BIG BANG NUCLEOSYNTHESIS: CONSISTENCY OR CRISIS?

GARY STEIGMAN

Departments of Physics and Astronomy
The Ohio State University
174 West 18th Avenue
Columbus, OH 43210, USA

ABSTRACT

The early hot, dense, expanding Universe was a primordial reactor in which the light nuclides D, ^{3}He, ^{4}He and ^{7}Li were synthesized in astrophysically interesting abundances. The challenge to the standard hot big bang model (Big Bang Nucleosynthesis $\equiv$ BBN) is the comparison between the observed and predicted abundances, the latter which depend only on the universal abundance of nucleons. The current status of observations is reviewed and the inferred primordial abundances are used to confront BBN. This comparison suggests consistency for BBN for a narrow range in the nucleon abundance but, looming on the horizon are some potential crises which will be outlined.

1

INTRODUCTION

Observations of an expanding Universe filled with black body radiation lead naturally to the inference that the early Universe was dense and hot and evolved through an epoch in which the entire Universe was a Primordial Nuclear Reactor. During the first $\sim$ thousand seconds ($\sim$ 20 minutes) the light elements D, ^{3}He, ^{4}He and ^{7}Li are synthesized in measurable abundances which range from $\sim 10^{-10}$ (for Li/H) to $\sim 10^{-5}$ (for D/H and ^{3}He/H) to $\sim 10^{-1}$ (for ^{4}He/H) (for a review and references see Boesgaard & Steigman 1985; for more recent results and references see Walker et al. 1991 (WSSOK)). The predicted abundances depend on the nucleon density, conveniently measured by the "nucleon abundance", the nucleon-to-photon ratio $\eta \equiv n_N/n_\gamma$ ($\eta_{10} \equiv 10^{10}\eta$; for $T_\gamma = 2.726$K, $n_\gamma = 411$ cm^{-3}). Thus, BBN provides a test of the consistency of the hot big bang model and a probe of cosmology (e.g., of the universal density of nucleons). Specifically, is there a value (or a range of values) of η such that all the predicted abundances are consistent with the inferred primordial abundances derived from the observational data? Further, if there is consistency, is the inferred nucleon density (based on processes which occurred during the first $\sim 10^3$ sec. of the Universe) consistent with that observed at present (when the Universe is $\sim$10 Gyr old)?

According to WSSOK, both questions are answered in the affirmative with $2.8 \lesssim \eta_{10} \lesssim 4.0$. The nucleon density parameter ($\Omega_N \equiv \rho_N/\rho_{CRIT}$) is related to the nucleon abundance and the Hubble parameter ($h_{50} \equiv H_0/50 km s^{-1} Mpc^{-1}$) by,

$$\Omega_N h_{50}^2 = 0.015 \ \eta_{10}, \tag{1}$$

(for $T_\gamma = 2.726 \pm 0.010(2\sigma)$, the coefficient in (1) varies from 0.0145 to 0.0148). Thus, for $2.8 \lesssim \eta_{10} \lesssim 4.0$, $0.04 \lesssim \Omega_N h_{50}^2 \lesssim 0.06$, which leads to the conclusion that there are dark baryons ($\Omega_N > \Omega_{LUM}$) but, not all dark matter is baryonic ($\Omega_N < \Omega_{DYN}$).

The physics of BBN is, by now, well understood; for overviews see Boesgaard & Steigman (1985) and Smith, Kawano & Malaney (1993). It is, however, worth emphasizing that Primordial Alchemy is conventional physics. For example, the timescales are long ($\sim 10^{-1} - 10^3$ sec.) and the temperatures (thermal energies) are low (kT$\sim$ 10 keV - 1 MeV) . Although the early Universe is dense, it is dilute on the scale of nuclear physics during the epoch of BBN. For example, for T $\lesssim 1/2$ MeV, the internucleon separation is $\gtrsim 10^6$ fermis. Thus, collective and/or many body effects are entirely negligible. The nucleon reaction network is very limited (effectively, $A \leq 7$) and simple. More importantly, the cross sections are measured at lab energies comparable to the thermal energies during BBN. Thus, in stark contrast to stellar nucleosynthesis (where $kT_\star \ll E_{1ab}$), large and uncertain extrapolations are not required. Thus, for fixed η, the BBN predicted abundances of D, ^{3}He and ^{7}Li are known to better than $\sim$ 20 % and the ^{4}He mass fraction (Y_{BBN}) is known to $|\delta Y_{BBN}| \lesssim 6 \times 10^4$ (Thomas et al. 1994).

Since the BBN abundances of D, ^{3}He and ^{7}Li vary noticeably with η, those nuclides serve as "baryometers", leading to constraining lower and upper bounds to η (e.g., WSSOK). Y_{BBN} varies little ($\sim$ logarithmically) with η and, thus, serves as the key to testing the consistency of BBN. In the next sections we first survey the observational data on D, ^{3}He and ^{7}Li and derive bounds to their primordial abundances. Next, the predicted and inferred primordial abundances are compared to test for consistency and to bound η. Then, the ^{4}He abundance is studied for consistency – or crisis. Finally, the health of BBN is assessed and possible crises are outlined.

DEUTERIUM

BBN is the only source of astrophysical deuterium. Whenever cycled through stars, D is destroyed (burned to ^{3}He, even during pre-main sequence evolution). Thus, the mass fraction (X_2) of primordial deuterium is no smaller than that observed anywhere in the Universe: $X_{2P} \geq X_{2OBS}$.

As with all of the light elements, there is both bad news and good news. The bad news is that, at least until recently (possibly!), deuterium has been observed only locally (in the interstellar medium (ISM) and the solar system). The good news is that the data is accurate.

Geiss (1993) has reanalyzed the solar system D and ^{3}He data. Using Geiss' results, Steigman & Tosi (1994) find

$$X_{2\odot} = 3.6 \pm 1.3 \times 10^{-5}. \tag{2}$$

Using older Copernicus and IUE data, along with newer HST data (Linsky et al. 1993), Steigman & Tosi (1994) have noted that over a range of two orders of magnitude in HI column density, $(D/H)_{ISM}$ is constant at a value of $1.6 \pm 0.2 \times 10^{-5}$. To determine X_{2ISM} requires knowledge of the H mass fraction in the ISM, for $Y_{ISM} \approx 0.28 \pm 0.02$ and $Z_{ISM} \approx 0.02$, $X_{ISM} \approx 0.70 \pm 0.02$ and,

$$X_{2ISM} = 2.2 \pm 0.3 \times 10^{-5}. \tag{3}$$

It is expected that X_2 should have decreased in the 4.6 Gyr between the formation of the solar system and the present (although as Steigman and Tosi (1992) show, the decrease may be small). The data are marginally consistent with this expectation: $X_{2\odot}/X_{2ISM} = 1.6 \pm 0.6$.

A lower bound to X_{2OBS} leads to a lower bound to X_{2P} which, in turn, leads to an upper bound to η. For $X_{2P} \geq X_{2ISM} \geq 1.7 \times 10^{-5} (2\sigma)$,

$$D: \quad \eta_{10} \leq 9.0 \tag{4}$$

HELIUM-3

When deuterium is cycled through stars it is burned to ^{3}He. ^{3}He burns at a higher temperature than D so that ^{3}He survives in the cooler, outer layers of stars. Furthermore, since hydrogen burning is incomplete in low mass stars, such stars are net sources of ^{3}He. Thus, any primordial ^{3}He is modified by the competition between stellar production and destruction and, therefore, a detailed evolution model – with its attendant uncertainties – is needed to relate the observed and BBN abundances (Steigman & Tosi 1992). However, since *all* stars do burn D to ^{3}He and, *some* ^{3}He does survive stellar processing, the primordial D + ^{3}He may be bounded by the observed D and ^{3}He (Yang et al. 1984 (YTSSO); Dearborn, Schramm & Steigman 1986). The YTSSO analysis, which has recently been updated (Steigman & Tosi 1994), is "generic" in the sense that it should be consistent with any specific model for Galactic chemical evolution. Its predictions do, however, depend on one model specific parameter g_3, the "effective" survival fraction of ^{3}He.

Since the deuterium observations have already been used to bound the primordial D mass fraction from below, here we are interested in using the solar system observations of D and ^{3}He to bound X_{2P} from above. If any net stellar production of ^{3}He is neglected (so that ^{3}He only increases by burning D and decreases by stellar destruction), it can be shown that (YTSSO; Steigman & Tosi 1994)

$$X_{2P} < X_{2P}^{MAX} = \left[1 - \frac{1}{g_3}\left(\frac{y_3}{y_{23}}\right)_P\right]X_{2\odot} + \frac{2/3}{g_3}\left(\frac{y_2}{y_{23}}\right)_P X_{3\odot}. \qquad (5)$$

In (5), the primordial D and ^{3}He abundances (by number) are $y_{2P} = (D/H)_P$ and $y_{3P} = (^3He/H)_P$; $y_{23P} = y_{2P} + y_{3P}$; g_3 is the "effective" survival fraction of ^{3}He (which is model dependent). It can be seen from (5) that the higher/lower the primordial/solar system ^{3}He abundances, the more restrictive the upper bound on primordial deuterium.

Of course, since primordial abundances appear on both sides of eq. 5, care must be excersized in finding the bound. One approach is to evaluate both sides of (5) using the *predicted* abundances as a function of η, identifying those values of η for which the inequality is satisfied (Steigman & Tosi 1994). Alternatively, the inequality can be further relaxed by entirely neglecting *any* primordial ^{3}He. Since $y_{3P} > 0$, we may write,

$$X_{2P} < X_{2P}^{MAX} < (X_{2P}^{MAX})^0 = X_{2\odot} + \left(\frac{2/3}{g_3}\right)X_{3\odot}. \qquad (6)$$

The inequality in (6) may be further reinforced to relate y_{2P} to $y_{2\odot}$ and $y_{3\odot}$ since the hydrogen mass fraction always decreases from its primordial value ($X_{H\odot} < X_{HP}$),

$$y_{2P} < (y_{2P}^{MAX})^0 < y_{2\odot} + g_3^{-1}y_{3\odot}. \qquad (7)$$

Using the Geiss (1993) solar system abundances and $g_3 > 1/4$ (Dearborn, Schramm

4

& Steigman 1986), Steigman & Tosi (1994) find $X_{2P} < 11 \times 10^{-5}$ ($y_{2P} < 7.4 \times 10^{-5}$) which leads to a *lower* bound to η,

$$D + {}^3He: \quad \eta_{10} \gtrsim 3.1 \tag{8}$$

Note that if the more restrictive survival fraction $g_3 > 1/2$ (Steigman & Tosi 1992) is used, we would infer $X_{2P} < 7 \times 10^{-5}$ and $\eta_{10} \gtrsim 4$. It should also be noted that 2σ upper bounds to $X_{2\odot}$ and $X_{3\odot}$ are used in reaching these conclusions.

To summarize the progress so far, solar system and interstellar observations of D and ${}^3He$ have permitted us to bound primordial deuterium from above and below ($1.6 \lesssim 10^5 X_{2P} \lesssim 11$) which leads to consistent upper and lower bounds on η ($3.1 \lesssim \eta_{10} \lesssim 9.0$). Next, we turn to the first consistency test of BBN by considering lithium-7.

LITHIUM-7

As with the other light nuclides, the status of lithium observations has good news and bad news. The good news is that lithium is observed, with relatively good statistical accuracy, in dozens and dozens of stars of varying metallicity, mass (or temperature), evolutionary stage, population, etc. Among the bad news, these stars are all in the Galaxy and, therefore, provide a sample which is not necessarily universal. More serious, however, are the essential corrections which are required to go from the observed surface abundances to their unmodified (by stellar evolution) prestellar values and, to account for the production/destruction of lithium in the course of Galactic chemical evolution.

The overwhelming influence of stellar evolution on the stellar surface lithium abundance is reflected in the enormous range of observed values in Population I stars. The Sun is a case in point. Whereas the meteoritic abundance of lithium is $\sim 2 \times 10^{-9}$([Li] $\equiv 12 + \log(Li/H) = 3.31$), the solar photosphere abundance is smaller by some two orders of magnitude (Grevesse & Anders 1989). There is, however, evidence for a maximum PopI lithium abundance as inferred from observations of the warmest stars in young open clusters (Balachandran 1994), [Li]$_{PopI} = 3.2 \pm 0.2(2\sigma)$. And, further, there is evidence (e.g., Beckman, Robolo & Molaro 1986) that this maximum decreases with decreasing metalicity until, for [Fe/H] $\lesssim -1.3$, the "Spite Plateau" is reached.

The Spites' discovery (Spite & Spite 1982a,b), subsequently confirmed by many observations (e.g., see WSSOK for an overview and references and, see Thorburn 1994 for the latest observations), is that the warmest ($T \gtrsim 5700K$), most metal-poor stars ([Fe/H] $\lesssim -1.3$) have, with remarkably few exceptions, the *same* lithium abundance: [Li]$_{PopII} \approx 2.1$ (WSSOK; the values from Thorburn (1994) are systematically higher by ~ 0.2 dex). The value of the Spites' discovery cannot be overestimated but, too, caution is advised. On the one hand, the "plateau" in Fe/H (or, where available, in oxygen abundance) suggests that [Li]$_{PopII}$ may provide an estimate of the primordial abundance free from a (significant) correction for Galactic chemical evolution. On the other hand, the temperature plateau suggests that, "what you see

5

is what you get". That is, the surface abundances of lithium in the warmest PopII stars provide a fair sample of the lithium abundances in the gas out of which those stars formed. If, indeed, $[\text{Li}]_P \approx [\text{Li}]_{PopII} \approx 2.1 \pm 0.2$ (the uncertainty is mainly systematic, the statistical uncertainties are much smaller (WSSOK)), then BBN is constrained significantly; for $(\text{Li/H})_{BBN} \lesssim 2 \times 10^{-10}$, $1.6 \lesssim \eta_{10} \lesssim 4.0$. However, analysis of Thorburn's (1994) extensive data set raises questions about the *flatness* of the lithium temperature/metallicity plateaus.

Furthermore, it is not clear that corrections for chemical evolution are entirely negligible, even for the very old, very metal-poor PopII stars. Lithium-7 (as well as ^6Li) may be produced by $\alpha - \alpha$ fusion reactions in Cosmic Ray Nucleosynthesis (CRN; Steigman & Walker 1992) as well as by the more familiar spallation reactions of p and α on CNO nuclei. Since the spallation reactions require CNO targets (and/or projectiles) whereas the fusion reactions can utilize primordial ^4He, CRN lithium production has a component which is shallower in its metallicity dependence than that of Be and/or B which are only synthesized in spallation reactions. Thus, if $(\text{Be/H})_{PopII} \sim (\text{Fe/H})^\alpha$, $\Delta(^7\text{Li/H})_{\alpha\alpha} \sim (\text{Fe/H})^{\alpha-1}$ and, since current data (Gilmore et al. 1992; Boesgaard & King 1993) suggests $\alpha \approx 1$, $(\Delta y_7)_{\alpha\alpha}$ should be nearly independent of metallicity and, so, will mimic a primordial component ($y_7 \equiv {}^7\text{Li/H}$). Thus, even neglecting any early (PopII) stellar production/destruction of ^7Li, the BBN and observed PopII lithium abundances are, in general related by,

$$y_{7OBS} = f_7(y_{7BBN} + (\Delta y_7)_{CRN}), \qquad (9)$$

where $f_7(\leq 1)$ is the stellar surface destruction/dilution factor for ^7Li. Although "standard" (i.e., nonrotating) models for the warmest PopII stars suggest $f_7 \approx 1$ (Chaboyer et al. 1992), models with rotation may permit a significant correction ($f_7 \gtrsim 0.1 - 0.2$; Pinsonneault, Deliyannis & Demarque 1992; Charbonel & Vauclair 1992). The observations of the much more fragile ^6Li in two PopII stars (Smith, Lambert & Nissen 1992; Hobbs & Thorburn 1994) suggests that $f_7 \approx 1$ but this important issue remains unresolved at present. Thus, although the PopII stellar data appears consistent with $[\text{Li}]_{BBN} \lesssim 2.3$, it is unclear that the much higher bound $[\text{Li}]_{BBN} \lesssim 3.0$ (Pinsonneault, Deliyannis & Demarque 1992) can be entirely excluded.

Fortunately, another – independent – path to primordial lithium exists. Lithium has been observed in the ISM of the Galaxy (Hobbs 1984; White 1986) and, searched for in the ISM of the LMC (in front of SN87A; Baade et al. 1991). The interstellar data has assets and liabilities of its own which, however, are *different* from those of the stellar data. Among the liabilities is a large and uncertain ionization correction since LiI is observed but most ISM ^7Li is LiII. Another problem is the correction for lithium removed from the gas phase of the ISM (where it is observed) by grains and/or molecules (where it is unobserved). Steigman (1994a) has proposed avoiding these obstacles by comparing lithium to potasium (which shares the ionization/depletion problems with lithium) and evaluating the *relative* abundances (Li/K rather than Li/H). Comparing Galactic ($[\text{Fe/H}] \approx 0$) Li/K with the absence

of Li and the presence of K in the LMC ($[Fe/H]_{LMC} \approx -0.3$), Steigman (1994a) has concluded that $(Li/K)_{LMC} \lesssim 1/2(Li/K)_{GAL}$. Since potassium has no primordial component, this bound can be used to derive an upper bound to primordial lithium (Steigman 1994a): $[Li]_P \lesssim 2.3 - 2.8$. Thus, although it appears that the Spite Plateau bound $[Li]_{BBN} \lesssim 2.3$ is supported, a higher value cannot be entirely excluded. Here, in the absence of evidence to the contrary, I will use the above bound $((Li/H)_{BBN} \lesssim 2 \times 10^{-10})$ to constrain η,

$$^7Li : 1.6 \lesssim \eta_{10} \lesssim 4.0. \tag{10}$$

CONSISTENCY AMONG D, ^{3}He & ^{7}Li?

Before moving on to the keystone of BBN, helium-4, it is useful to pause at this point to consolidate the progress thus far. Solar system and interstellar observations of D and ^{3}He have been employed to set lower and upper bounds to primordial deuterium ($1.6 \lesssim 10^5 X_{2P} \lesssim 11$) which result in bounds on the nucleon abundance ($3.1 \lesssim \eta_{10} \lesssim 9.0$). PopII and ISM observations of lithium are consistent with an upper bound on primordial lithium which may be as small as $(Li/H)_P \lesssim 2 \times 10^{-10}$ but, which could also be consistent with a larger value $(Li/H)_P \lesssim 6 - 8 \times 10^{-10}$. Utilizing the more restrictive lithium bound, consistency among the BBN predicted abundances is achieved provided that η is restricted to a relatively narrow range,

$$D, \ ^3He, \ ^7Li : \ \ 3.1 \lesssim \ \eta_{10} \lesssim \ 4.0. \tag{11}$$

From (1) it follows that the present density in nucleons is similarly restricted,

$$0.045 \lesssim \ \Omega_N h_{50}^2 \lesssim \ 0.059 \tag{12}$$

which, for $40 \le H_0 \le 100 km s^{-1} Mpc^{-1}$, corresponds to, $0.011 \lesssim \Omega_N \lesssim 0.093$. The lower bound $\Omega_N \gtrsim 0.01$ exceeds the estimate of the mass associated with "luminous" matter, suggesting the presence of Baryonic Dark Matter, while the restrictive upper bound $\Omega_N \lesssim 0.09$ is strong evidence for the existence of Non-Baryonic Dark Matter.

HELIUM-4

The good news about ^{4}He is that it is ubiquitous and can be seen everywhere in the Universe. And, since its abundance is large, its value can be determined with high statistical accuracy. The bad news is that the path from observations to abundances to primordial helium is strewn with corrections which are accompanied by potentially large systematic uncertainties.

As stars burn, hydrogen is consumed producing ^{4}He which is returned to the galactic pool out of which subsequent generations of stars form. Thus, any observed abundances must be corrected for the ^{4}He enhancement from the debris of earlier generations of stars. To minimize this correction and its attendant uncertainties, the most valuable observational data is that from the low metallicity, extragalactic HII regions (e.g., Pagel et al. 1992). It is the emission lines from the recombination

of $^4\text{He}^+$ and $^4\text{He}^{++}$ (as well as H^+) which are observed from these regions. Since neutral helium (in the zone of ionized hydrogen) is unobserved, its correction – which carries with it systematic uncertainties – is minimized by restricting attention to the hottest, highest excitation regions (Pagel et al. 1992) where the correction may be negligible (or, even, negative in the sense that HII regions ionized by very hot – metal-poor – stars may have HeII zones larger in extent than the HII zones). Finally, to benefit from the high statistical accuracy of the observational data, corrections for collisional excitation, radiation trapping and destruction by dust, etc. must be considered.

The best (i.e., most coherent) data set of Pagel et al. (1992) has recently been supplemented (Skillman et al. 1993) by the addition of $\sim$ a dozen very low metallicity HII regions. Olive and Steigman (1994) have analyzed this data; there are some four dozen HII regions whose oxygen abundances extend down to $\sim 1/50$ solar and whose nitrogen abundances go down to $\sim 1\%$ of solar. For this data Olive and Steigman (1994) find that an extrapolation to zero metallicity yields,

$$Y_P = 0.232 \pm 0.003, \tag{13}$$

where the uncertainty is a 1σ *statistical* uncertainty. Thus, at 2σ, $Y_{BBN} \lesssim 0.238$. It is difficult to estimate the possible *systematic* uncertainty; Pagel (1993), WSSOK, and Olive & Steigman (1994) suggest ± 0.005 (i.e., $\sim 2\%$). If so, the upper bound may be relaxed to $Y_{BBN} \lesssim 0.243$ which, as will be seen shortly, may be crucial.

The BBN predicted ^4He mass fraction is known to high accuracy (as a function of η). For the standard case of three light neutrinos ($N_\nu = 3$) and a neutron lifetime in the range $\tau_n = 889 \pm 4 (2\sigma)$ sec, the bounds from observation $Y_{BBN} \leq 0.238(0.243)$ require $\eta_{10} \leq 2.5(3.9)$. Here, we have the first serious crisis confronting BBN! Unless systematic corrections increase the primordial abundance of helium inferred from the observational data, the upper bound on η from ^4He is exceeded by the lower bound on η from D (and ^3He). With, however, allowance for a possible $\sim 2\%$ uncertainty, consistency is maintained. Thus, for D, ^3He, ^7Li and $Y_{BBN} \leq 0.243$,

$$3.1 \leq \eta_{10} \leq 3.9. \tag{14}$$

Of course, the upper bound to η from ^4He will reflect the uncertainty in the obserational bound to Y_P. For $\eta_{10} \sim 4$, $\Delta Y_{BBN} \approx 0.012(\Delta\eta/\eta)$ so that an uncertainty of 0.003 in Y corresponds to a 25% uncertainty in $\eta(\Delta\eta_{10} \approx \pm 1)$.

The importance of ^4He is that the predicted primordial abundance is robust – relatively insensitive to η and, as a function of η, accurately calculated (to better than ± 0.001). And, being abundant, ^4He is observable throughout the Universe and, systematic uncertainties aside, the derived abundance is known to high statistical accuracy ($\lesssim \pm 0.003$). Thus, ^4He is the keystone to testing the consistency of BBN.

A HELIUM-4 CRISIS?

Solar system data on D and ^{3}He, along with a "generic" model for galactic evolution (Steigman & Tosi 1994) leads to a *lower* bound to η ($\eta_{10} \gtrsim 3.1$) and, therefore, to a *lower* bound to the predicted BBN abundance of ^{4}He; for $N_\nu = 3$, $\tau_N \geq 885$ sec and $\eta_{10} \geq 3.1$, $Y_{BBN} \geq 0.241$. In contrast, accounting only for statistical uncertainties, $Y_P \leq 0.238$ (at 2σ; Olive & Steigman 1994). Thus, the issue of whether or not this is a crisis for BBN hinges on whether or not Y_P is known to three significant figures. Allowance for a possible, modest ($\sim 2\%$), systematic uncertainty of order 0.005 would transform this potential crisis to consistency.

A DEUTERIUM CRISIS?

Recently, two groups have independently reported the possible detection of extragalactic deuterium in the spectrum of a high z (redshift), low Z (metallicity) QSO absorption system (Songaila et al. 1994; Carswell et al. 1994). If, indeed, the absorption is due to deuterium, the inferred abundance is surprisingly high: $D/H \approx 19 - 25 \times 10^{-5}$. This high abundance – an order of magnitude larger than the pre- solar or ISM values – poses no problem for cosmology in the sense that for $(D/H)_{BBN} \sim 2 \times 10^{-4}$, $\eta_{10} \sim 1.5$ and $Y_{BBN} \sim 0.23$ and $(^7\text{Li}/\text{H})_{BBN} \sim 2 \times 10^{-10}$, which are in excellent agreement with the observational data. If, indeed, $\eta_{10} \sim 1.5$, then $\Omega_N h_{50}^2 \sim 0.022$, reinforcing the argument for non-baryonic dark matter (for $H_0 \gtrsim 40 km s^{-1} Mpc^{-1}$, $\Omega_N \lesssim 0.034$)

But, such a high primordial abundance does pose a serious challenge to our understanding of the stellar and galactic evolution of helium-3. The issue is that if $\sim 90\%$ of primordial deuterium has been destroyed prior to the formation of the solar system, then the solar nebula abundance of ^{3}He should be much larger than observed (Steigman 1994b) since D burns to ^{3}He and some ^{3}He survives. Earlier, we have used the solar system data to infer a primordial bound $y_{2P} < 7.4 \times 10^{-5}$ (for $g_3 \geq 1/4$). A primordial abundance as large as $\sim 2 \times 10^{-4}$ would require much more efficient stellar destruction of ^{3}He ($g_3 \lesssim 0.09$).

It is, however, possible that the observed absorption feature is not due to high z, low Z deuterium at all but, rather, to a hydrogen interloper (Steigman 1994b). That is, the absorption may be from a very small cloud of neutral hydrogen whose velocity is shifted from that of the main absorber by just the "right" amount so that it mimics deuterium absorption. As Carswell et al. (1994) note, the probability for such an accidental coincidence is not negligible ($\sim 15\%$). This possibility can only be resolved statistically when there are other candidate D-absorbers. Data from Keck and the HST is eagerly anticipated.

THE X-RAY CLUSTER CRISIS?

This overview concludes with a glimpse of yet another potential crisis for BBN. Large clusters of galaxies are expected to provide a "fair sample" of the Universe in the sense that, up to factors not much different from unity, the baryon fraction in clusters should be the same as the universal baryon fraction.

$$f_B = \Omega_B/\Omega \approx (M_B/M_{TOT})_{Clusters} \tag{15}$$

In (15) the baryon density parameter Ω_B is another name for what we have been calling the nucleon density parameter Ω_N and Ω is the ratio of the total density to the critical density. For x-ray clusters M_B is dominated by the mass in hot, x-ray emitting, intercluster gas ($M_B \approx M_{HG} + M_{GAL} \gtrsim M_{HG}$) so that,

$$\Omega \lesssim \Omega_{BBN}/f_{HG}, \tag{16}$$

where $\Omega_{BBN} = 0.015\eta_{10}h_{50}^{-2}$ and f_{HG} is the hot gas fraction in x-ray clusters. Since M_{HG} and M_{TOT} scale differently with the distance to the cluster, f_{HG} depends on the choice of Hubble parameter (e.g., Steigman 1985): $f_{HG} = A_{50}h_{50}^{-3/2}$. Thus, (16) may be written as,

$$\Omega h_{50}^{1/2} \lesssim 0.6 \left(\frac{0.10}{A_{50}}\right)\left(\frac{\eta_{10}}{4.0}\right), \tag{17}$$

where x-ray observations yield A_{50}.

The x-ray cluster crisis was perhaps first noted by White et al. (1993) for Coma where: $A_{50}(Coma) = 0.14 \pm 0.04$. For $A_{50} \gtrsim 0.10$ and $\eta_{10} \lesssim 4.0$, $\Omega = 1$ requires $H_0 \lesssim 18kms^{-1}Mpc^{-1}$! Thus, either $\Omega < 1$ or the BBN upper bound to η is wrong. Further x-ray data, however, makes this latter choice less likely. White et al. (1994) find for Abell 478, $A_{50}(A478) = 0.28 \pm 0.01$, a result supported by White & Fabian's (1994) survey of 19 x-ray clusters which finds, at an Abell radius of $\sim 3h_{50}^{-1}Mpc$, $A_{50} \approx 0.24$. For $A_{50} \approx 0.24$, $\Omega h_{50}^{1/2} \lesssim \eta_{10}/16$, strongly hinting at $\Omega < 1$. For $\Omega = 1$ and any sensible choice of H_0, η_{10} would have to be so large as to violate – separately – the observational bounds on D, ^{4}He, and ^{7}Li. The x-ray cluster crisis – if real – is a crisis for $\Omega = 1$ but, not for BBN.

BBN is alive and well and the healthy confrontation of theory with observation continues.

REFERENCES

- Baade, D., Cristiani, S., Lanz, T., Malaney, R.A., Sahu, K. C. & Vladilo, G. 1991, *A & A*, **251**, 253

- Balachandran, S. 1994, Preprint (Submitted to *ApJ*)

- Beckman, J. E., Rebolo, R. & Molaro, P. 1986, "Advances in Nuclear Astrophysics" (eds. E. Vangioni-Flam, J. Audouze, M. Cassé, J. P. Chièze & J. TranThanh Van; Editions Frontiéres) p. 29

- Boesgaard, A. M. & Steigman, G. 1985, *Ann. Rev. Astron. Astrophys.* **23**, 319

- Boesgaard, A. M. & King, J. R. 1993, *AJ* **106**, 2309

- Carswell, R. F., Rauch, M., Weymann, R. J., Cooke, A. J. & Webb, J. K. 1994, *MNRAS* **268**, L1

- Chaboyer, B., Deliyannis, C. P., Demarque, P., Pinsonneault, M. H. & Sarajedini, A. 1992, *ApJ*, **388**, 372

- Charbonnel, C. & Vauclair, S. 1992, *A & A*, **265**, 55

- Geiss, J. 1993 "Origin and Evolution of the Elements" (eds. N. Prantzos, E. Vangioni-Flam & M. Cassé; Cambridge Univ. Press) p. 89

- Gilmore, G., Gustafsson, B., Edvardsson, B. & Nissen, P. E. 1992, *Nature*, **357**, 379

- Grevesse, N. & Anders, E. 1989, in *ATP Conf. Proc. 183*, "Cosmic Abundances of Matter", (ed. C. J. Waddington; AIP), p.1

- Hobbs, L. M. 1984, *ApJ* **286**, 252

- Hobbs, L. M. & Thorburn, J. A. 1994, *ApJ* **428**, L25

- Linsky, J. L., Brown, A., Gayley, K., Diplas, A., Savage, B. D., Ayres, T. R., Landsman, W., Shore, S. W. & Heap, S. 1993, *ApJ* **402**, 694

- Olive, K. A. & Steigman, G. 1994, *ApJS* In Press

- Pagel, B. E. J., Simonson, E. A., Terlevich, R. J. & Edmunds, M. G. 1992, *MNRAS* **255**, 325

- Pagel, B. E. J. 1993, *Proc. Nat. Acad. Sci.* **90**, 4789

- Pinsonneault, M. H., Deliyannis, C. P. & Demarque, P. 1992, *ApJS* **78**, 179

- Skillman, E. D., Terlevich, R. J., Terlevich, E., Kennicutt, R. C. & Garnett, D. R. 1993, *Ann. N. Y. Acad. Sci.* **688**, 739

- Smith, M. S., Kawano, L. H. & Malaney, R. A. 1993, *ApJS* **85**, 219

- Songaila, A., Cowie, L. L., Hogan, C. & Rugers, M. 1994, *Nature* **368**, 599

- Spite, M. & Spite, F. 1982a, *Nature* **297**, 483

- Spite, F. & Spite, M. 1982b, *A & A*, **115**, 357

- Steigman, G. 1985, "Theory and Observational Limits in Cosmology" (ed. W. R. Stoeger; Specola Vaticana), p. 149

- Steigman, G. 1994a, "Cosmic Lithium: Going Up Or Coming Down?" (Preprint) OSU-TA-18/94

- Steigman, G. 1994b, *MNRAS*, **269**, L53

- Steigman, G. & Tosi, M. 1992, *ApJ* **401**, 150

- Steigman, G. & Tosi, M. 1994, "Generic Evolution of Deuterium and Helium-3" (Preprint) OSU-TA-12/94

- Steigman, G. & Walker, T. P. 1992, *ApJ* **385**, L13

- Thomas, D., Hata, N., Scherrer, R., Steigman, G. & Walker, T. 1994, In Preparation

- Thorburn, J. A. 1994, *ApJ* **421**, 318

- Walker, T. P., Steigman, G., Schramm, D. N., Olive, K. A. & Kang, H.-S, 1991, *ApJ* **376**, 51 (WSSOK)

- White, R. E. 1986, *ApJ* **307**, 777

- White, D. A., Fabian, A. C., Allen, S. W., Edge, A. C., Crawford, C. S., Johnstone, R. M., Stewart, G. C., & Voges, W. 1994, *MNRAS* **269**, 598

- White, D. A. & Fabian, A. 1994 Preprint (Submitted to MNRAS)

- White, S. D. M., Navarro, J. F., Evrard, A. E. & Frenk, C. S. 1993, *Nature* **366**, 429

- Yang, J., Turner, M. S., Steigman, G., Schramm, D. N. & Olive, K. A. 1984, *ApJ* **281**, 493 (YTSSO)