matters arising

Particle creation and Dirac's Large Number Hypothesis

IN a recent paper[1] Steigman claims to show that the creation of matter as postulated by Dirac[2] is unnecessary. In particular he claims that a theory with a gravitational constant G varying as t^{-1} automatically implies that the number of nucleons within the horizon should increase as t^2. If so, Dirac's hypothesis that $N \sim t^2$ must be due to spontaneous matter creation becomes unnecessary. We here show Steigman's claim to be incorrect.

First, note that within Dirac cosmology the present radius of the Universe varies as $R \sim t$. Assuming such a time dependence holds in the very early Universe, as Steigman does, then there is no horizon since the integral

$$d_H(t) \equiv cR(t)\int_0^t \frac{d\tau}{R(\tau)} \qquad (1)$$

defining the horizon distance diverges logarithmically. Therefore, any increase of mass, M, with time, t, no matter how, must be ascribed to spontaneous creation since no matter is entering the space, V, across the expanding horizon.

We now show how matter creation must be an independent hypothesis for Steigman's equation (1) to be correct. As shown in ref. 3, the correct Einstein equation in atomic units is given by

$$\left[\frac{\dot{R}}{R}+\frac{\dot{\beta}}{\beta}\right]^2 + \frac{k}{R^2} = \frac{8\pi}{3}\bar{G}\bar{\rho}\beta^2 \qquad (2)$$

Here β is the gauge function which varies asymptotically as t^{-1}, and $\bar{G}$ and $\bar{\rho}$ are given in Einstein units. In Einstein units $\bar{G}$ is constant, and $\bar{\rho}$ is given by

$$\bar{\rho} = \bar{M} / \bar{R}^3 \qquad (3)$$

where, following Dirac[2], $\bar{M}$ and $\bar{R}$ are constant so $\bar{\rho}$ is constant. Since $\bar{R} = \beta R$, where $\bar{R}$ and R are the radii of the Universe in Einstein and atomic units, respectively, equation (2) becomes

$$G\bar{\rho}\beta t^2 \quad \text{constant} \qquad (4)$$

where we have used $G = \bar{G}\beta \sim t^{-1}$ and $R(t) \sim t$. Equation (4) coincides with Steigman's equation (1) only if we define

$$M/R^3 \equiv \rho = \bar{\rho}\beta \equiv \bar{M}\beta/\bar{R}^3 \qquad (5)$$

Since $\bar{R} = \beta R$ it follows that the mass entering the definition of ρ, that is, M, must be related to the constant mass $\bar{M}$ by the relationship

$$M = \bar{M}/\beta^2 = \bar{M}t^2 \qquad (6)$$

which explicity shows matter creation.

The error in Steigman's reasoning lies in the postulate of his equation (1) which does not have the backing and theoretical framework that justifies and correctly defines each quantity in the equation. One cannot simply postulate the existence of a relationship of the type

$$G\rho t^2 = \text{constant} \qquad (7)$$

and then take $G \sim t^{-1}$ assuming, as Steigman does, that ρ does not contain matter creation. If such a theory exists, as it might well do, it cannot be presented under the name Dirac cosmology. In fact, the full Dirac theory yields a relationship like equation (7) only if ρ is defined by equation (5), that is, if it already contains matter creation.

The second part of Steigman's criticism is invalid for a different reason. Here he points out that Dirac's large Number Hypothesis (LNH) implies such things as the fact that there can be no primordial nucleosynthesis, and that for $T \sim 10^{10}$ K the number of baryons in the Universe is of order unity.

In fact Dirac[2] has repeatedly stressed that the LNH is an asymptotic theory valid only for relatively large times over most of the age of the Universe, but not necessarily at very early epochs. Thus the second part of Steigman's paper strongly supports Dirac's statements and in no way invalidates the LNH.

In summary, Steigman's claim that Dirac's LNH does not require particle creation is wrong because he has assumed that which he was seeking to prove, that is that ρ does not contain matter creation. Steigman's claim that Dirac's LNH leads to nonsensical results in the very early Universe is superficially correct, but this only supports Dirac's contention that the LNH may not be valid in the very early Universe.

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1 Steigman, G., *Nature*, **261**, 479 (1976).
2 Dirac, P. A. M., *Proc. R. Soc.*, **A338**, 439 (1974).
3 Adams, P. J., Canuto, V., Hsieh, S. H. and E. Tsiang, *Phys. Rev. D.* (in the press).

STEIGMAN REPLIES—In Dirac's original cosmology the scale factor varies as $R \sim t^{1/3}$ (there is a possible confusion by Canuto *et al.* between 'scale factor' and 'radius of the Universe'). In this model there is a horizon and the results and conclusions of my paper apply. There are, of course, a large number of possible modifications of Dirac's original model. In the variation chosen by Canuto *et al.*[1] ($R \sim t$) there is no horizon. In this model then, there are always an infinite number of particles 'in the Universe' and, clearly, Dirac's Large Number Hypothesis (LNH) cannot apply.

Canuto *et al.* argue that several of my criticisms of Dirac's theory are invalid because the LNH is an 'asymptotic' theory. It is certainly not clear why this should be so; why do the equations in Canuto *et al.* not apply for all times? A cosmological theory which only predicts the present epoch is of questionable value.

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1 Canuto, V., Adams, P. J., Hsieh, S. H., and Tsiang, E., *Nature*, **263**, 485 (1976).

The pre-palaeozoic basement in south-eastern Scotland and the southern uplands fault

BASEMENT xenoliths in Carboniferous volcanics in the vicinity of Partan Crag along the south side of the Firth of Forth have been used to infer the character of the immediately underlying basement by Upton *et al.*[1]. These