Michel Grenon & Sushma Mallik

Chantal Taçoy & Nadège Lagarde

https://doi.org/10.1017/S1743921310003819 Published online by Cambridge University Press

Light Elements in the Universe
Proceedings IAU Symposium No. 268, 2009
C. Charbonnel, M. Tosi, F. Primas & C. Chiappini, eds.

doi:10.1017/S1743921310003819

Primordial nucleosynthesis: A cosmological probe

Gary Steigman

Departments of Physics and Astronomy
Center for Cosmology and Astro-Particle Physics
The Ohio State University
192 West Woodruff Avenue
Columbus, OH 43210 USA
email: steigman@mps.ohio-state.edu

Abstract. During its early evolution the Universe provided a laboratory to probe fundamental physics at high energies. Relics from those early epochs, such as the light elements synthesized during primordial nucleosynthesis when the Universe was only a few minutes old, and the cosmic background photons, last scattered when the protons (and alphas) and electrons (re)combined some 400 thousand years later, may be used to probe the standard models of cosmology and of particle physics. The internal consistency of primordial nucleosynthesis is tested by comparing the predicted and observed abundances of the light elements, and the consistency of the standard models is explored by comparing the values of the cosmological parameters inferred from primordial nucleosynthesis with those determined by studying the cosmic background radiation.

Keywords. cosmology: early universe, nucleosynthesis, cosmological parameters

---

1. Introduction

Primordial nucleosynthesis provides a key probe of the physics and early evolution of the Universe. Big Bang Nucleosynthesis (BBN; ~ 20 minutes) and the cosmic microwave background (CMB) photons, last scattered at recombination (~ 400 kyr), provide complementary probes of the physics of the early evolution of the Universe.

For a brief period during its early evolution the hot, dense Universe is a cosmic nuclear reactor. Since the Universe is expanding and cooling rapidly, there is only time to synthesize in astrophysically interesting abundances the very lightest nuclides (D, ^{3}He, ^{4}He, and ^{7}Li). In the standard models of cosmology and particle physics described by General Relativity, the universal expansion rate, the Hubble parameter, H, is determined by the total mass/energy density: $H^2 \propto G\rho$, where $H = H(z)$, z is the redshift, G is the gravitational constant, and ρ is the energy density. During such early epochs, the Universe, which is filled with relativistic particles including three flavors of light neutrinos ($\mathrm{N}_\nu = 3$), is "radiation dominated", and the abundances of the nuclides synthesized during BBN depend on only one cosmological parameter, $\eta_{\rm B}$, which provides a measure of the universal density of baryons.

$$\eta_{\rm B} \equiv n_{\rm B}/n_\gamma \equiv 10^{-10}\eta_{10}. \tag{1.1}$$

In eq. 1.1, $n_{\rm B}$ is the number density of baryons and n_γ is the number density of cosmic background photons. The only baryons present at BBN are nucleons, *i.e.*, protons and neutrons. In contrast to the standard model of cosmology, there is a class of non-standard cosmological (and/or particle physics) models in which the expansion rate may differ from its standard model value, $H' \neq H$. In these non-standard models the expansion rate can be parameterized by an "expansion rate parameter", S, or equivalently, by an "effective number of neutrinos", $N_\nu \neq 3$, where

$$S^2 \equiv (H'/H)^2 \equiv G'\rho'/G\rho \equiv 1 + 7\Delta N_\nu/43. \quad (1.2)$$

More generally, the effective number of "extra" neutrinos, $\Delta N_\nu \equiv N_\nu - 3$, parameterizes any non-standard energy density ($\rho' \neq \rho$), normalized to the contribution from one standard model neutrino by,

$$\Delta N_\nu \equiv (\rho' - \rho)/\rho_\nu. \quad (1.3)$$

However, even if $\rho' = \rho$, it could be that $N_\nu \neq 3$ ($\Delta N_\nu \neq 0$) if the early-Universe gravitational constant differs from its current value, $G' \neq G$,

$$G'/G = S^2 = 1 + 7\Delta N_\nu/43. \quad (1.4)$$

As will be seen below, in this class of non-standard models the BBN-predicted (nSBBN) primordial abundance of deuterium depends largely on the baryon density parameter, η_B (deuterium is a cosmological baryometer), while that of helium-4 is sensitive to the early Universe expansion rate, S (^{4}He is an early universe chronometer).

In order to test the standard models of cosmology and particle physics, two key questions are addressed:

1. Do the light element abundances predicted by BBN agree with the primordial abundances inferred from observations?

2. Do the BBN values of η_B and S (N_ν) agree with those inferred from independent, non-BBN observations (e.g., from the CMB)?

2. Standard Big Bang Nucleosynthesis (SBBN)

For SBBN ($N_\nu = 3$), the light element relic abundances are only a function of the baryon density parameter, η_B. Among the light nuclides, deuterium is the baryometer of choice. There are several reasons why D occupies this special place. One is that the post-BBN evolution of deuterium is simple and monotonic: as gas is cycled through stars (producing the heavy elements), D is only destroyed (Reeves *et al.* 1973, Epstein, Lattimer, & Schramm 1976). As a result, if deuterium is observed anywhere in the Universe, at any time in its evolution, the observed abundance will be no larger than the primordial value: $(D/H)_{OBS} \leqslant (D/H)_P$. In addition, for systems of low metallicity, a sign that very little of their gas has been cycled through stars which destroy deuterium, the observed D abundance should approach the primordial value: $(D/H)_{OBS} \to (D/H)_P$ (the "Deuterium Plateau"). Another reason to prefer D is that its predicted primordial abundance is sensitive to the baryon density parameter; since $(D/H)_P \propto \eta_B^{-1.6}$, a $\sim 10\%$ determination of $(D/H)_P$ results in a $\sim 6\%$ determination of η_B.

The deuterium abundance is determined by comparing the H I and D I column densities inferred from observations of absorption of radiation from background UV sources by intervening gas. In searching for the Deuterium Plateau the relelvant data is provided by observations of high-redshift, low-metallicity, QSO Absorption Line Systems (QSOALS). Unfortunately, at present there are only seven, relatively reliable D abundance determinations (Pettini *et al.* 2008), which are shown in Figure 1.

The weighted mean of the seven D abundances is $\log(y_{DP}) = 0.45$. However, as may be seen from the Figure 1, only three of the seven abundances lie within 1σ of the mean. Indeed, the fit to the weighted mean of these seven data points has a $\chi^2 = 18$ ($\chi^2/dof = 3$). Either the quoted errors are too small or, one (or more) of the determinations is wrong, perhaps contaminated by unidentified (and, therefore, uncorrected) systematic

https://doi.org/10.1017/S1743921310003819 Published online by Cambridge University Press

errors. In the absence of evidence identifying the reason(s) for such a large dispersion, the best that can be done at present is to adopt the mean D abundance and to inflate the error in the mean in an attempt to account for the unexpectedly large dispersion among the D abundances (Steigman 2007).

$$\log(y_{\rm DP}) \equiv 0.45 \pm 0.03. \tag{2.1}$$

For this relic D abundance, SBBN predicts that the baryon density parameter is

$$\eta_{10}(\mathrm{SBBN}) = 5.80 \pm 0.28, \tag{2.2}$$

corresponding to a baryon mass density $\Omega_{\rm B} h^2 = 0.0212 \pm 0.0010$.

For η_{10}(SBBN), the SBBN-predicted abundances of the remaining light nuclides are

$$y_{3\rm P} \equiv 10^5(^3\mathrm{He/H})_{\rm P} = 1.07 \pm 0.04, \tag{2.3}$$

$$\mathrm{Y_P} = 0.2482 \pm 0.0007, \tag{2.4}$$

$$[\mathrm{Li}]_{\rm P} \equiv 12 + \log(\mathrm{Li/H})_{\rm P} = 2.67^{+0.06}_{-0.07}. \tag{2.5}$$

2.1. *Consistency of SBBN?*

Having used the deuterium observations along with the predictions of SBBN to determine the baryon density parameter, we may now ask if the observed abundances of ^{3}He, ^{4}He, and ^{7}Li are consistent with their SBBN-predicted primordial values.

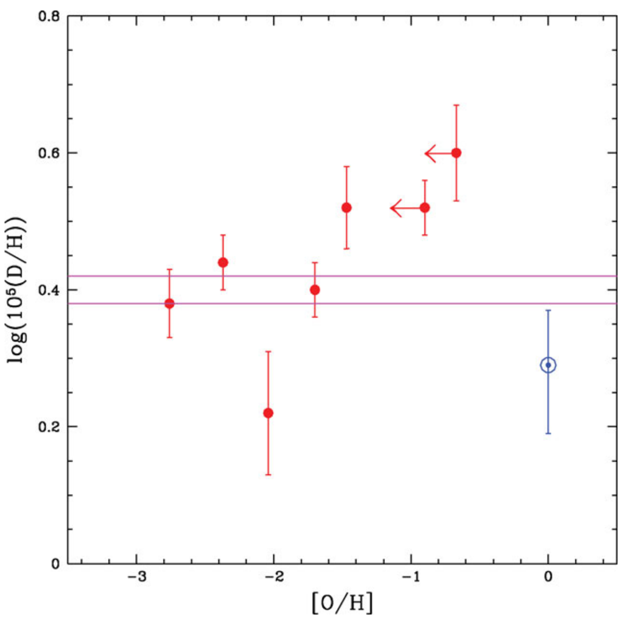

Figure 1. The logs of the deuterium abundances, $y_{\rm D} \equiv 10^5$(D/H), observed in high-z, low-Z QSO Absorption Line Systems (Pettini *et al.* 2008), as a function of the corresponding oxygen abundances. For comparison, the solar deuterium and oxygen abundances are shown (Geiss & Gloeckler 1998). The band indicated by the solid lines is the 68% range of the SBBN-predicted primordial D abundance using the CMB-determined baryon density parameter (see §3).

https://doi.org/10.1017/S1743921310003819 Published online by Cambridge University Press

Helium - 3.

The post-BBN evolution of ^{3}He is model dependent and, considerably more complicated than that of D. Overall, the ^{3}He abundance is expected to increase during Galactic chemical evolution (see, *e.g.*, Rood 1972, Rood, Steigman & Tinsey 1976). Observations of ^{3}He are limited to the relatively evolved H II regions in the Galaxy (Bania, Rood, & Balser 2002). The data are shown in Figure 2, where the observed ^{3}He abundances are plotted versus the corresponding H II region oxygen abundances. The data reveal a *minimum* (primordial?) ^{3}He abundance which is consistent with the SBBN prediction. While the higher observed abundances support the expectation of net post-BBN production of ^{3}He, the absence of a correlation with the oxygen abundances is puzzling.

Helium - 4.

The primordial abundance (mass fraction) of ^{4}He is inferred from observations helium and hydrogen recombination lines from metal-poor, extragalactic H II regions (Blue Compact Galaxies: BCDs). In using these data to determine the primordial helium abundance, the systematic errors (underlying stellar absorption, temperature and density inhomogeneities, ionization corrections, atomic emissivities, etc.) dominate over the statistical errors and the uncertain extrapolation to zero metallicity. In my opinion, the uncertainty in $\mathrm{Y_P}$ is $sigma(\mathrm{Y_P}) \approx 0.006$ and **not** $\sigma(\mathrm{Y_P}) < 0.001$, as claimed in some published papers. Therefore, rather than show the helium abundances inferred from observations of hundreds of BCDs, in Figure 3 are shown the handful of helium abundances determined from careful observations of a few H II regions where attention has been paid to some but, even here, not all, sources of systematic uncertainties (Olive & Skillman 2004, Peimbert, Luridiana & Peimbert 2007). The seven Olive & Skillman (2004) H II regions are

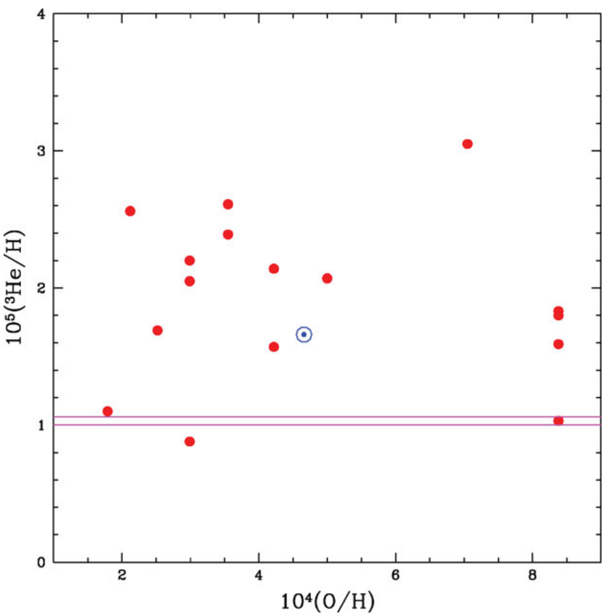

Figure 2. The ^{3}He abundances, $y_3 \equiv 10^5\,(^3\mathrm{He/H})$, observed in Galactic H IIregions from Bania, Rood, & Balser (2002) are shown as a function of the corresponding oxygen abundances. For comparison, the solar helium-3 and oxygen abundances are shown. The band indicated by the solid lines is the 68% range of the SBBN prediction for the primordial ^{3}He abundance using the CMB-determined baryon density parameter (see §3).

https://doi.org/10.1017/S1743921310003819 Published online by Cambridge University Press

consistent with **no** correlation between the helium and oxygen abundances, leading to a weighted mean, $Y_{OS} = 0.2500 \pm 0.0030$. The same is true for the five H II regions studied by Peimbert, Luridiana, & Peimbert (2007), with $Y_{PLP} = 0.2517 \pm 0.0043$, where the PLP statistical and systematic errors have been added linearly. The independent analyses of OS and PLP agree. The surprising absence of evidence for statistically significant slopes in their Y versus O/H relations prevents an extrapolation to zero metallicity in order to find Y_P. However, the weighted means do provide *upper bounds* to Y_P: $Y_P < \langle Y \rangle$. As may be seen by comparison with eq. 2.4, these data are consistent with the SBBN prediction.

Lithium - 7.

Like deuterium, lithium (^{6}Li and ^{7}Li) is fragile. In contrast to deuterium, post-BBN lithium is produced via Cosmic Ray Nucleosynthesis and by some stars (see these Proceedings). This is confirmed by Galactic observations of lithium as a function of metallicity. It is therefore expected that in the limit of low metallicity the lithium abundance should approach a plateau, the "Spite Plateau". However, while the primordial abundances of ^{3}He and ^{4}He inferred from the observational data are consistent with the SBBN predicted abundances based on the deuterium abundance, ^{7}Li poses a severe problem. As may be seen from Figure 4, the lithium abundances derived from observations of the most metal-poor halo and globular cluster stars in the Galaxy lie well below the SBBN-predicted value (see eq. 2.5). The discrepancy between the prediction and the observations is a factor of $\sim 3 - 5$. In addition, at the lowest iron abundances, the lithium

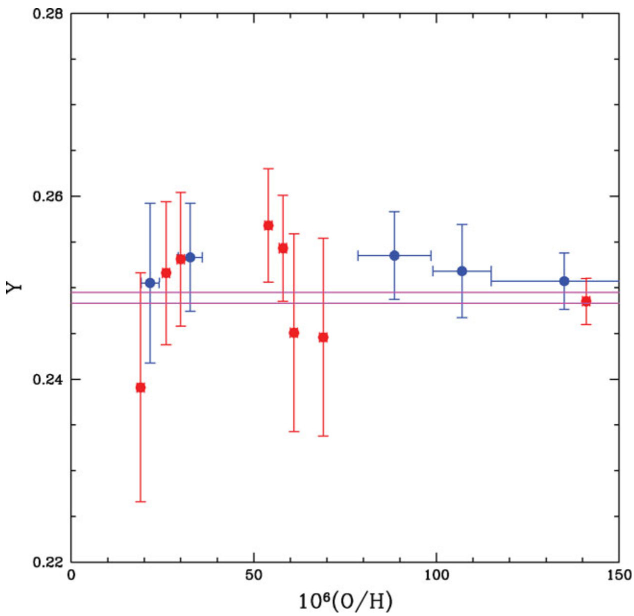

Figure 3. The ^{4}He mass fractions, Y, derived from a selected sample (see the text) of low metallicity, extragalactic H II regions, as a function of the corresponding H II region oxygen abundances. The blue filled circles are from Peimbert, Luridiana, & Peimbert (2007) and the red filled squares are from Olive & Skillman (2004). The band indicated by the solid lines is the 68% range of the SBBN prediction for the primordial ^{4}He mass fraction using the CMB-determined baryon density parameter (see §3).

abundances appear to be decreasing with metallicity. Where is the Spite Plateau? What is the value of $[\mathrm{Li}]_\mathrm{P}$?

Thus, although the predictions and observations of D, ^{3}He, and ^{4}He are consistent with SBBN, lithium is a problem. Setting lithium aside, we may ask if SBBN is consistent with the CMB?

3. SBBN with the CMB-inferred baryon density parameter

The CMB temperature anisotropy spectrum depends on the baryon density parameter η_B (see the contribution by Dunkley). From the WMAP data Dunkley *et al.* (2009) find $\Omega_\mathrm{B} h^2 = 0.02273 \pm 0.00062$, which corresponds to (Steigman 2006)

$$\eta_{10}(\mathrm{CMB}) = 6.226 \pm 0.170. \tag{3.1}$$

The baryon density parameters inferred from deuterium and SBBN, when the Universe was ~ 20 minutes old, and from the CMB, last scattered some 400 thousand years later, agree within $\sim 1.5\sigma$ (the glass is half full). SBBN and the CMB are consistent (modulo the lithium problem).

It is interesting to check the consistency of SBBN and the CMB by comparing the SBBN-predicted primordial light nuclide abundances determined using the CMB value of baryon density parameter to the observations. These comparisons are shown by the

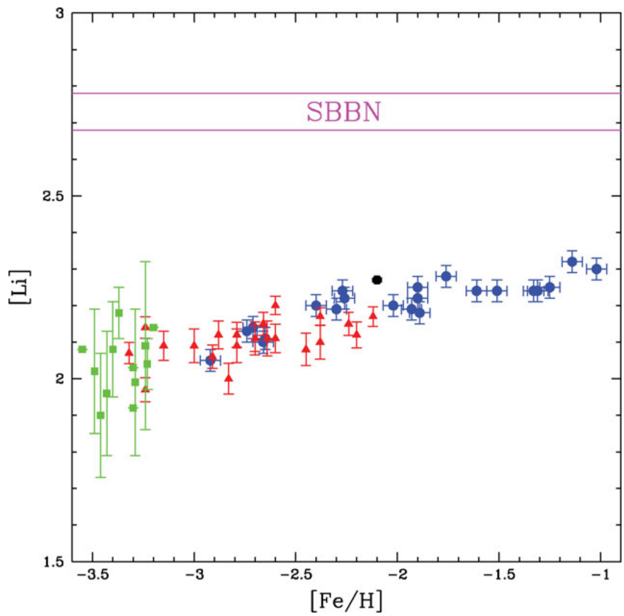

Figure 4. The lithium abundances, $[\mathrm{Li}] \equiv 12+\log(\mathrm{Li/H})$, derived from observations of low metallicity Galactic halo and globular cluster stars as a function of the iron abundance (relative to solar). Blue filled circles (Asplund *et al.* 2006), red, filled triangles (Boesgard *et al.* 2005), green filled squares (Aoki *et al.* 2009). The black filled circle (Lind *et al.* 2009) is for the globular cluster NGC6397. The band indicated by the solid lines is the 68% range of the SBBN prediction for the primordial ^{7}Li abundance using the CMB-determined baryon density parameter (see §3).

horizontal bands in Figures 1-4. For SBBN with $\eta_{\rm B}$(CMB),

$$\log(y_{\rm DP}) = 0.40 \pm 0.02 \quad (y_{\rm DP} = 2.52 \pm 0.13), \tag{3.2}$$

$$y_{\rm 3P} = 1.03 \pm 0.03, \tag{3.3}$$

$$Y_{\rm P} = 0.2489 \pm 0.0006, \tag{3.4}$$

$$[\rm Li]_{\rm P} = 2.74 \pm 0.05. \tag{3.5}$$

The SBBN/CMB-predicted abundances of D, ^{3}He, and ^{4}He are consistent with their observationally-inferred primordial values, but the lithium discrepancy is exacerbated. SBBN ($N_\nu = 3$) and the CMB are consistent (but lithium is a problem!).

4. Non-Standard Big Bang Nucleosynthesis (nSBBN): $N_\nu \neq 3$

For non-standard BBN (nSBBN) with $N_\nu \neq 3$, the relic abundances of the light nuclides are functions of two parameters, $\eta_{\rm B}$ and N_ν. First, consider deuterium. The nSBBN primordial abundance is predicted to vary as $y_{\rm DP} \propto \eta_{\rm D}^{-1.6}$, where $\eta_{\rm D} = \eta_{\rm D}(\eta_{10}, N_\nu)$ (see, *e.g.*, Kneller & Steigman 2004, Steigman 2007). It is interesting to explore the consequences of using the CMB (Dunkley *et al.* 2009) to fix η_{10} and the observed primordial D abundance to determine $\eta_{\rm D}$. This leads to a combined BBN and CMB prediction for N_ν. For $\log(y_{\rm D}) = 0.45 \pm 0.03$ and $\eta_{10}({\rm CMB}) = 6.23 \pm 0.17$, $N_\nu = 4.0 \pm 0.7$. Here, the relative insensitivity of $y_{\rm DP}$ to N_ν has amplified the small difference between η_{10} and $\eta_{\rm D}$ into a relatively large value (and uncertainty) of $\Delta N_\nu = 1.0 \pm 0.7$. Although the central value of the effective number of neutrinos determined this way is $N_\nu \neq 3$, this result is consistent with $N_\nu = 3$ at $\sim 1.4\sigma$. Using this value of N_ν along with η_{10}(CMB), how do the predicted BBN abundances of the remaining light nuclides compare with their observationally inferred primordial values? Here, I concentrate on the two key elements, ^{4}He and ^{7}Li (by construction, D is de facto consistent).

For this combination of η_{10} and N_ν, the primordial ^{4}He mass fraction is $Y_{\rm P} = 0.261 \pm 0.009$. Here, the sensitivity of $Y_{\rm P}$ to N_ν has amplified the small difference between η_{10} and $\eta_{\rm D}$ into a relatively large value (and uncertainty) of $Y_{\rm P}$. As may be seen from Figure 3, within the large uncertainty of this prediction, the very high central value is consistent with the data.

The BBN-predicted abundances of D and ^{7}Li are very tightly correlated, both for $N_\nu = 3$ and $N_\nu \neq 3$ (Kneller & Steigman 2004, Steigman 2007). As a result, even for this example of nSBBN, the predicted primordial lithium abundance is very similar to its SBBN value, $[\rm Li]_{\rm P} = 2.70^{+0.05}_{-0.06}$, in conflict with the observational data in Figure 4.

Thus, although this variant of nSBBN is consistent with D, ^{3}He, and ^{4}He, the lithium problem persists! Nonetheless, this example illustrates the potential value of combining BBN and the CMB to constrain and test non-standard models of particle physics and cosmology. A slightly different variant of this approach is presented in the next section.

5. Using ^{4}He and the CMB to constrain N_ν

Of the light nuclides synthesized during BBN, the ^{4}He mass fraction is most sensitive to non-standard physics ($N_\nu \neq 3$). Indeed, for $|\Delta N_\nu| \lesssim 1$, $\Delta Y_{\rm P} \approx 0.013\Delta N_\nu$, so that a good bound (small uncertainty) to $Y_{\rm P}$ would result in a tight constraint on N_ν. According to Kneller & Steigman (2004) and Steigman (2007), using η_{10}(CMB)$= 6.23 \pm 0.17$, a very good fit to $Y_{\rm P}$, is

$$Y_{\rm P} \approx 0.2486 \pm 0.0007 + 0.013\Delta N_\nu. \tag{5.1}$$

As mentioned earlier, the present uncertainty in the observationally inferred value of Y_P is dominated by systematic errors. To illustrate the potential value of an accurate determination of Y_P, let's adopt the weighted mean of the Olive & Skillman (2004) helium abundances as an *upper bound* to the primordial ^{4}He mass fraction: $Y_P < \langle Y \rangle_{OS} = 0.2500 \pm 0.0030$. Comparing this BBN prediction of Y_P with the upper bound inferred from the data leads to an *upper bound* on the effective number of neutrinos,

$$\Delta N_\nu < 0.11 \pm 0.24 \ \ (N_\nu < 3.11 \pm 0.24). \tag{5.2}$$

If, instead, we had adopted the weighted mean of the Peimbert, Luridiana, & Peimbert (2007) helium abundances, we would have found $\Delta N_\nu < 0.24 \pm 0.33$ ($N_\nu = 3.24 \pm 0.33$). Just a few good H II region ^{4}He abundances are all that is needed to obtain a very strong constraint on N_ν. For these combinations of η_{10}(CMB) and N_ν, the bounds to the D and ^{3}He abundances are consistent with the data, while lithium remains a problem.

6. Challenges

In answer to the first question posed in §1, yes, SBBN ($N_\nu = 3$) is consistent with the observationally-inferred primordial abundances of D, ^{3}He, and ^{4}He, but ^{7}Li poses a problem. The answer to the second question posed in §1 is also yes, the CMB and the BBN values of η_B and S agree. SBBN and the CMB in combination allow, but also constrain, some models of non-standard physics. The challenges facing BBN, largely observational, makes the timing of this meeting ideal. Having had the luxury of being one of the first speakers, I will end by presenting my list of challenges to those who follow.

1. Why is the spread in the observed deuterium abundances so large?
2. Why are the observed ^{3}He abundances uncorrelated with either the oxygen abundances or with the distance from the center of the Galaxy?
3. What are the sources (and the magnitudes) of the systematic errors in Y_P and, are there observing strategies to reduce them?
4. What is the primordial abundance of ^{7}Li (and of ^{6}Li)?

References

Aoki, W. *et al.* 2009, *ApJ*, 698, 1803.
Asplund, M. *et al.* 2006, *ApJ*, 644, 229.
Bania, T. M., Rood, R. T., & Balser, D. S. 2002, *Nature*, 415, 54.
Boesgaard, A. M., Stephens, A., & Deliyannis, C. P. 2005, *ApJ*, 633, 398.
Dunkley, J. *et al.* 2009, *ApJS*, 180, 306.
Epstein, R. I., Lattimer, J. M., & Schramm, D. N. 1976, *Nature*, 265, 219.
Geiss, J. & Gloeckler, J. G. 1998, *Space Sci. Rev.* 84, 239.
Kneller, J. P. & Steigman, G. 2004, *New J. Phys.*, 6, 117.
Lind, K. *et al.* 2009, *A&A*, 503, 545.
Olive, K. A. & Skillman, E. D. 2004, *ApJ*, 617, 29
Peimbert, M., Luridiana, V., & Peimbert, A. 2007, *ApJ*, 666, 634
Pettini, M., Zych, B. J., Murphy, M. T., Lewis, A., & Steidel, C. C. 2008, *MNRAS*, 391, 1499.
Reeves, H., Audouze, J., Fowler, W. A., & Schramm, D. N. 1973, *ApJ*, 179, 909.
Rood, R. T. 1972, *ApJ*, 177, 681.
Rood, R. T., Steigman, G., & Tinsley, B. M. 1976, *ApJL*, 207, L57.
Steigman, G. 2006, *JCAP*, 10, 016.
Steigman, G. 2007, *Ann. Rev. Nucl. Part. Sci.*, 57, 463.

https://doi.org/10.1017/S1743921310003819 Published online by Cambridge University Press