OSU-TA-6/93

Challenges to the Standard Model of Big Bang Nucleosynthesis *

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JUL 21 1993
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Abstract

Big Bang Nucleosynthesis (BBN) provides a unique probe of the early evolution of the Universe and a critical test of the consistency of the standard hot big bang cosmological model. Although the primordial abundances of $D, {}^3He, {}^4He$, and ${}^7Li$ inferred from current observational data are in agreement with those predicted by BBN, recent analysis has severely restricted the consistent range for the nucleon-to-photo ratio: $3.7 \leq \eta_{10} \leq 4.0$. Increased accuracy in the estimate of primordial ${}^4He$ and observations of Be and B in Pop II stars are offering new challenges to the standard model and suggest that **no** new, light particles may be allowed $\left(N_\nu^{BBN} \leq 3.0\right)$.

* Talk presented at the National Academy of Sciences Colloquium "Physical Cosmology" (Irvine, CA; 27-28 March 1992). To appear in Proc. Natl. Acad. Sci. USA, Vol. 90 (1993).

1. INTRODUCTION

A hot, dense genesis for the Universe is strongly suggested by the presently observed expansion coupled with the thermal spectrum of the cosmic background radiation. Along with the observed large scale isotropy and homogeneity, these empirical data form the basis of the "standard" (i.e., simplest) hot big bang cosmological model. Extrapolation to very early epochs within the context of this model point to the infant Universe as a primordial nuclear reactor. It is the comparison of the predicted abundances of those elements synthesized during the early evolution of the Universe with those inferred from current observational data that provides one of the very few direct tests of the standard model as well as constraints on alternative cosmologies (1-3). At this symposium Pagel (4) and Schramm (5) have reviewed the current status – and successes – of the standard model. The consistency between the predictions of standard big bang nucleosynthesis (BBN) and the observational data not only lends support to the hot big bang model but also leads to constraints on the baryon density of the Universe (1-5) and on particle physics beyond the standard model (6).

As impressive as the successes of the standard hot big bang model are, eternal vigilance is a prerequisite for the success of any scientific enterprise. Any model worthy of consideration is worthy of challenge. Here, I will complement the contributions of Pagel (4) and Schramm (5) by examining those challenges to the consistency of (standard) BBN that seem most serious at present. As a potentially falsifiable model for the structure and evolution of the Universe, the hot big bang cosmology should be the subject of constant scrutiny.

2. THE STANDARD MODEL

Within the context of the standard model, when the Universe was a few minutes old conditions were right for nuclear reactions to proceed rapidly, building the lightest nuclides (D, ^3He, ^4He, ^7Li) (see 1-5 and references therein). The gap at mass-5 ensured that ^4He would be the second most abundant element (after hydrogen) in the Universe and that any heavier elements would be produced only in trace amounts. Since D and ^3He (as well as ^3H) are being burned to ^4He, the higher the nucleon abundance the more rapidly are D and ^3He burned away and the smaller will be their relic abundance. The magnitude of the nucleon abundance (as measured by the universal ratio of nucleons to (CBR) photons: $\eta \equiv N/\gamma$; $\eta_{10} \equiv 10^{10}\eta$) is crucial also to bridging the gap at mass-5 and, therefore the mass-7 abundance is sensitive to η. As a result, the relic abundances of D, ^3He, and ^7Li provide both *upper* and *lower* bounds to the universal abundance of nucleons (3),

$$D,\ ^3He,\ ^7Li: \quad 2.8 \leq \eta_{10} \leq 4.0 \tag{1}$$

The CBR temperature ($T_{\gamma 0} = 2.74$) at present (7) permits us to infer the present density of nucleons (in terms of the critical density),

$$\Omega_N h^2 = 0.0037\eta_{10}, \tag{2a}$$

$$0.010 \leq \Omega_N h^2 \leq 0.015. \tag{2b}$$

In eq. 2, $\Omega_N \equiv \rho_N/\rho_c$ is the ratio of the nucleon density to the critical density and the Hubble parameter is $H_0 = 100h\ kms^{-1}Mpc^{-1}$ (or, $H_0^{-1} = 9.8\ h^{-1}$ Gyr). This BBN bound on Ω_N may be compared with various estimates of the current mass density thus connecting directly the early and present Universe. For $h \leq 1$, $\Omega_N \gtrsim 0.01$ suggesting that *some* (perhaps *most*) nucleons in the Universe are "dark" (3). For a lower bound of $H_0 \gtrsim 40\ kms^{-1}Mpc^{-1}$(8), $\Omega_N \lesssim 0.09$ providing strong support for the possibility that the Universe is dominated by non-baryonic matter.

The relic abundance of ^4He is very sensitive to the balance between the universal expansion rate and the weak interaction rate, providing a sensitive probe of "new physics" (6). For an inferred primordial ^4He mass fraction (4,9) $Y_P \leq 0.240$, there is a very restrictive bound on light, weakly interacting particles (3),

$$\Delta N_\nu = N_\nu - 3 \leq 0.3. \tag{3}$$

If, indeed, the standard (homogeneous, isotropic, ...) hot big bang model provides an accurate description of the early evolution of the Universe, the inferred upper and lower bounds to η should approach each other *without crossing*. Also, the LEP data (10) confirming the standard model result that $N_\nu \geq 3.0$ (but, recall that LEP is sensitive to very massive particles – $\lesssim M_Z/2$ – which, if present, would play no role in BBN) leads to a *lower* bound to the predicted primordial abundance of ^4He (3), $Y_P \geq 0.236$, which must be tested.

3. DEUTERIUM

Observations of deuterium, yield *lower* bounds to its primordial abundance (11) since D is destroyed in the course of galactic evolution. Very recent HST observations (12) of the local interstellar gas towards Capella yield,

$$10^5\,(D/H)_{ISM} = 1.65^{+0.07}_{-0.18}. \tag{4}$$

This is completely consistent with the earlier *Copernicus* results summarized by Steigman (13) who found an average $10^5\,(D/H)_{ISM} = 1.6^{+0.9}_{-0.6}$. It is of interest to compare this interstellar abundance with the presolar value (13). The 95% CL (2σ) ranges are,

$$1.29 \leq 10^5 (D/H)_{ISM} \leq 1.79, \tag{5a}$$

$$1.85 \leq 10^5 (D/H)_{\odot} \leq 3.27, \tag{5b}$$

hinting at the possibility of some slight astration of deuterium in the $\sim$ 4.6 Gyr since the formation of the solar system.

Recently, Steigman & Tosi (14) have followed the evolution of D (and ^3He) using models for the chemical evolution of the Galaxy. In all models there is little destruction of deuterium between solar system formation and the present epoch (less than a factor of 2.3), consistent with the results in eq. 5. Steigman & Tosi (14) use solar system observations and their evolution models to set *upper* and *lower* bounds to primordial D, $3.9 \leq 10^5 X_{2P} \leq 9.0$ which leads to constraints on the nucleon abundance, $3.4 \leq \eta_{10} \leq 5.6$ that are more restrictive than previous constraints (3). Note, in particular that the restrictive new upper bound to D ($X_{2P} \leq 9.0 \times 10^{-5} \Rightarrow (D/H)_P \lesssim 5.9 \times 10^{-5}$) raises the *lower* bound to η_{10} (from 2.8 to 3.4; see eq. 1).

4. HELIUM-3

Although all deuterium cycled through the stars is destroyed, some helium-3 survives stellar processing. This result was exploited by Yang et al. (1)to derive an *upper* bound to primordial D *plus* ^3He from solar system observations. Current data (3, 13) provide the *upper* bound $[(D + {}^3He)/H]_P \leq 1.0 \times 10^{-4}$ which is responsible for the *lower* bound to η in eq. 1 ($\eta_{10} \geq 2.8$). As we have just seen, the results of Steigman & Tosi (14) raise this lower bound. They (14) have also used their models to track the evolution of ^3He which, as anticipated, hardly changes from its primordial value. For the (95% CL) range of the primordial *mass fraction* of D *plus* ^3He consistent with solar system data, Steigman & Tosi (14) find $6.3 \leq 10^5 X_{23P} \leq 11$, which corresponds to $3.7 \leq \eta_{10} \leq 5.7$. Thus, this (galactic chemical evolution) model-dependent approach has raised the previous lower bound to η, considerably narrowing the "window of consistency."

$$D,\ {}^3He: \quad 3.7 \leq \eta_{10} \leq 5.6. \tag{6}$$

5. LITHIUM-7

The warmer Pop II stars are observed to have the *same* lithium abundance within a very narrow range (the "Spite plateau"; ref. 15). For several dozen such stars (3, 13),

$$10^{10} (Li/H)_{PopII} = 1.2 \pm 0.2 \tag{7}$$

With allowance for theoretical uncertainties, possible systematic observational uncertainties and, for possible destruction of lithium in these stars, Walker et al. (3) inferred $(Li/H)_P \lesssim 2 \times 10^{-10}$, which leads to the bounds on the nucleon abundance,

$$^7Li: \quad 1.5 \leq \eta_{10} \leq 4.0. \tag{8}$$

Recently, a new wrinkle has been added to the quest for primordial lithium. Beryllium (16-18) and Boron (19) have been observed in several of the "Spite plateau" Pop II stars. The best (only ?) candidate for Be and B production in the early Galaxy is cosmic ray (spallation/fusion) nucleosynthesis (20-23). Along with any Be and B produced, $^{6,7}Li$ will also be synthesized by CNO spallation and, particularly, by a $\alpha\alpha$ fusion (22). Although model-dependent uncertainties render very uncertain the prediction of absolute abundances of cosmic ray produced Li, Be, B, *relative* abundances are less uncertain (22). Current Pop II Be and B data (16-19) are consistent with cosmic ray origin (22,23) and suggest that perhaps $\sim 1/4$ of the Li observed in the "Spite plateau" (15) stars may have a galactic (i.e. nonprimordial) origin. Since there is a "floor" to BBN production of lithium ($(Li/H)_{BBN} \geq 1.1 \times 10^{-10}$), it is crucial to attempt to separate the galactic and primordial contributions to the Li observed in Pop II stars. This could provide a crucial test of the consistency of the standard, hot big bang cosmology.

6. CHALLENGES

Reanalysis of the D and ^3He observations in the context of models for the chemical evolution of the Galaxy (14) have narrowed the window of consistency. The inferred primordial abundances of D, ^3He and ^7Li are still in concordance with the predictions of standard BBN (3) but, for a much more restrictive range of nucleon abundance. Comparing eqs. 6 & 8, we have,

$$D,\ ^3He,\ ^7Li: \quad 3.7 \leq \eta_{10} \leq 4.0. \tag{9}$$

Fortunately, the tighter constraints from D (& ^3He) can be tested. Solar system and ISM observations combined with the bounds on D astration (14) lead to a predicted *upper* bound to primordial deuterium: $(D/H)_P \lesssim 6 \times 10^{-5}$. Future UV observations (24) in metal-poor extragalactic systems could test this prediction (and, in the process, provide a less model-dependent estimate of the primordial abundance).

What of ^4He and the Steigman, Schramm & Gunn (6) bound to N_ν ? Pagel (4) has reviewed the observational situation; see also (9). At present, although the third decimal place is surely uncertain, the primordial ^4He mass fraction is bounded from above (95% CL) by,

$$Y_P^{OBS} \leq 0.240. \tag{10}$$

If, indeed, the new lower bound to η from $D + {}^3He$ (14) is correct ($\eta_{10} \geq 3.7$), then for a neutron lifetime ≥ 882 sec (3) the *minimum* BBN ${}^4He$ mass fraction (for $N_\nu \geq 3$) is predicted to be,

$$Y_P^{OBS} \geq 0.240. \tag{11}$$

The window is closed (?)! That is (to the extent that the third decimal place may be trusted!), there is **no** room for any additional light particles,

$$\Delta N_\nu = N_\nu - 3 \leq 0. \tag{12}$$

This, truly, is a challenge of the standard model.

7. CONCLUSIONS

The standard model of cosmology is testable. BBN and the observed abundances of the light elements provide a unique probe of the early Universe and a crucial test of the standard model. In particular, D, ${}^3He$ & ${}^7Li$ provide upper and lower bounds to the nucleon abundance which, at present, are very restrictive (see eq. 9). The dynamics of stars, galaxies, and clusters provides a means for determining the present density of nucleons. How do they compare? Returning to eq. 2 but using the tighter constraints in eq. 9, the allowed range for the present density of nucleons is only slightly modified but, tightly constrained,

$$0.014 \leq \Omega_N h^2 \leq 0.015. \tag{13}$$

Thus, the case for baryonic dark matter is strengthened; most of the nucleons in the Universe are not shining. Since the upper bound has not changed, nucleons still fail – by a wide margin – to close the Universe and, the higher lower bound strengthens the case for non-baryonic dark matter dominating the Universe.

Still, the standard hot big bang model is facing some serious challenges. New estimates (14) of a *lower* primordial abundance of deuterium has driven the lower bound to η very close to the upper bound. Will they cross like ships in the night? Detection of Be and B in Pop II stars (16-19) suggests that some of the lithium observed in these stars is not primordial. Will the eventual upper bound to primordial Li fall below the minimum abundance predicted by BBN ? Consistency of the standard model awaits the outcome of these confrontations. Finally, ${}^4He$ the second most abundant element in the Universe, is also the most accurately measured. Is its abundance known sufficiently accurately to decisively challenge the standard model?

The present turbulent cosmological scene is evident of healthy science. The standard model can be, and is being tested. We all await anxiously the test results.

ACKNOWLEDGEMENTS

I am grateful to my colleagues, H.S. Kang, K.A. Olive, B.E.J. Pagel, D.N. Schramm, M. Tosi, and T.P. Walker, for valuable discussions. This work is supported by the DOE.

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