25. Baryon Non-Conservation and Cosmology

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I. HISTORICAL BACKGROUND

In 1928, long before cosmology as a subject became recognized as a part of science, the astrophysicist James Jeans had this to say:

> The type of conjecture which presents itself somewhat insistantly, is that the centres of the nebulae (galaxies) are of the nature of singular points, at which matter is poured into our universe . . .
>
> —Astronomy and Cosmogony, Cambridge 1928

The idea of matter creation 'out of nothing' was of course anathema to physicists for whom the law of conservation of matter (and energy) is a tenet that cannot be violated. Jeans's idea did, however, find an echo in the steady state theory of the universe, put forward independently in 1948 by Bondi and Gold[1] and by Hoyle.[2] In the expanding steady state model, matter must be continually created to maintain a constant density. Did this phenomenon violate the matter conservation law?

In Hoyle's version, the steady state model was obtained as a solution of Einstein's equations of general relativity and therefore the conservation law could not be violated. The 'trick' lay in hypothesizing a negative energy reservoir in the form of a massless scalar field, often called the C-field. Steady state was maintained by creating matter from this reservoir whose strength remained unchanged because of expansion. (In the absence of expansion the magnitude of the energy would have grown through matter creation.)

In the 1950's and the early 1960's the steady state model offered a viable alternative to the big-bang models, so far as astronomical observations were concerned. The physicists, however, raised another objection to the steady state model, namely that its matter creation violated the empirical law of conservation of baryon number. For, if the baryon number were to be conserved equal amounts of matter and antimatter would have to be created. These would quickly annihilate each other and produce a background of gamma rays that was too large to be consistent with observations.[3] In 1958 Gold and Hoyle[4] explored the consequences of continuous creation of matter in the form of neutrons. This assumption preserved the conservation of electric charge but not of baryon number. The decay of neutrons generated electrons with high kinetic temperature and as a result thermal gradients were set up. Gold and Hoyle argued that these thermal gradients would help form galaxies in large groups or superclusters. The characteristic dimension of a supercluster in this hot universe came out as ~50 Mpc.

Although the hot universe fell in disrepute because of its apparent overestimate of the x-ray background, the above idea was probably the first input ever of a result from particle physics (i.e., neutron decay) into cosmogony. It also demonstrated how fundamental physics might be relevant to such cosmological issues as galaxy formation.

Meanwhile a cold steady state universe was studied within the framework of the C-field. A paper entitled 'On the nonconservation of baryons in cosmology' was published by Hoyle and I in 1966, discussing details of matter creation in the C-field formalism.[5]

Thus the nonconservation of baryons was necessarily implied by the steady state cosmology in spite of the prevailing beliefs of the particle physicists that the baryon number must be conserved. However, the tide turned against the steady state cosmology mainly by the discovery of the cosmic microwave background. The measurements of the background spectrum and the finding that it has the black body form led in the early 1970s to the general belief in the big-bang scenario.

However, the question of baryon nonconservation which had receded in the background with the unpopularity of the steady state model reappeared in the late 1970s in the context of the big-bang model. Let us look at the problem as it appeared then—prior to the current revolution in particle physics.

II. THE BARYON TO PHOTON RATIO

Let us suppose that the matter in the present universe is largely made of baryons. Taking the typical baryonic mass as equal to the mass of the proton $m_p \cong 1.6 \times 10^{-24}\, g$ suppose that there are N_b baryons in unit volume in a 'smoothed out' model of the universe. Then the baryonic density of the universe is given by

$$\rho_b = N_b m_p \tag{2.1}$$

Let us suppose that ρ_b is a fraction f of the total density ρ of the universe. ρ itself may be expressed in the form

$$\rho = \Omega\rho_c \equiv \Omega_0 \cdot \frac{3H_0^2}{8\pi G} \tag{2.2}$$

where ρ_c is the 'closure' density and H_0 is the present value of Hubble's constant. For the density parameter exceeding unity the spatial geometry of the universe is closed and it eventually contracts. For $\Omega_0 \leqslant 1$ the spatial geometry is open and the universe expands forever. The value of Hubble's constant is best expressed as

$$H_0 = 100 h_0 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

where the possible range of the parameter h_0 between 0.5 and 1 describes the present uncertainty in the measurement of H_0.

Assuming that the microwave background is a strictly black body curve of temperature $T_0(\approx 3\text{ K})$ the number density of photons in the universe is given by

$$N_\gamma = \frac{2.404}{\pi^2}\left(\frac{kT_0}{c\hbar}\right)^3 \tag{2.3}$$

where k = Boltzmann's constant, c = speed of light and $\hbar$ = Planck's constant.

Combining the above relations we get the baryon to photon number ratio as

$$\begin{aligned}\frac{N_b}{N_\gamma} &= \left(\frac{3H_0^2\Omega_0}{8\pi G m_p}\right) \Big/ \left(\frac{2.404}{\pi^2}\left(\frac{kT_0}{c\hbar}\right)^3\right)\\ &\simeq 2.2\times 10^{-8}(\Omega_0 h_0^2)\left(\frac{T_0}{3}\right)^{-3}\end{aligned} \tag{2.4}$$

It should be emphasized that when, on the basis of Eq. (2.4) the statement is made that N_b/N_γ lies in the range 10^{-10} to 10^{-8} the following implicit assumptions are made:

1. the uncertainty of h_0 between 0.5 and 1.
2. the uncertainty of Ω_0 of f which involves individual prejudices about how much hidden non-baryonic matter is present in the universe. Observations of luminous matter suggest that Ω_b lies in the range 0.1-0.2.
3. the unverified assumption that there is hardly any antimatter in the universe. We have no means of telling whether a distant galaxy is made of matter or antimatter since both behave identically with light, our sole carrier of information.

As the universe expands and its scale factor $S(t)$ increases with time, both N_b and N_γ tend to drop off as S^{-3} provided there has been no net generation of photons or baryons.

If we assume that the baryon number is conserved except at very high energies and also that there has not been any significant addition to the photon number since the very early times then the ratio N_b/N_γ must have effectively remained unchanged since primordial times. Consequently calculations of the particle interactions in the very early universe should yield this ratio.

An attempt to estimate this ratio was made in the mid-1970s (see Steigmann[6]). Assuming (i) thermodynamic equilibrium, (ii) particle-antiparticle symmetry, and (iii) conservation of baryon number, led Steigmann to the result that the primordial composition consisted of N_b baryons, $N_{\bar{b}}$ anti-baryons and N_γ photons where

$$\frac{N_b}{N_\gamma}=\frac{N_{\bar{b}}}{N_\gamma}\approx 10^{-18} \tag{2.5}$$

The ratio is too small compared to Eq. (2.4). Moreover, because of the net balance between baryons and anti-baryons the effective baryon number is zero. Thus a simplified first attempt to understand the ratio given by Eq. (2.4) does not work.

It is not difficult to understand the number [Eq. (2.5)] which arises basically from a comparison of reaction rates of the type

$$B+\bar{B}\leftrightarrow \gamma+\gamma \tag{2.6}$$

where B is a baryon and $\bar{B}$ its antiparticle, with the Hubble constant of the early universe. The ratio [Eq. (2.5)] turns out to be of the order of magnitude $\alpha_G^{1/2}$ where

$$\alpha_G=\frac{Gm_B^2}{\hbar c} \tag{2.7}$$

is the baryonic gravitational fine structure constant (see Ref. 7 for details). Obviously, fundamental particle physics has to provide new inputs to explain the N_b/N_γ ratio.

III. THE NEW RECIPE

These inputs began to come in towards the end of the last decade. The success of gauge theoretic framework in unifying the electromagnetic and weak interactions inspired further work to unify these two interactions with the strong interaction. The emerging theory has the somewhat grandiose title of 'Grand Unified Theory', often shortened to GUT. Such a theory has not yet reached an acceptable final shape although there are several candidates in the field.

Although there are several GUTs with different mathematical structures, they all agree on one point, that the baryon number is not a conserved quantity. For example, the simplest of the GUTs, the so called 'minimal SU (5)' envisages conversion of quarks to leptons and vice versa through the exchanges of gauge bosons, designated for want of any specific name by the title X-bosons. The SU (5) theory introduces 12 such new bosons and in a typical reaction (see Fig. 25.1) the proton decays to a positron and a neutral pion

$$p\rightarrow e^{+}+\pi$$

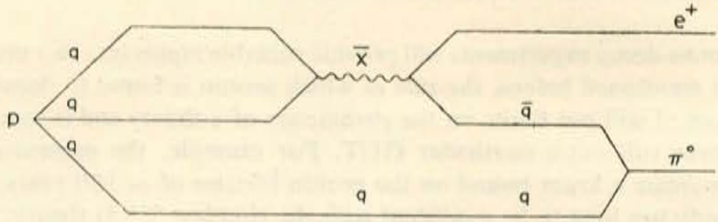

Fig. 25.1 **The decay of the proton takes place in the above mode through the combination of two of its three quarks into a gauge boson *X* which decays into a positron and an antiquark. The latter combines with the third quark to form a pion.**

through the mediation of the *X*-bosons. If the *X*-boson mediating in the decay has mass m_x, then dimensional considerations tell us that the decay time scale for the proton is of the order

$$\tau_p \sim \frac{\hbar m_x^4}{m_p^5 c^2} \sim 2.87 \times 10^{-32} [m_x c^2 \mathrm{GeV}]^4 \text{ years} \qquad (3.1)$$

Experiments set lower limits on τ_p of at least 10^{29} years. These require $m_x c^2 > 10^{15}$ GeV. The *X*-bosons therefore have to be very massive if the protons are not to decay too rapidly. We will return to this point later.

Assuming that a satisfactory GUT is found ultimately, how does it help in understanding the ratio N_b/N_γ? First, by introducing the possibility of generating or destroying baryons it provides one necessary ingredient for the scenario of making up a net baryon excess in the universe. However, this is not sufficient. In addition it is necessary to ensure that (i) there is an asymmetry (*CP*-violation) in the way baryons and antibaryons are produced (or destroyed) and (ii) there is a lack of thermodynamic equilibrium while these reactions are going on. The latter assumption is needed to ensure that reactions creating baryons are not exactly balanced by their opposite reactions destroying baryons.

Thus if an *X*-boson decays into two states of baryon numbers B_1 and B_2 with fractions r in state 1 and $(1-r)$ in state 2, the anti-boson $\bar{X}$ will decay into states of baryon number $-B_1$, $-B_2$, with fractions $\bar{r}$ and $(1-\bar{r})$ with $r \neq \bar{r}$. The net baryon number generated in the process is therefore

$$\Delta B = (r - \bar{r}) B_1 - B_2) \qquad (3.2)$$

Departure from thermodynamic equilibrium ensures that ΔB is not cancelled out by the reverse reactions. ΔB can then be related to N_b.

It is too early to say whether these calculations can explain the ratio N_b/N_γ. There are far too many uncertain parameters that go into the recipe to generate a confidence that the final outcome is reliable. No doubt as our theoretical understanding of GUTs improves, the answer may become more trustworthy.

IV. PROTON-DECAY AND COSMOLOGY

The proton-decay experiments will provide valuable inputs into this problem. For, as mentioned before, the rate at which proton is found to decay (if at all it decays) will put limits on the parameters of a theory and in some cases it may even rule out a particular GUT. For example, the present experiments indicate a lower bound on the proton lifetime of $\sim 10^{31}$ years. These are already too long to be consistent with the simplest SU(5) theory.

To the uninitiated, the connection between candidate events recorded in the deep underground pile of steel in the mines of Kolar Gold Fields and the state of the universe when it was only 10^{-35} s old, may appear tenuous. The underlying links in the chain are the grand unified theories, the observation of microwave background radiation, the estimate of baryonic density of matter in the universe and of course, the big-bang cosmological model obtained from Einstein's field equations. Thanks to Professor Sreekantan's realization of the importance of this chain between particle physics and cosmology the KGF experiment was the first among many to become operational.

A word of caution is necessary here. The proton decay experiment could be used to rule out some of the GUTs—but it can never provide the full dynamical verification of any such theory. In this sense the GUTs cannot be considered verifiable: no man-made accelerator can generate energies of the order of 10^{15} GeV to test the interactions of particles under a grand unified theory. The only conceivable scenario for the operation of GUTs is provided by the early universe. We thus have a situation wherein neither the GUTs can be verified without assuming the validity of the early universe scenario nor can the relics of the early universe be identified without assuming the validity of GUTs. In other words we can *never* hope to demonstrate in *absolute* terms both the validity of the early universe and GUTs. The best that can be achieved is a selfconsistent match of particle physics with cosmology.

Viewed in this light, the proton decay experiment and the observation of the ratio N_b/N_γ are inputs respectively from particle physics and cosmology which impose constraints on such a selfconsistent match. Monopoles, massive neutrinos and other exotic particles are similar inputs from particle physics that need to be matched with cosmological inputs like hidden matter, the density fluctuation in the form of galaxies and small scale anisotropies of the microwave background. To what extent this match between two frontier areas succeeds still remains to be seen.

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