome by separating matter into two components, baryonic and nonbaryonic, with

$$\rho_{\text{baryonic}} = \Omega\rho , \quad (40)$$

defining the baryonic density in terms of the total density ρ in equation (39). Just as in big bang cosmology, a low value of Ω is required. For $\Omega = 10^{-2}$,

$$\rho_{\text{baryonic}} \approx 10^{-32} T^3 , \quad (41)$$

and the situation is virtually identical to that in big bang cosmology.

For the purpose of demonstrating an alternative to the big bang, this is already sufficient. However, there are two grounds for hesitating over such an attempted resolution of the problem of primordial nucleosynthesis, one tactical and the other strategic. The tactical difficulty is to identify the main component of matter. In recent years many cosmologists have become so convinced of the existence of "missing matter," hot or cold or whatever, that they are hunting for it with much resolution, but so far without success. An initially long list of possibilities—esoteric and otherwise—has been partly reduced. While there is no doubt that some dark matter is present, it may be that nonbaryonic missing mass is missing because it really is not there because the argument for $\Omega \ll 1$ is wrong.

The strategic difficulty is that extending $\rho \propto T^3$ back to times before the initial situation to which equations (27) and (29) apply takes each of our objects inside the event horizon determined by equation (26). The objects become what have been termed white holes, with similar metaphysical questions applying to them as to the big bang. If the objects are considered to be creation events, triggered in their explosive activity by some exterior controlling cosmological field, how is this to be done in a finite time as seen by an exterior observer, and how are the moments of outburst of many white holes to be arranged more or less contemporaneously from the point of view of an exterior observer? With the objects inside their event horizons at earlier times, these questions seem logically unanswerable. They parallel the question of what happens before the big bang, for which no one has yet found a satisfactory answer. The bold policy is to have done with it, and to see what else there might be. However unusual or unexpected an alternative might be, it can hardly be worse than going outside physics.

In our view the objects discussed in the previous section are creation events, the largest creation events within our purview. Their nature and cause were stated in § 3, where mathematical rules governing the creation of matter were stated. The rules suggest that matter at creation is of the form, not of baryons, but of Planck particles, particles of mass

$$\left(\frac{3c\hbar}{4\pi G}\right)^{1/2} = 10^{-5} \text{ g} . \tag{42}$$

Planck particles are unstable, decaying into bosons, designated X, $\bar{\text{X}}$, in a time that is some moderate multiple of 10^{-43} s. It is from this decay time that 10^{-43} s appears as the earliest time scale in big bang cosmology. The same decays will arise here, with the advantage to the particle physicist of this happening in the recent universe, and likely on a reduced scale (cf. § 7) even in the present universe.

Further decays follow, leading to a quark-antiquark sea, and eventually to hadrons in a moderate multiple of 10^{-24} s. The annihilation of particles with antiparticles, but leaving a small biased residuum of matter, is supposed to lead to a situation with the large ratio of radiation to matter that was mentioned before, a baryon-to-photon ratio of about 3×10^{-10}. The situation here differs markedly from this last part of the big bang scenario, however. We regard Planck particles as being already biased toward particles at their creation.

The sources of the C-field on the right-hand side of equation (9) are at the creation points of matter, while the creation points are themselves determined by the C-field in a closed loop (as in electrodynamics, the motion of matter is determined by the field and the field is determined by the matter). This is to establish an ongoing situation with the loop taken as definitely one form of matter, either matter or antimatter but not both.

The equipartition (28) between matter and radiation quickly turns into an equipartition between the rest energies of baryons and their kinetic energies of expansion, with the radiation going largely into the expansion. Thus comparatively little in the way of radiation emerges directly from Planck fireballs. What emerges are rapidly moving particles that experience energetic collisions with the ambient medium outside the fireballs. As the kinetic energies of emerging particles are thus degraded, a secondary radiation field arises, and in a situation in which most or all of the matter in the system has come from Planck fireballs, it is the energy density of the secondary radiation, satisfying condition (28) of § 5, that becomes the field considered in the previous section and which ultimately becomes the microwave background. During the degradation of a system of particles, each with an initial kinetic energy of order 1 GeV, there is ample scope for high-energy secondary processes and it is from these that we regard all, or at any rate most, of the phenomena of high-energy astrophysics as being derived.

Allowing for the fraction of the decay energy going into radiation, the mass $\sim 10^{-5}$ g of a Planck particle is sufficient to produce $\sim 5 \times 10^{18}$ baryons. The thermal motions of the particles being nonrelativistic, the adiabatic relation between the particle density n and the temperature T in an expanding Planck fireball is of the form $n \propto T^{3/2}$, and not $n \propto T^3$ as is the case in big bang cosmology. In an investigation of the nuclear reactions taking place within such a fireball, and using the methods originally discussed by Wagoner, Fowler, & Hoyle (1967), Hoyle (1992) has considered a situation in which all members of the baryon octet are equally represented, with the particle density of each baryon type given by

$$2\,\frac{(2\pi mkT)^{3/2}}{h^3}\,\zeta\,, \tag{43}$$

the parameter ζ expressing the balance between radiation and matter. Here m is taken to be an average baryon mass of ~ 1 GeV, h is Planck's constant, and k is the Boltzmann constant.

Nuclear reactions take place when the temperature is generally in the range 10^{10} K to about 3×10^{10} K, so that for a reasonable choice of ζ expression (43) gives $\sim 10^{35}$ particles cm^{-3}, when the radius of the fireball is $\sim 10^{-6}$ cm and the time scale for its expansion is $\sim 10^{-16}$ s, which is too short for reactions involving either γ-ray emission or the weak interactions to take place. The only baryon of the octet that is unstable in a time of 10^{-16} s is Σ^0, which goes to Λ. It is considered that, because of their eventual instability in a time scale of 10^{-10} s, Λ, Σ^+, Σ^-, Ξ^0, Ξ^- do not form stable nuclei. They survive the expansion of a fireball, first giving P and N and ultimately P after the decays of N in $\sim 10^3$ s. On the other hand, the initial protons and neutrons in an expanding fireball combine in a time scale 10^{-16} s into ^{4}He. They do so as the temperature T falls below 3×10^{10} K. Investigating the detailed nuclear reactions which produce helium for the case $\log \zeta = -0.5$, Hoyle (1992) has found that all but about 5% of the initial protons and neutrons go into ^{4}He, from which the mass fraction Y of ^{4}He in the emerging material is seen to be

$$Y = 0.95 \times \tfrac{2}{8} = 0.238\,, \tag{44}$$

the fraction $\frac{2}{8}$ coming from the P and N each being one-eighth of the emerging baryons.

The choice $\log \zeta = -0.5$ implies that most of the early radiative energy has gone into the adiabatic expansion of the fireball at the stage where the helium is produced. The result in equation (44) is not sensitive to the precise choice of ζ, although widely different choices would move Y from the interesting value in equation (44) to values generally in the range from ~ 0.2 to ~ 0.3.

The release of energy from helium production temporarily destroys the adiabatic condition, in effect reducing ζ as the energy becomes transferred first to the radiation field and then into the energy of expansion of the fireball. A possibly stronger departure from the adiabatic condition may come from the decay of π^0 mesons, for which the lifetime happens to be 10^{-16} s, the same as the expansion time of the fireball. It was considered by Hoyle that these two sources of energy, following the production of ^{4}He, could lower the effective value of ζ from $\log \zeta = -0.5$ to $\log \zeta = -1.5$ during the later expansion. Using nuclear reaction rates for the latter value of $\log \zeta$, the abundances relative to hydrogen of the light isotopes were calculated by Hoyle (1992). These abundances are shown in Table 1, their method of calculation being sketched in Appendix B.

It is a source of considerable surprise that results like Table 1 and equation (44), even superior to those of big bang cosmology, should be obtainable from such very different choices of density, temperatures, and time scale. The density is a factor of

TABLE 1

LIGHT-ELEMENT ABUNDANCES EMERGING FROM PLANCK FIREBALLS

Element Ratios	Approximate Numerical Values
D/H	2×10^{-5}
^{3}He/H	2×10^{-5}
^{7}Li/H	10^{-9}
^{9}Be/H	3×10^{-11}
^{11}B/H	10^{-10}
^{6}Li/^{7}Li	10^{-1}
^{10}B/^{11}B	10^{-1}

order 10^{15} higher than is the case at the helium-forming epoch in big bang cosmology, and the time scale is of order 10^{20} times shorter. One is tempted to argue inferentially, namely, that, since it would be exceedingly unlikely to obtain such very good results from a wrong theory, the theory is not wrong. The inference is that it is the big bang explanation of the genesis of the light elements which is wrong.

The stranglehold of light-element synthesis on cosmology can be broken in this way. Setting the above results at their lowest, they show that an alternative view of light-element synthesis is possible. More investigation is certainly needed along the lines initiated by Wagoner et al. (1967) and also by Wagoner (1973). The essential point here is that the difference between the cosmological density of 10^{-29} g cm^{-3} and the observed density of $\sim 3 \times 10^{-31}$ g cm^{-3} of visible material need no longer be nonbaryonic, as it must be in big bang cosmology. The "missing mass" can be in the form of very faint stars or large planets, "Jupiters" as they have been called, possibilities that are forbidden in big bang cosmology. Or, more radically, the missing mass can be in the form of objects of the type considered in the previous section, objects which are lying dormant, waiting to burst out in a new episode of the kind discussed in § 3. The light-crossing time R/c, with R given by equation (26), is $2GM/c^3$. Putting $M = 10^{15}\ M_\odot$, we find the value $\sim 10^{10}$ s. However, the time of outburst of such an object, as determined by an external observer, must contain a relativistic time dilatation factor $(1 - 2GM/rc^2)^{-1/2}$, which can be large if the object is poised near its event horizon. Thus for

$$\frac{\text{Mass of newly created particle}}{\text{Cosmological boson energy}} = \left(1 - \frac{2GM}{rc^2}\right)^{-1/2} \simeq 10^8 , \tag{45}$$

say, with r the surface radius of the object; the time of outburst of an external observer is $\sim 10^{18}$ s, comparable to but greater than H_0^{-1}. It is in this sense that an object can lie dormant, waiting until sufficient time has elapsed in the external world for its outburst to become apparent. This concept and the physical reasons for the approach to an event horizon and for the eventual outburst were discussed in § 3.

Because the time scale of 10^{-16} s is too short for nuclear reactions involving γ-ray emission to be important in a Planck fireball, not much ^{12}C can be produced by the usual triple-α reaction. But there are other ways in which ^{12}C can be reached, depending somewhat sensitively on the value of the parameter ζ. It is possible for ζ to be such that significant quantities of ^{12}C are produced, in which case there will be a further building to heavier elements. It can be shown, for example, that a time scale of 10^{-16} s, a temperature of 2×10^{10} K, and a density of $\sim 10^{11}$ g cm^{-3} are adequate for the reactions ^{12}C + ^{12}C, ^{12}C + ^{16}O, ^{16}O + ^{16}O to take place. There is accordingly the possibility of some moderate concentration of heavier elements being already present in matter at the time of its origin, quite apart from what is produced later in stars. This would explain why heavy elements are apparently always found in objects at high redshifts, and it might lead to the view that there is no need to invoke the presence of Population III stars.

It can be argued that some old stars in our own Galaxy contain only small quantities of heavy elements, or none at all. But this is not a secure argument. With the heavier elements condensed into dust particles, there are opportunities for fractionation processes to occur. In the early history of our Galaxy, for example, dielectric dust particles of dimensions 10^{-5} cm can sediment in 10^9 yr under gravity from the early halo toward the Galactic plane, while dust particles in dwarf galaxies could be lost from weak gravitational fields by radiation pressure. It is also interesting that, with heavier elements formed in Planck fireballs, metallic needles could very well be already present within the material of the expanding objects discussed in the preceding section. There would then be no difficulty in understanding how metallic needles come to be universally distributed, and how they come to thermalize and smooth the microwave background. Or, again arguing inferentially, one could say that the microwave background is evidence that this is so.

If heavier elements form in this way, a second approximation to the value of Y is needed. Instead of equation (44), we have, for material emerging from fireballs,

$$Y + Z = 0.238 , \tag{46}$$

where Z is the mass fraction of the heavier elements built from helium. A value near 0.23 rather than 0.24 is then expected for Y.

7. THE AGES OF GALAXIES

It has often been stated that an argument in favor of the hot big bang cosmological world is that the "age" from the expansion $\frac{2}{3}H_0^{-1}$ is comparable to the ages of the oldest stars in our Galaxy. In fact, if the larger value of H_0 often used is correct, i.e., $H_0 = 80$ km s^{-1} Mpc^{-1}, it appears that $\frac{2}{3}H_0^{-1}$ is less than the ages of the oldest globular cluster stars in our Galaxy. Some then invoke the cosmological constant to save the evolutionary model. Even for a value of $H_0 = 50$ km s^{-1} Mpc^{-1}, the ages of the oldest stars are only marginally less than the age of the universe.

Whether or not the ages of the oldest stars are compatible with the age in the hot big bang, it is generally supposed in the model associated with this cosmology that all galaxies are formed in the first 10^9 years or so after the big bang. On the other hand, in the cosmological model that we are proposing here we would expect that galaxies form at all epochs, and in particular we would expect that young galaxies with ages $\leqslant 10^9$ yr are present. Also, different components in the same galaxy can have different ages.

We believe that observational evidence found in the last few years supports this view. This evidence is of several different kinds:

a) A class of faint galaxies often called simply H II galaxies, which were originally investigated by Sargent & Searle (1970) and Kunth & Sargent (1983), are found fairly frequently in studies of faint galaxies. Their spectra have very weak continua and line emission characteristic of H II regions together with O and B stars. All of the strong features in the spectra arise from stars with ages $\leq 10^8$ yr. There is some ambiguity about the continua. In one case, Sandage (1963) argued that the colors of the continuum in NGC 2444–2445 were similar to those in the Large Magellanic Cloud and that there could be an underlying old system. However, in general there is no strong evidence that any old stellar population is present.

b) Highly luminous *IRAS* galaxies: Far-infrared observations ($\sim$25–200 μm) made originally in a few cases from the ground or high-flying aircraft, and then much more extensively from *IRAS*, have shown that there is a large population of spiral and irregular galaxies which emit powerfully in the far-infrared (Soifer, Houck, & Neugebauer 1988). It is generally believed that the far-infrared radiation is thermal emission from dust heated by main-sequence stars, and that the powerful sources are regions in which star formation is dominant—so-called starburst regions. The most extreme examples are the high-luminosity *IRAS* galaxies with luminosities in excess of $10^{12}\ L_\odot$, practically all in the far-infrared. Nearby examples of such galaxies are Arp 220 and NGC 6240. Such systems are all very irregular. While it has often been argued that such objects are a result of mergers between previously separate galaxies (cf. monograph edited by Wielen 1989), one of us (Burbidge 1986; Burbidge & Hewitt 1988) has made the case that these objects are genuinely young ($\ll 10^9$ years old) systems made up of successive generations starting with fairly massive stars ($20\ M_\odot \leq M \leq 50\ M_\odot$) which have themselves in the early generations made the dust which is now being heated by ultraviolet radiation from later generations. These galaxies fulfill all of the tests for young systems. There are no stars detected in them older than A-type systems, they contain huge masses of molecules, and we predict that the dust in them will not be of typical galactic form, since it will have condensed from metallic oxides and other compositions typical of material ejected from massive stars. According to our proposal made here, galaxies of the types found in categories *a* and *b* have arisen from recent mass-creation events. Another unexpected observational discovery has been the finding of very young stellar systems in old galaxies. There are many examples. We mention here two recent discoveries.

c) In our own Galaxy, Krabbe et al. (1991) have shown that within 0.5 pc of the center there is a cluster of young massive stars with random motions of $\sim$200 km s^{-1}. These have been found by high-resolution imaging of a 2.06 μm recombination line of He I. The stars are broad emission line objects which must have ages less than 10^6 yr. The radio source Sgr A lies in this cluster. This can readily be explained by mass creation very close to the center.

d) Recent observations using the *HST* have shown what appear to be very young globular clusters in the central region of the well-known radio galaxy NGC 1275 (Holtzman et al. 1992). This galaxy gives every indication that parts of it at least have an age $\sim 10^{10}$ yr. Both of these examples suggest that mass creation may well be continuing at a low level in the nuclear regions of old galaxies.

A more general question is to what extent there is good evidence that the majority of galaxies have ages $\sim 10^{10}$ yr. In fact we can only determine ages accurately when we can observe the color-magnitude diagrams of clusters of coeval stars and detect their turn-off on the main sequence or the positions of their horizontal branches. This restricts us so far to our Galaxy and objects like the LMC. The arguments based on color measurements which have been made in general (cf. Larson & Tinsley 1978) involve assumptions about the mix of stellar populations that are not very secure, though they are often implicitly assumed to support the claim that the majority of galaxies are old. If we look at dynamical motions, clusters of galaxies like the Coma Cluster appear from their forms to be totally relaxed, and this means that they are very well mixed. Since in a typical case it takes about 10^9 yr for a galaxy to traverse a cluster diameter, such cluster galaxies should have ages $\gtrsim 10^{10}$ yr. On the other hand, there are many clusters which are clearly not relaxed (e.g., the Hercules Cluster) which contain many bright spirals. The dynamical argument would then suggest that the age is no more than $\sim 10^9$ yr. This was the position taken by Ambartsumian (1958, 1965) when he first discussed expanding associations of galaxies.

In this section we have only sketched rather briefly the large amount of evidence that suggests now that there is a wide range of ages of galaxies, and that in very old galaxies very young components may exist. Nowadays, these results are put under the heading of starburst activity, since it is tacitly assumed that extensive star formation can often take place in galaxies which may be very old. This situation is very different from that which existed in the 1960s when the argument that all galaxies were old was used as an argument against the classical steady state cosmology (cf. Burbidge, Burbidge, & Hoyle 1963; Sandage 1963; also McVittie 1962). We therefore consider that it is important to stress not only that a wide range of ages since star formation began may exist in many galaxies but also that this is to be expected within the framework of a cosmology in which mass creation can take place at many different places and at many different times.

8. RADIO GALAXIES, QUASI-STELLAR OBJECTS, AND OTHER ACTIVE NUCLEI

In the last section we discussed the ages of apparently quiescent galaxies and argued that a wide range of ages is probably present. This is expected in the framework of the QSSC, since mass creation can take place at all epochs. The creation process is taking place comparatively quietly in these cases, since the matter which is emerging is able to interact with gas already present to form stars that evolve in the normal way.

However, there are other important types of extragalactic objects which are ejecting matter at high speeds and giving rise to all of the features that we expect for nonthermal phenomena in a spasmodically violent universe. Thus we need to ask whether we can explain the presence of jets, large fluxes of relativistic particles, high-energy photons, etc., through mass-creation events.

The classical explanation, previously referred to in § 1, is that all of the phenomena arise in a rather mysterious way after some matter from an accretion disk falls into a black hole. A discussion of the many ingenious arguments which have been made has recently been summarized by Blandford & Rees (1992). How are these phenomena to be alternatively explained in a mass-creation event?

The creation units described in this paper have an early stage in which gravitational fields are strong, with creation taking place closer to an event horizon, which introduces a time dilatation factor large compared with unity, a factor upward of 10^6 for large creation units. This influences the time scale as measured by an external observer in which the creation unit bursts away from its state near the event horizon, an effect of a strong negative pressure term in the dynamical equations similar to that in the inflationary model (Guth 1981). Now it seems unlikely, especially for a rotating object, that the time dilatation factor will be everywhere the same. Using spherical polar coordinates, the dilatation factor will not be precisely of the form $(1 - 2GM/r)^{-1/2}$ but will also have some dependence on the angular coordinates as in the Kerr metric. To an external observer the moment of breakout from the strong gravitation field will therefore appear dependent on θ and φ. Even though to a comoving observer the times of breakout may not be greatly variable with respect to θ, φ, to an external observer the situation will appear otherwise. That is to say, instead of the object expanding after the creation phase as a uniform object, it is likely to emerge in a series of blobs or jerks, every blob appearing as a distinct object in its own right. This type of model may be important in attempts to understand the properties of radio galaxies and other active objects in which matter and high-energy particles are ejected in jets.

Let us consider a few examples starting with M87, the classical radio galaxy with a jet interpreted in this way. In Figure 2*a* we show the well-known synchrotron jet in the large galaxy M87 in position angle 290°, while in Figure 2*b* we show the general field of galaxies around M87. It has been known since 1960 that the position angle of the line joining M87 to the radio galaxy M84 is coincident with the position angle of the jet (Wade 1960). This is as direct evidence as one can have of the process we have just described, namely, a blob ejected from a changing gravitating object at the center of M87, a blob that later becomes the galaxy which we know as M84. Arguing from the angular coincidence of the position angles, the probability of this being so was already about 100 to 1 in favor, while now we have at least the beginning of a theoretical explanation of how such situations arise. Indeed, taking place repeatedly from the breakup of an initial large mass, the product would be a cluster of galaxies. It is an interesting possibility that the Virgo Cluster was formed in this way or, at any rate, the elliptical galaxies in the Virgo Cluster. The spirals are more likely to have been formed as gas from the object, created as M87, impinging on gas from other neighboring creation units, as we have already described in § 5. The circumstance that we still see the jet of M87 suggests that the process of forming M84 occurred fairly recently and that here we have good evidence of a young galaxy.

In addition to this, Arp (1987) has shown that a number of X-ray–emitting QSOs are also aligned in the position angle of the jet, and this also is very suggestive of ejection.

We suggest that it is this type of event—creation process in

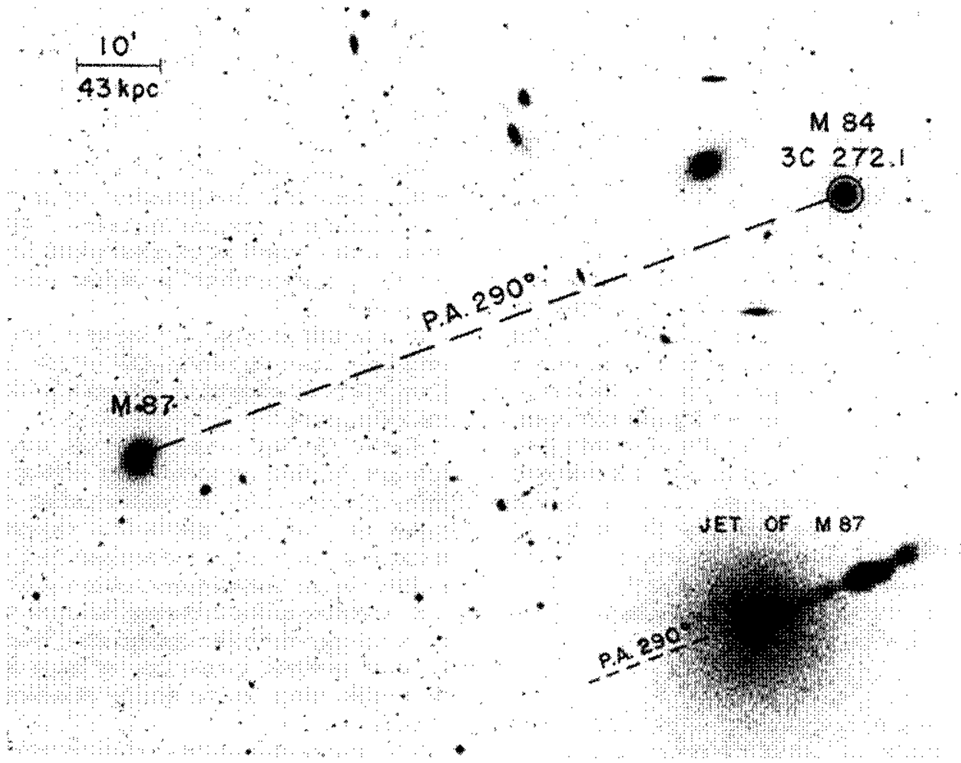

FIG. 2*a* FIG. 2*b*

FIG. 2.—(*a*) Reproduction of the central region of the Virgo Cluster taken from the Palomar 48 inch (1.2 m) plate of that region. We have marked on it the line joining M87 to M84 which lies at position angle 290° exactly (to within 1°) at the position angle of the optical jet of M87, as was pointed out by Wade (1960). This diagram is taken from a very early review article by G. and E. M. Burbidge. (*b*) This inset (*lower right*) shows an early optical image of the jet showing the blobby structure. More recent optical images (Arp 1987) taken from the ground, optical and UV maps taken with the *HST* (Boksenberg et al. 1992), radio maps (Owen, Hardee, & Bignell 1980; Biretta, Owen, & Hardee 1983), and X-ray maps (Biretta, Stern, & Harris 1991) show that the bloblike structure is very similar over a wide range of wavelengths. The radiation is due to incoherent synchrotron process and some Compton scattering. It originates from highly relativistic electrons which we suspect were generated from protons generated in the creation events.

the center of a massive object—which is largely responsible for the generation of powerful radio sources associated with elliptical galaxies.

There is nearly always a preferred axis of ejection in a powerful source, and many optical and near-IR observations have shown that there is a great deal of optical emission along the major axis of the radio emission. Most of these galaxies are very faint, and many have $z > 1$. In some cases blobs are seen, but most of them are far enough away so that structure of the kind seen in M87 will not be detected.

The recent studies (McCarthy et al. 1991; McCarthy, Elston, & Eisenhardt 1992a; McCarthy, Persson, & West 1992b; McCarthy 1991) show that the optical emission is correlated with the radio emission, and everything suggests that the activity takes place from the inside out.

We would also like to explain the existence of QSOs ejected from galaxies as a variation on this same process, but here much more work needs to be done before we have a satisfactory model. Certainly the ejection process may be understood within the framework of the creation in an active nucleus, and there are some very well aligned ejection cases (cf. Arp 1987; Burbidge et al. 1990). While we believe that the large number of associations between bright galaxies (often spirals) and QSOs with large redshifts provide overwhelming evidence for noncosmological redshifts, we have not yet found any way of explaining these redshifts using the theory outlined in this paper. We believe that this aspect of the problem of violent activity remains a major challenge.

9. DISCUSSION

Those who strongly believe in the hot big bang cosmology (cf. Peebles et al. 1991) consider that the existence of the microwave background and its observed degree of smoothness provides them with the certainty of a basically correct position. This is despite the obstinate refusal of big bang cosmology to relate to astrophysics in a satisfactory way. However, we have shown that this position is insecure. The facts of the situation are that the energy density of the background is only about 1/10,000 or so of the energy density of matter, so that only a small conversion of the latter into radiation is sufficient to supply the former. Moreover, the mass absorption coefficient of metallic whiskers is high at the wavelengths of microwaves, so that only a small extragalactic whisker density is required to explain the smoothness of the background. The properties of the whiskers are shown in Figure 1. Small-scale fluctuations of the background are removed in only a few absorptions and emissions, while large angle fluctuations persist only at a level determined by $\exp(-\tau)$, where τ is the optical depth experienced by the background, with

$$\tau = \kappa \rho c t g , \quad (47)$$

where κ is the mass absorption coefficient, ρ the cosmological density, and g the fraction of the material in the form of whiskers. If we suppose that the density is about 10^{-27} g cm^{-3} during thermalization of the background, with t as the time scale, say 10^{16} s, we get $\tau = 10$ for $\kappa = 10^7$ cm g^{-1}, $g = 3 \times 10^{-6}$, i.e., g very small.

Our picture is of a universe in which there was a major creation episode when the mean universal density was $\sim 10^{-27}$ g cm^{-3}. Since then the universal expansion has been slowing down with the parameter $q = -S\ddot{S}/\dot{S}^2$ (in the usual notation), rising from a negative value to its present-day value q_0 close to $+1$. Also at the present day with $t \simeq 3 \times 10^{17}$ s, $\rho \simeq 10^{-29}$ g cm^{-3}, the above equation gives $\tau \simeq 3$. This is for microwaves at wavelengths of a few millimeters. For wavelengths of a few centimeters the corresponding τ, using the κ-values of Figure 1, is of order unity, while for wavelengths greater than 10 cm the present-day value is $\tau \simeq 0.3$ or less. Thus extragalactic astronomy at optical and radio wavelengths is not hindered by this absorption.

Explicit equations for the creation of matter have been given. In a cosmological approximation these lead to equations (15) and (16) for the time dependence of the cosmological scale factor $S(t)$. These do *not* lead to the requirement $S(t) \to 0$ at some finite t, as happens in big bang cosmology, and so the equations can have a universality that is absent from big bang cosmology and which is a defect of that theory, a defect we believe to be mortal.

Creation occurs when certain conservation equations involving the gradient of a scalar field, C_i, are satisfied. C-field bosons falling into the strong gravitational field of a local body come to satisfy this conservation requirement provided that the field is strong enough, as it must be, should the body approach an event horizon sufficiently closely. The resulting establishment of a strong negative pressure, tending to infinity as the event horizon is approached, acts to halt implosion, converting the implosion of a local body into explosion, or leading to a steady outpouring of matter should an event horizon be approached secularly, as in the case of a rotating object. The Kerr solution for a rotating object shows that an event horizon is first approached at its two poles, without the intervention of the ergosphere, for which reason the outpouring of matter in such cases occurs in the form of two polar jets.

The situation at either pole is like the approach of a portion of the surface of an axisymmetric object to its event horizon. As is well known in this case, particles or light rays must be radially ejected to reach the external world, regaining the two polar jets for a rotating object to appear collimated to an external observer.

It is to this process, varying with respect to mass and time scales of secular variations, that we attribute the wide range of phenomena mentioned in the introduction and considered in more detail in § 7.

Unlike the big bang cosmology, where the all-important primary creation event is unseen and undetectable (as well as being unrepeatable), the mass-creation events proposed here satisfy the standard criteria of a physical theory by making testable predictions. As discussed in § 4, the gravity waves emitted by an anisotropic creation event can be detected by laser-interferometric detectors currently being planned. Moreover, the gravity wave background generated cosmologically by such creation events can be large enough to produce a detectable effect on the timing measurements of millisecond pulsars.

The theory also carries the expectation that newly created particles have initial masses that are related to the gravitational constant G by $(3\hbar c/4\pi G)^{1/2} \simeq m$. That is to say, newly created matter is in the form of Planck particles of mass $\sim 10^{-5}$ g. These are unstable on a time scale of $\sim 10^{-43}$ s. The decays of Planck particles lead to an interesting possibility for explaining the origin of light nuclei, especially as ^{6}Li, ^{9}Be, ^{10}B, and ^{11}B are produced as well as D, ^{3}He, ^{4}He, and ^{7}Li. On the hypothesis that all baryons of the octet are produced equally—

Λ, $\Sigma^{\pm}$, Σ^0, Ξ^0, and Ξ^- as well as N and P—the helium mass fraction Y can be seen to satisfy the simple equation

$$Y + Z \simeq 0.24 , \tag{48}$$

where Z is a small correction term included to take account of the possibility that a nonnegligible quantity of ^{12}C and higher elements may be produced.

With the light elements synthesized in this way, there is no requirement for so-called missing mass to be nonbaryonic. The missing mass could be in the form of small stars or, perhaps more interestingly and certainly more adventurously, it could be in the form of condensed massive objects waiting like buds to burst out in a new generation of creation events, the time for a mass M of radius r before outburst becomes manifest to an external observer being given by

$$\frac{2GM}{c^3}\left(1-\frac{2GM}{c^2 r}\right)^{-1/2} . \tag{49}$$

Although to a comoving observer the time scale is $2GM/c^3 \simeq 10^{-5}\ M/M_{\odot}$, to an external observer it can be much larger than this because of the square-root factor in equation (49). For $M \simeq 10^{16}\ M_{\odot}$ close enough to its event horizon at $r \simeq 3 \times 10^{22}$ cm this can indeed be $\sim H_0^{-1}$.

When the masses created are $\ll 10^{16}\ M_{\odot}$, we have attempted to indicate in § 7 and elsewhere that it may very well be possible to explain a variety of phenomena currently observed. These range from young galaxies and galactic groups and clusters with positive total energy to explosive events in the nuclei of galaxies where in every case the motion seen is outward. We feel that we have only begun to scratch the surface of these problems that can now be tackled, and we hope that others will be encouraged to do this.

This paper is not intended to give a finished view of cosmology. It is intended rather to open the door to a new view which at present is blocked by a fixation with big bang cosmology and, on a smaller scale, by an obsession with black holes and accretion disks. We believe that the alternative scheme described here has sufficient robustness to withstand observational tests as well as to provide a sound physical foundation for cosmology, and on both these counts it compares favorably with big bang cosmology.

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APPENDIX A

ESCAPE OF RADIATION FROM AN EXPANDING CREATION UNIT

Suppose that the radiation escapes when the radius of an expanding creation unit is x times its gravitational radius, and write λ for the mean free path of the radiation at this stage. Then x is to be determined from the condition that $(2GM/c^2)x$ divided by λ is equal to the average radial velocity of radiation, $c/2$, divided by the speed of expansion of the creation unit. Taking the latter to be the parabolic speed $(GM/2GMxc^{-2})^{1/2}$, we have

$$\frac{4GMx}{\lambda c^2} = (2x)^{1/2} , \tag{A1}$$

where the required density ρ is given by

$$\frac{4\pi}{3}\left(\frac{2GM}{c^2}x\right)^3 \rho = M . \tag{A2}$$

Putting $\lambda\kappa\rho = 1$ and eliminating x between equations (A1) and (A2) gives

$$\begin{aligned}\rho &= \left[\left(\frac{4\pi}{3M}\right)^{2/3} \frac{c}{(16\pi G)^{1/2}}\kappa^{-1}\right]^{6/5} \\ &= \left[2.7 \times 10^{-9}\left(\frac{M_{\odot}}{M}\right)^{2/3}\kappa^{-1}\right]^{6/5} \text{ g cm}^{-3} .\end{aligned} \tag{A3}$$

APPENDIX B

LIGHT-ELEMENT SYNTHESIS

We suppose that Planck particles decay with the following properties:

1. The decay energy of $\sim 10^{-5}$ g is taken to be equally divided between radiation and $\sim 3 \times 10^{18}$ baryons, with the radiation going at an early stage of the expansion into the kinetic energy of motion of the baryons, which separate as a cloud in an effective time of $\sim 10^{-16}$ s from the point of view of nuclear reactions.
2. The expanding cloud is electrically neutral.

3. The up, down, and strange quarks are equally represented among the emerging baryons, requiring Λ, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^- to be represented equally with P and N. Thus the number of each type of baryon is $\sim 4 \times 10^{17}$. On the time scale of 10^{-16} s other quark flavors which may have been present initially have gone.

All the baryons except Σ^0 are stable on a time scale of 10^{-16} s, and even the decay of Σ^0 to Λ is prevented initially by degeneracy, until the energy at the Fermi surface falls below 75 MeV, the energy of Σ^0 decay. At the very high densities still involved at this stage, 10^{36} cm^{-3} for each baryon type, electron pairs are created in a time much shorter than 10^{-16} s. These block the escape of radiation from the cloud, and they also serve to thermalize the energy, yielding ~ 9 MeV per baryon, corresponding to a thermal kinetic energy $T_9 \simeq 70$, where T_9 is the temperature in units of 10^9 K.

The internal motions at this and lower temperatures are nonrelativistic, so that as the cloud expands, say with speed 0.5c, the temperature falls as the $\frac{2}{3}$ power of the particle density. As will be seen shortly, as T_9 falls below 40, most of the protons and neutrons go into α-particles. This gives a thermal yield of about 7 MeV per N or P. And a further source of thermal energy may well come from π^0 mesons which decay into γ-ray pairs in $\sim 10^{-16}$ s, the same as the time scale for helium formation. Emerging from helium formation are two density-temperature relations which play important roles in the synthesis of the other light nuclei listed in Table 1,

$$n(\mathrm{N}) = n(\mathrm{P}) \approx 10^{33}\left(\frac{T_9}{15}\right)^{3/2} \mathrm{cm}^{-3} , \tag{B1}$$

$$n(\mathrm{A}) = 10^{34}\left(\frac{T_9}{15}\right)^{3/2} \mathrm{cm}^{-3} , \tag{B2}$$

where n(N), n(P), n(A) are the densities of free neutrons, protons and α-particles respectively.

Where a nuclei of atomic number $A + 4k$ and charge $Z + 2k$ is connected statistically to one of number A and charge Z through the absorption and emission of k α-particles, the equation of statistical equilibrium between the number densities $n(A + 4k, Z + 2k)$, $n(A, Z)$ is

$$\begin{aligned} \log \frac{n(A + 4k, Z + 2k)}{n(A, Z)} &= \frac{3}{2} \log \frac{A + 4k}{A} + \log \frac{\omega(A + 4k, Z + 2k)}{\omega(A, Z)} \\ &\quad + k\left[\log n(A) - 33.77 - \frac{3}{2} \log 4 - \frac{3}{2} \log T_9\right] \\ &\quad + \frac{5.04}{T_9} [Q(A + 4k, Z + 2k) - Q(A, Z)] , \end{aligned} \tag{B3}$$

where $Q(A, Z)$ is the binding energy in MeV of all the nucleons in A, Z, and $\omega(A, Z)$ is the partition function of A, Z at temperature T. In the case of light nuclei it is sufficient to put the partition function equal to $2J + 1$, where J is the spin of the ground state.

When a nuclide is connected statistically to the free protons and free neutrons, rather than the α-particles, equilibrium is expressed by

$$\begin{aligned} \log N(A, Z) &= \log \omega(A, Z) + 33.77 + \frac{3}{2} \log T_9 + \frac{3}{2} \log A \\ &\quad + (A - Z)\left[\log n(\mathrm{N}) - 34.07 - \frac{3}{2} \log T_9\right] \\ &\quad + Z\left[\log n(\mathrm{P}) - 34.07 - \frac{3}{2} \log T_9\right] \\ &\quad + \frac{5.04}{T_9} Q(A, Z) , \end{aligned} \tag{B4}$$

the logarithms in equations (B3) and (B4) being to base 10.

B1. THE FREE-NUCLEON–HELIUM BALANCE

Write $y(T_9)$ for the fraction of neutrons and protons that remain free at temperatute T_9. Neglecting other nuclei in comparison with ^{4}He, the fraction of nucleons bound in ^{4}He is thus $1 - y$. A parameter ζ can be defined by

$$n(\mathrm{P}) = n(\mathrm{N}) = 2 \frac{(2\pi mkT)^{3/2}}{h^3} y\zeta , \tag{B5}$$

where m is the average nucleon mass, about 1.67×10^{-24} g. Taking Σ^0 decay to be the source of thermal energy, together with half of the energy released by helium synthesis, it is not hard to show that $\log \zeta \simeq -0.5$. However, later π^0 decays lower this value of ζ, but by an amount which is uncertain. Equation (B1) implies a lowering of an order of magnitude to $\log \zeta = -1.5$. But this uncertainty applies only to the situation following helium synthesis. During helium synthesis $\log \zeta = -0.5$ is the appropriate value consistent with the model described above.

So long as the relevant nuclear reactions remain fast enough, the free nucleons remain in equilibrium with the α-particles, an equilibrium expressed by

$$\log n(4, 2) - 33.77 - \frac{3}{2} \log T_9 - \frac{3}{2} \log 4 - \frac{5.04}{T_9} \times 28.3 = 4\left[\frac{1}{2} \log n(\mathrm{N}) + \frac{1}{2} \log n(\mathrm{P}) - 33.77 - \frac{3}{2} \log T_9 - \log 2\right], \tag{B6}$$

to which from the definitions of y, ζ can be added:

$$n(4, 2) = \frac{1 - y}{2y} n(\mathrm{P}) = \frac{(2\pi mkT)^{3/2}}{h^3} (1 - y)\zeta , \tag{B7}$$

the logarithm of $(2\pi mkT)^{3/2}/h^3$ being $33.77 + (3/2) \log T_9$. Substituting equations (B5) and (B7) in equation (B6) leads to

$$\log \frac{1 - y}{y^4} = 0.90 + 3 \log \zeta + \frac{142.6}{T_9} . \tag{B8}$$

Because ζ appears only weakly in equation (B8), and because of the large numerator in the final term, any reasonable choice for ζ leads to essentially a unique dependence of y on T_9, a dependence given explicitly in Table 2 calculated for $\log \zeta = -0.5$.

Since Σ^0 decay occurs at the upper end of the temperature values in this table, about half of the original nucleons go into helium already at the stage of Σ^0 decay, adding the energy of their formation to the thermal energy generated by the decays and thence, after a straightforward calculation, to the choice $\log \zeta = -0.5$.

At some point as T_9 declines, the sharply falling value of y becomes insufficient to maintain the helium-producing reactions at rates sufficient to reduce y much further. Equation (B6) of statistical equilibrium then becomes inapplicable. Thereafter the relation between the free-nucleon density and T_9 becomes separated from the relation between the α-particle density and T_9, as was taken to be the situation in equations (B1) and (B2), with the ratio of the coefficients in these equations determined by the value of y at the freezing of equation (B6).

According to Fowler, Caughlan, & Zimmerman (1975, hereafter FCZ), the fastest reactions to α-particles from free nucleons with $n(\mathrm{N}) = n(\mathrm{P})$ have the rates

D(D, P)T:

$$4.17 \times 10^8 T_9^{-2/3} \exp(-4.258 T_9^{-1/3})(1 + 0.098 T_9^{-1/3} + 0.518 T_9^{2/3} + 0.355 T_9 - 0.010 T_9^{4/3} - 0.018 T_9^{5/3}) ,$$

T(T, 2N)^{4}He:

$$1.67 \times 10^9 T_9^{-2/3} \exp(-4.872 T_9^{-1/3})(1 + 0.086 T_9^{1/3} - 0.455 T_9^{2/3} - 0.272 T_9 + 0.148 T_9^{4/3} + 0.255 T_9^{5/3}) . \tag{B9}$$

The notation of FCZ is such that the number of reactions of each type taking place per cubic centimeter per second is obtained by multiplying equation (B9) by the density of each of the reactants and then dividing by Avogadro's number, 6.022×10^{23}. At $T_9 = 30$, for example, the numbers of reaction per cubic centimeter per second are

$$1.19 \times 10^8 n(\mathrm{D})^2/6.023 \times 10^{23} , \qquad 2.75 \times 10^9 n(\mathrm{T})^2/6.023 \times 10^{23} . \tag{B10}$$

Next, to obtain $n(\mathrm{D})$, $n(\mathrm{T})$ in terms of $n(\mathrm{P}) = n(\mathrm{N})$, use the equilibrium equations

$$\log \frac{n(\mathrm{D})}{n(\mathrm{P})} = \frac{3}{2} \log 2 + \log \frac{3}{2} + \log y\zeta + \frac{5.04}{T_9} \times 2.22 , \tag{B11}$$

$$\log \frac{n(\mathrm{T})}{n(\mathrm{P})} = \frac{3}{2} \log 3 + 2 \log y\zeta + \frac{5.04}{T_9} \times 8.48 . \tag{B12}$$

Then, writing equations (B5) and (B7) in logarithmic form, viz.,

$$\log n(\mathrm{P}) = 34.07 + \frac{3}{2} \log T_9 + \log y\zeta , \tag{B13}$$

$$\log n(4, 2) = 33.77 + \frac{3}{2} \log T_9 + \log (1 - y)\zeta , \tag{B14}$$

TABLE 2

FRACTION y OF NUCLEONS REMAINING FREE AT T_9

	y						
	0.5	0.4	0.3	0.2	0.1	0.05	0.03
T_9	94.9	72.4	56.2	43.2	31.3	24.7	21.4

the problem, subject to ζ being specified, is to find the least value of y for which the number of helium-producing reactions exceeds equation (B14), the available time scale being 10^{-16} s. The result of such a calculation is $y \simeq 0.05$, from which

$$\frac{n(4, 2)}{n(\mathrm{P})} = \frac{1-y}{2y} \simeq 0.1 , \tag{B15}$$

at the stage where the helium-producing reactions freeze. This is the ratio that appeared already in equations (B1) and (B2), which becomes determined by the present considerations. The absolute values of the coefficients in equations (B1) and (B2), as opposed to their ratio, depends on the thermal energy released in π^0 decays. With this unknown a free parameter necessarily appears in the theory. While this is a pity, it is nevertheless an improvement on the many parameters which appear in the usual theory. The above discussion was for a choice of the thermal energy from π^0 decays leading to $\log \zeta = -1.5$ in the phases after helium formation.

The equilibrium equation (B11) assumes that the triplet ground state of the deuteron is reachable. When γ-ray emission is excluded as too slow, the ground state must be reached through collisional de-excitation of the slightly unstable single state, D* say, which de-excitations happen at adequate speed during the helium-formation phase, because in this phase the particle density is high. At later stages, however, with the particle density much lower, γ-ray emission is needed to produce stable deuterium. For this reason the eventual D/H ratio of emerging material must be calculated dynamically with respect to γ-ray emission, not from equation (B11). This will be done in the next subsection.

B2. OTHER LIGHT NUCLEI

As noted immediately above, the deuterium abundance $n(\mathrm{D})$, present in eventually emerging material, cannot be calculated from equation (B11) but must be estimated dynamically. According to Wagoner et al. (1967), the lifetime in seconds of a proton against conversion to deuteron by P(N, γ)D is the inverse of

$$2.5 \times 10^4 n(\mathrm{N})/6.023 \times 10^{23} , \tag{B16}$$

giving

$$n(\mathrm{D}) = 4.15 \times 10^{-36} n(\mathrm{N}) n(\mathrm{P}) \tag{B17}$$

for the deuterium density produced in 10^{-16} s. This is after deuterium has ceased to be destroyed in the emerging material. From equation (B17) we have a deuterium-to-hydrogen ratio D/H which can be written in the form

$$\begin{aligned} \frac{\mathrm{D}}{\mathrm{H}} &= \frac{n(\mathrm{D})}{n(\mathrm{P})} \frac{n(\mathrm{P})}{n(4, 2)} \frac{n(4, 2)}{\mathrm{H}} \\ &= 4.15 \times 10^{-36} n(\mathrm{N}) \frac{n(\mathrm{P})}{n(4, 2)} \frac{n(4, 2)}{\mathrm{H}} , \end{aligned} \tag{B18}$$

in which $n(\mathrm{P})/n(\mathrm{A}) = 1/10$ and $n(\mathrm{A})/\mathrm{H} = 1/12$. Putting $T_9 \simeq 10$ in equation (B1) for the temperature in question gives $n(\mathrm{N}) = 5 \times 10^{32}\ \mathrm{cm}^{-3}$, and equation (B18) leads to

$$\frac{\mathrm{D}}{\mathrm{H}} \simeq 2 \times 10^{-5} , \tag{B19}$$

as in Table 1 in the main body of the paper.

Tritium decays eventually into ^{3}He, but in Planck fireballs tritium is dominant over ^{3}He. The tritium density $n(\mathrm{T})$ continues to fall after effective ^{4}He formation has ceased, as T_9 falls from ~ 30 to ~ 20 and below. This happens so long as the tritium lifetime against T(T, 2N)^{4}He is less than $\sim 10^{-16}$ s. According to the second of the reaction rates in equations (B10), taken in this case at $T_9 = 20$, $n(\mathrm{T})$ falls to such a value that

$$\frac{1.43 \times 10^9}{6.02 \times 10^{23}} n(\mathrm{T}) = 10^{16} , \tag{B20}$$

i.e., $n(\mathrm{T}) = 4.21 \times 10^{30}\ \mathrm{cm}^{-3}$, giving

$$\frac{^3\mathrm{He}}{\mathrm{H}} = \frac{n(\mathrm{T})}{\mathrm{H}} \simeq 2.3 \times 10^{-5} , \tag{B21}$$

since the eventual hydrogen abundance is ~ 12He and the α-particle density at $T_9 = 20$ is $10^{34}(4/3)^{3/2}\ \mathrm{cm}^{-3}$ from equation (B2). This is the estimate given in Table 1.

The Li-Be-B group of elements is especially fragile and, therefore, subject to breakback reactions, as with ^{7}Li (P, A)^{4}He. Lower freezing temperatures than anything encountered hitherto are therefore to be expected for this group. This can be verified directly from the reaction rate given by FCZ for ^{7}Li(P, A)^{4}He:

$$1.07 \times 10^{10} T_9^{-3/2} \exp(-30.443/T_9) , \tag{B22}$$

which for $T_9 = 10$ and for the proton density $n(\mathrm{P}) = 10^{33}(T_9/15)^{3/2}$ gives a destruction lifetime for ^{7}Li of $\sim 10^{-16}$ s, the same as the expansion time scale. The ^{7}Li abundance is thus given by the equilibrium value at this temperature, which can be calculated from

$$\log \frac{^7\mathrm{Li}}{^8\mathrm{Be}} = \frac{3}{2} \log \frac{7}{8} + \log 4 - \log n(\mathrm{P}) + 34.07 + \frac{3}{2} \log T_9 - \frac{5.04}{T_9} \times 17.35 , \tag{B23}$$

the second term on the right-hand side coming from the spin 3/2 of ^{7}Li. For $T_9 = 10$ equation (B23) gives log (^{7}Li/^{8}Be) = -5.40. Now an equilibrium calculation using equations (B2) and (B3) gives log (^{8}Be/^{4}He) $\simeq -2.3$, which, with ^{4}He/H = 1/12, leads to

$$\frac{^7\mathrm{Li}}{\mathrm{H}} = \frac{^7\mathrm{Li}}{^8\mathrm{Be}} \frac{^8\mathrm{Be}}{^4\mathrm{He}} \frac{^4\mathrm{He}}{\mathrm{H}} \simeq 10^{-9} , \tag{B24}$$

as in Table 1. Equilibrium for the lithium isotopes is determined by

$$\log \frac{^6\mathrm{Li}}{^7\mathrm{Li}} = \frac{3}{2} \log \frac{6}{7} + \log \frac{3}{4} - \log n(\mathrm{N}) + 34.07 + \frac{3}{2} \log T_9 - \frac{5.04}{T_9} \times 7.25 , \tag{B25}$$

which for $T_9 = 10$ and $n(\mathrm{N}) = 10^{33}(T_9/15)^{3/2}$ cm^{-3} gives

$$\frac{^6\mathrm{Li}}{^7\mathrm{Li}} = \frac{1}{11} , \tag{B26}$$

again as in Table 1.

Unfortunately, FCZ do not discuss the reaction rate of ^{10}B(N, ^{4}He)^{7}Li, but it is reasonable to take it to be effectively the same as for ^{10}B(P, ^{4}He)^{7}Be, which has a main term of the form

$$2.59 \times 10^9 T_9^{-1} \exp(-12.26/T_9) . \tag{B27}$$

With $n(\mathrm{P}) = 10^{33}(T_9/15)^{3/2}$ cm^{-3}, the product of equation (B27) with $n(\mathrm{P})/6.023 \times 10^{23}$ is equal to the dynamical time scale of 10^{-16} s for a freezing temperature as low as $T_9 \simeq 5$, appreciably less than anything encountered so far, a situation arising from the weak dependence of the exponential factor of equation (B27) on T_9. Equilibrium for ^{10}B can be determined by putting $T_9 = 5$ in the equation of balance between ^{10}B and ^{7}Li,

$$\log \frac{^{10}\mathrm{B}}{^7\mathrm{Li}} = \frac{3}{2} \log \frac{10}{7} + \log n(4, 2) - 33.77 - \frac{3}{2} \log T_9 - \frac{3}{2} \log 4 - \log n(\mathrm{N}) + 34.07 + \frac{3}{2} \log T_9 + \log \frac{7}{4} - \frac{5.04}{T_9} \times 2.79 , \tag{B28}$$

noting that the partition function ratio contributes the penultimate term on the right-hand side of equation (B28). With $n(4, 2)/n(\mathrm{N}) = 10$ and $T_9 = 5$, this gives

$$\log \frac{^{10}\mathrm{B}}{^7\mathrm{Li}} = -1.94 , \tag{B29}$$

i.e. log (^{10}B/H) $\simeq 10^{-11}$ as in Table 1.

The nuclide ^{9}Be provides the most extreme example of a low freezing temperature, so low that the time scale of freezing must be increased from $\sim 10^{-16}$ s, operative for $T_9 \simeq 20$, to $\sim 10^{-15}$ s operative for $T_9 < 1$. Equilibrium for the reaction ^{9}Be(P, D)^{8}Be is expressed by

$$\log \frac{^9\mathrm{Be}}{^8\mathrm{Be}} = \frac{3}{2} \log \frac{9}{8} + \log n(\mathrm{D}) - 33.77 - \frac{3}{2} \log T_9 - \frac{3}{2} \log 2 - \left[\log n(\mathrm{P}) - 34.07 - \frac{3}{2} \log T_9 \right] + \log \frac{4}{3} - \frac{5.04}{T_9} \times 0.65 , \tag{B30}$$

which can be written in the form

$$\log \frac{^9\mathrm{Be}}{\mathrm{H}} = \frac{3}{2} \log \frac{9}{8} + \log \frac{4}{3} - 0.15 + \log \frac{\mathrm{D}}{\mathrm{H}} + \log \frac{^8\mathrm{Be}}{^4\mathrm{He}} + \log \frac{^4\mathrm{He}}{n(\mathrm{P})} - \frac{3.28}{T_9} . \tag{B31}$$

The term log (4/3) comes from the partition function factors, the spins of the ground states of ^{9}Be and D being 3/2 and 1, respectively. Putting D/H = 2×10^{-5}, log (^{8}Be/^{4}He) = -2.3, log [^{4}He/n(P)] = 1.00, leads to

$$\log \frac{^9\mathrm{Be}}{\mathrm{H}} = -6.0 - \frac{3.28}{T_9} . \tag{B32}$$

At low temperatures $T_9 \simeq 1$ the reaction ^{8}Be(P, A)^{6}Li contributes to the destruction of ^{9}Be about equally with ^{9}Be(P, D)^{8}Be. But at $T_9 \simeq 1$ this second reaction contributes essentially nothing to the formation of ^{9}Be. The effect is to lower the ^{9}Be concentration by a factor ~ 2, modifying equation (B32) to

$$\log \frac{^9\mathrm{Be}}{\mathrm{H}} \simeq -6.3 - \frac{3.28}{T_9} . \tag{B33}$$

The reaction rates given by FCZ give a destruction rate, neglecting small terms of

$$\sim 10^9 T_9^{-1} \exp(-3.046/T_9) , \tag{B34}$$

1993ApJ...410..437H

combining both ^{9}Be(P, D)^{8}Be and ^{9}Be(P, A)^{6}Li. Multiplying expression (B34) by n(P)/6.023 × 10^{23} with n(P) given by equation (B1) and then taking the inverse gives a destruction lifetime of

$$3.5 \times 10^{-17} T_9^{-1/2} \exp(3.046/T_9)\,, \tag{B35}$$

which becomes equal to a destruction time scale of 10^{-15} s at $T_9 = 0.92$. With this value in equation (B33), we have log (^{9}Be/H) = −9.88. More accurately, equality of expression (B35) to the dynamical time scale produces a situation in which a fraction e^{-1} of the ^{9}Be concentration survives in the eventually emerging material, giving ultimately for the ^{9}Be abundance

$$\log \frac{^9\mathrm{Be}}{\mathrm{H}} \simeq -10.4\,, \tag{B36}$$

close to the value in Table 1.

Equilibrium for ^{11}B in the reaction ^{11}B(P, A)^{8}Be reduces to

$$\log \frac{^{11}\mathrm{B}}{\mathrm{H}} = \frac{3}{2} \log \frac{11}{8} + \log \frac{^4\mathrm{He}}{n(\mathrm{P})} + \log \frac{^8\mathrm{Be}}{^4\mathrm{He}} + \log \frac{^4\mathrm{He}}{\mathrm{H}} - \frac{5.04}{T_9} \times 8.682\,. \tag{B37}$$

Starting with the situation at $T_9 = 15$, where equilibrium is considered to be established, equation (B37) gives

$$\left(\log \frac{^{11}\mathrm{B}}{\mathrm{H}}\right)_{T_9=15} = -5.1\,. \tag{B38}$$

The high Q-value of 8.682 MeV for this reaction implies that as T_9 falls from ~15, little more ^{11}B is produced from ^{8}Be, whereas the destruction of ^{11}Be continues at appreciable rates down to significantly lower temperatures. This is shown by the detailed reaction rates given by FCZ. Augmentation of ^{11}B from ^{8}Be falls off with T_9 very steeply with the factor exp (−100.758/T_9), whereas destruction falls off only as

$$8.14 \times 10^9 T_9^{-3/2} \exp\left(-\frac{7.177}{T_9}\right). \tag{B39}$$

Starting from equation (B38), it is easy to calculate an approximation in which augmentation is neglected but destruction is included. Multiplying expression (B39) by n(P)/6.023 × 10^{23} with $n(\mathrm{P}) = 10^{33}(T_9/15)^{3/2}$ cm^{-3} gives an inverse lifetime for ^{11}B of

$$2.3 \times 10^{17} \exp\left(-\frac{7.177}{T_9}\right) \mathrm{s}^{-1}\,. \tag{B40}$$

The weakly temperature-dependent factor in expression (B40) can be taken at some mean value of T_9 from the range 15 down to low values, say at $T_9 = 10$ when expression (B40) gives 1.1 × 10^{17} s^{-1}. Hence, in a time scale of ~10^{-16} s for the temperature fall from $T_9 = 15$, the ^{11}B concentration is weakened by exp (−11), and the ^{11}B concentration in emerging material is given by

$$\log \frac{^{11}\mathrm{B}}{\mathrm{H}} = -5.1 - 4.8 = -9.9\,, \tag{B41}$$

completing the entries in Table 1.

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