THE X-RAY CLUSTER BARYON CRISIS

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Abstract. Nucleosynthesis in the standard hot big bang cosmology offers a successful account of the production of the light nuclides during the early evolution of the Universe. Consistency among the predicted and observed abundances of D, $^3$He, $^4$He and $^7$Li leads to restrictive lower and upper bounds to the present density of nucleons. In particular, the upper bound ensures that nucleons cannot account for more than a small fraction ($<0.06h_{50}^2$) of the mass in a critical density (Einstein-de Sitter) Universe. In contrast, x-ray observations of rich clusters of galaxies suggest strongly that baryons (in hot gas) contribute a significant fraction of the total cluster mass ($\geq0.2h_{50}^{-3/2}$). If, indeed, clusters do provide a “fair” sample of the mass in the Universe, this “crisis” forces us to consider other ways of mitigating it, including the politically incorrect possibility that $\Omega<1$. The options, including magnetic or turbulent pressure, clumping, and non-zero space curvature and/or cosmological constant, are discussed.

1. Introduction

The standard, hot big bang cosmology provides a successful model of an expanding Universe filled with radiation. As Gamow and his collaborators Alpher and Herman realized, the Universe described by this model would have passed through an early, hot, dense epoch when nuclear reactions transformed neutrons and protons into the light nuclides deuterium, helium-3, helium-4 and lithium-7 (e.g., Boesgaard & Steigman 1985).

The primordial abundances predicted by Big Bang Nucleosynthesis (BBN) in the standard model depend on only one adjustable parameter – the nucleon density at BBN. For relatively high nucleon density models (as measured by the nucleon-to-photon ratio $\eta = n_N/n_\gamma$; $\eta_{10} = 10^{10}\eta$), nucleosynthesis begins early, when neutrons are relatively abundant. In this case, D and $^3$He are quickly burned to $^4$He, and it is easier to bridge the gap at mass-5 and produce relatively large yields of mass-7. Thus for “high” $\eta$ the primordial abundances of D and $^3$He are “small” while those of $^4$He and $^7$Li are “large”. In contrast, for relatively low nucleon density models, the start of BBN is somewhat delayed, permitting some neutrons to decay and resulting in a somewhat less efficient burning of deuterium and helium-3 (as well as lithium-7). So, for “low” $\eta$ the big bang yields of D and $^3$He (as well as $^7$Li) are “large” while that of $^4$He is “small”. With four predicted abundances
(relative to hydrogen) and only one adjustable parameter, the standard, hot big bang cosmology is a testable model. As a function of $\eta$ the predicted BBN yields range over some 10 orders of magnitude. So, too, do the "observed" primordial abundances as inferred from a wide diversity of astronomical observations [e.g., Walker et al. ("WSSOK") 1991; for a recent overview, see Steigman 1994a]. For quite some time now it has been known that theory and data are roughly consistent (at the $\sim$ 2-sigma level) provided that the nucleon abundance lies in a very narrow range: $2.8 \lesssim \eta_{10} \lesssim 4.0$ [WSSOK; or: $3.1 \lesssim \eta_{10} \lesssim 3.9$ (Steigman 1994a)].

It is, of course, not sufficient to find that a value (or narrow range of values) of $\eta$ exists such that BBN predicts correctly the primordial abundances of the light nuclides (although any cosmological model must pass this test). It is necessary, too, to see if the nucleon abundance $\eta$ inferred from processes in the youth of the Universe is consistent with that determined from observations in its maturity. Astronomical data exist on the dynamics of systems from galaxies to clusters of galaxies (and beyond), from which estimates of the universal mass density may be derived. The BBN inferred nucleon mass density must be compared with those estimates to further test the standard, hot big bang cosmology.

For convenience (as well as convention) we will use for our comparisons the density parameter $\Omega$, the ratio of the present mass density to the critical mass density $\rho_{\text{crit}}$.

$$\rho_{\text{crit}} = \frac{3H_0^2}{8\pi G} \approx 2.6h_{50}^2 \text{ keV cm}^{-3}. \quad (1)$$

In (1), $G$ is Newton's constant and we have written the Hubble constant as: $H_0 = 50h_{50}$ km s$^{-1}$ Mpc$^{-1}$. The nucleon-to-photon ratio $\eta$ (e.g., from BBN) and the present photon (Cosmic Background Radiation = CBR) temperature determine the present universal nucleon density. For $T_{\text{CBR}} \approx 2.73$ K,

$$\Omega_{BBN} h_{50}^2 \approx 0.0157 \eta_{10}. \quad (2)$$

[For $T_{\text{CBR}} = 2.726 \pm 0.010$ (Mather et al. 1994), $\Omega_{BBN} h_{50}^2/\eta_{10} = 0.0146^{+0.0002}_{-0.0001}$].

Thus, for $2.8 \lesssim \eta_{10} \lesssim 4.0$ (see Fig. 1),

$$0.04 \lesssim \Omega_{BBN} h_{50}^2 \lesssim 0.06. \quad (3)$$

We show this allowed range of $\Omega_{BBN}$ as a function of $H_0$ in Figure 1. For comparison, we show also an estimate of $\Omega_{\text{LUM}}$, the contribution to $\Omega$ by "luminous" baryonic matter; i.e., baryonic matter within optically visible galaxies. We obtained this value by assuming, within the luminous parts of galaxies, a mean ratio of baryonic mass to blue luminosity $\langle M/L_B \rangle = 7.5h_{50}$, and dividing by the critical ratio needed to obtain $\Omega = 1$,