BBN And The CBR Probe The Early Universe

Gary Steigman

Departments of Physics and Astronomy, The Ohio State University, 191 West Woodruff Avenue, Columbus, OH 43210, USA

Abstract. Big Bang Nucleosynthesis (BBN) and the Cosmic Background Radiation (CBR) provide complementary probes of the early evolution of the Universe and of its particle content. Neutrinos play important roles in both cases, influencing the primordial abundances of the nuclides produced by BBN during the first 20 minutes as well as the spectrum of temperature fluctuations imprinted on the CBR when the Universe is some 400 thousand years old. The physical effects relevant at these widely separated epochs are reviewed and the theoretical predictions are compared with observational data to explore the consistency of the standard models of cosmology and particle physics and to constrain beyond-the-standard-model physics and cosmology.

Keywords: Big Bang Nucleosynthesis, Cosmic Background Radiation, Neutrinos

PACS: 26.35.+c, 95.30.Cq, 98.80.Ft

INTRODUCTION

The Universe is expanding and is filled with radiation. All wavelengths, of photons as well as the deBroglie wavelengths of freely expanding massive particles, are stretched along with this expansion. As a result, during its earlier evolution the Universe was hot and dense. The combination of high temperature and density ensures that collision rates are very high during early epochs, guaranteeing that all particles, with the possible exception of those with only gravitational strength interactions, were in equilibrium at sufficiently early times. As the Universe expands and cools, interaction rates decline and, depending on the strength of their interactions, different particles depart from equilibrium at different epochs. For the standard, “active” neutrinos ($\nu_e$, $\nu_\mu$, $\nu_\tau$) departure from equilibrium occurs when the Universe is only a few tenths of a second old and the temperature of the CBR photons, $e^\pm$ pairs, and the neutrinos is a few MeV.

It should be emphasized that departure from equilibrium is not sharp and collisions continue to occur. For $T < 2\times 3$ MeV, the neutrino interaction rates become slower than the universal expansion rate (as measured by the Hubble parameter $H$), effectively decoupling the neutrinos from the CBR photons and $e^\pm$ pairs present at that time. However, electron neutrinos (and antineutrinos) continue to interact with the baryons (nucleons) via the charged-current, weak interactions until the Universe is a few seconds old and the temperature has dropped below an MeV. Once again, this decoupling is not abrupt (the neutrinos do not “freeze-out”). Two body reactions among neutrons, protons, $e^-$ and $\nu_e$($\bar{\nu}_e$) continue to influence the ratio of neutrons to protons, albeit not rapidly enough to allow the n/p ratio to track its equilibrium value of $n/p = \exp (\Delta m/T)$, where $\Delta m = m_n - m_p = 1.29$ MeV. As a result, the n/p ratio decreases from 1=6 at “freeze-out” to 1=7 when BBN begins at 200 sec ($T \approx 80$ keV). Since the neutrinos are extremely relativistic during these epochs, they can influence BBN in several ways. The
universal expansion rate in the standard cosmology is determined through the Friedman equation by the total energy density which is dominated during these early epochs by massless particles along with those massive particles which are extremely relativistic at these epochs: CBR photons, $e^-$ pairs, neutrinos. The early Universe is “radiation” dominated and neutrinos constitute a significant component of the “radiation”. In addition, through their charged-current weak interactions the electron-type neutrinos help to control the neutron-to-proton ratio, effectively limiting the primordial abundance of $^4\text{He}$.

Although $e^-$ pairs annihilated during the first few seconds, the surviving electrons, equal in number to the protons to ensure charge neutrality, are coupled to the CBR photons via Compton scattering. Only after the electrons and nuclides (mainly protons and alphas) combine to form neutral atoms (“recombination”) are the CBR photons released from the grasp of the electrons to propagate freely. This occurs when the Universe is some 400 thousand years old and the relic photons, redshifted to the currently observed black body radiation at $T = 2.725\text{K}$, provide us a snapshot of the universe at this early epoch. At this relatively late stage (compared to BBN) in the early evolution of the Universe, the key role of the freely propagating, relativistic neutrinos is their contribution to the total radiation density, which determines the universal expansion rate (e.g., the time – temperature relation). It should be noted that if the neutrino masses are sufficiently large the neutrinos will have become nonrelativistic and their free-streaming has the potential to damp density fluctuations in the baryon fluid. This important topic is not addressed here.

The primordial abundances of the relic nuclei produced during BBN depend on the baryon (nucleon) density and on the early-Universe expansion rate. The amplitudes and angular distribution of the CBR temperature fluctuations depend on these same parameters (as well as several others). The universal abundance of baryons may be quantified by comparing the number of baryons (nucleons) to the number of CBR photons,

$$\eta_{10} = 10^{10} \frac{n_B}{n_\gamma} :$$

As the Universe expands the densities of baryons and photons both decrease but the numbers of baryons and of CBR photons in a comoving volume are unchanged (post- $e^-$ annihilation) so that $\eta_{10}$ measured at present, at recombination, and at BBN should all be the same. This is one of the key cosmological tests. Since the baryon mass density ($\rho_B = \Omega_B \rho_c$, where $\rho_c = 3H_0^2=8\pi G$ is the present critical mass density) plays a direct role in the growth of perturbations, it is convenient to quantify the baryon abundance using a combination of $\Omega_B$ and $h$, the present value of the Hubble parameter ($H_0$) measured in units of 100 kms $^{-1}$Mpc $^{-1}$,

$$\eta_{10} = 274 \frac{\omega_B}{h^2} :$$

The Hubble parameter, $H = H(t)$, measures the expansion rate of the Universe. Deviations from the standard model ($\Delta H \neq 0$) may be parameterized by an expansion rate parameter $S \equiv \frac{H}{H_0}$. Since $H$ is determined in the standard model by the energy density in relativistic particles, deviations from the standard cosmology ($S \neq 1$) may also be quantified by the “equivalent number of neutrinos” $\Delta N_{\nu} \equiv N_{\nu} - 3$. Prior to $e^-$ annihilation,
these two parameters are related by

\[ S = (1 + 7 \Delta N_\nu = 43)^{1/2} : \]

(3)

\( \Delta N_\nu \) is an equivalent and convenient way to quantify any deviation from the standard model expansion rate (\( S \)); it is not necessarily related to extra (or fewer!) neutrinos.

The question considered here is, “Are the predictions and observations of the baryon density and the expansion rate of the Universe at 20 minutes (BBN) and 400 thousand years (CBR) in agreement with each other and with the standard models of cosmology and particle physics?”. If yes, what constraints are there on models of beyond-the-standard-model physics and/or cosmology? The current status of this quest is summarized here. For more detail and further references, see my recent review article [1].

THE UNIVERSE AT 20 MINUTES: BBN

Nuclear reactions among nucleons occur rapidly during the early evolution of the Universe but they fail to produce significant abundances of complex nuclides because of their competition with photo-destruction reactions involving the enormously more abundant CBR photons. When the Universe cools sufficiently (\( T < 80 \text{ keV}, \ t > 3 \text{ minutes} \)), reducing the number of photons capable of photo-destruction, BBN begins in earnest and the available neutrons are consumed very quickly to build \( ^4\text{He} \). All further nucleosynthesis among electrically charged nuclides (H, D, T, \( ^3\text{He}, ^4\text{He} \)) involves reactions which become Coulomb-suppressed as the Universe expands and cools. As a result BBN terminates when \( T < 30 \text{ keV} (t > 25 \text{ min}) \). In the first 20 minutes of its evolution the cosmic nuclear reactor produces (in astrophysically interesting abundances) deuterium, helium-3 (any tritium decays to \( ^3\text{He} \)), helium-4 and, because of the gaps at mass-5 and mass-8, only a tiny amount of lithium-7 (produced mainly as beryllium-7 which, later in the evolution captures an electron and decays to \( ^7\text{Li} \)).

The BBN-predicted abundances of D, \( ^3\text{He} \), and \( ^7\text{Li} \) are determined by the competition between production and destruction rates which depend on the overall density of baryons. As a result these nuclides are all potential baryometers. Among them, D is the baryometer of choice since its post-BBN evolution is simple (when gas is incorporated into stars D is only destroyed, burned to \( ^3\text{He} \) and beyond) and the BBN-predicted primordial D abundance is a relatively sensitive function of the baryon density (\( \text{D/H} \propto \eta_{10}^{1/6} \)). In contrast, the primordial abundance of \( ^4\text{He} \) is relatively insensitive to the baryon density, controlled mainly by the abundance of neutrons when BBN begins. The \( ^4\text{He} \) relic abundance is usually expressed as a “mass fraction” \( Y_P = 4y = (1 + 4y) \), where \( y = \frac{n_{^4\text{He}}}{n_{^4\text{H}}} \) (since this assumes \( m_{^4\text{He}} = m_{^4\text{H}} = 4 \)), \( Y_P \) is not the true helium mass fraction. Since the expansion rate (\( S \)), in combination with the rate of the charged-current weak interactions, plays an important role in regulating the pre-BBN neutron to proton ratio, \( Y_P \) is sensitive to \( S \). As shown by the D and \( ^4\text{He} \) isoabundance curves in Figure 1, deuterium and helium-4 provide complementary probes of the universal baryon density and expansion rate parameters.

For restricted but interestingly large ranges of \( \eta_{10}(\omega_B) \), \( \Delta N_\nu(S) \), Kneller and Steigman [2] found simple but accurate analytic fits to the BBN-predicted abun-
dances of the light nuclides as functions of $S$ and $\eta_{10}$. For D ($y_D = 10^5(D/H)$) and $^4$He ($Y_P$), these are

$$y_D = 46.5(1.03)\eta_D^{1/6}; \quad Y_P = 0.2384 \pm 0.0006 + \eta_{He}=625;$$

(4)

where

$$\eta_D \eta_{10} 6 (S - 1); \quad \eta_{He} \eta_{10} + 100 (S - 1);$$

(5)

**Observed Relic Abundances**

Observations of deuterium in the solar system and the interstellar medium (ISM) of the Galaxy provide interesting lower bounds to its primordial abundance but it is the handful of observations of D in high redshift, low metallicity, QSO absorption line systems (QSOALS) which are of most value in providing estimates of the primordial D abundance. The identical absorption spectra of D I and H I (modulo the velocity/wavelength shift resulting from the heavier reduced mass of the deuterium atom) is a liability, limiting the number of useful targets in the vast Lyman-alpha forest of QSO absorption spectra (see, e.g., Kirkman et al. [3] for further discussion). Until recently there were only five QSOALS with deuterium detections leading to reasonably reliable abundance determinations [3] (and references therein); these, along with a very recent sixth determination by O’Meara et al. [4], are shown in Figure 2. Also shown there for comparison are the solar system (pre-solar nebula) and ISM D abundances. Clearly there is
excessive dispersion among the low metallicity D abundance determinations, suggesting that systematic errors, whose magnitudes are hard to estimate, may have contaminated the determinations of at least some of the D\textsubscript{I} and/or H\textsubscript{I} column densities. This dispersion serves to mask the anticipated primordial deuterium plateau. The best that can be done with the present data is to identify the relic deuterium abundance with the weighted mean of the high-\(z\), low-Z D/H ratios: \(y_{D} = 2.68^{+0.27}_{-0.25}\), corresponding to \(\eta_{D} = 5.95^{+0.36}_{-0.39}\) (see eq. 4).

*FIGURE 2.* Observationally inferred deuterium abundances versus metallicity for six high redshift, low metallicity QSOALS (filled circles). Also shown are the abundances derived for the pre-solar nebula (Sun) and for the local interstellar medium (ISM).

The post-BBN evolution of \(^4\text{He}\) is also quite simple (monotonic). As gas cycles through generations of stars, hydrogen is burned to helium-4 (and beyond), increasing the \(^4\text{He}\) abundance above its primordial value. As a result, the present \(^4\text{He}\) mass fraction, \(Y_{0}\), has received a significant contribution from post-BBN, stellar nucleosynthesis, and \(Y_{0} > Y_{P}\). However, since the “metals” such as oxygen are produced by short-lived, massive stars and \(^4\text{He}\) is synthesized (to a greater or lesser extent) by stars of all masses, at very low metallicity the increase in \(Y\) should lag that in, e.g., O/H, so that as O/H \(\leq Y_{0} > Y_{P}\). Therefore, although \(^4\text{He}\) is observed in the SuFieldsn and in Galactic H\textsubscript{II} regions where the metallicity is relatively high, the crucial data for inferring its primordial abundance are provided by observations of helium and hydrogen emission (recombination) lines from low-metallicity, extragalactic H\textsubscript{II} regions. The present inventory of such regions studied for their helium content exceeds 80 (see Izotov & Thuan (IT) [5]). Since for such a large data set even modest observational errors for the individual H\textsubscript{II} regions can lead to an inferred primordial abundance whose *formal* statistical uncertainty is very small, special care must be taken to include hitherto ignored systematic corrections and/or errors. It is the general consensus that the present uncertainty in \(Y_{P}\) is dominated by the latter, rather than by the former.
Comparison Between Predicted And Observed Relic Abundances

The relic abundances adopted here correspond to $\eta_D = 5.95^{+0.36}_{-0.39}$ and $\eta_{He} = 0.25 \pm 0.05$, corresponding to $S = 0.94^{+0.01}_{-0.02}$, $S = 2.30^{+0.35}_{-0.34}$, and $\eta_{10} = 5.60^{+0.38}_{-0.41}$ ($\Omega_B h^2 = 0.020^{+0.014}_{-0.015}$). This is consistent with the standard model ($S = 1$, $N_{\nu} = 3$, at $2\sigma$. 

FIGURE 3. The OS-derived $^4$He versus oxygen abundances for 7 low metallicity H II regions from IT and one higher metallicity H II region from Peimbert et al. (filled circles). The horizontal line shows the weighted mean of the 8 helium abundances.
(see Figure 4). The confrontation of the BBN predictions with the relic abundance observations of D and $^{4}\text{He}$ reveals internal consistency (at $< 2\sigma$) of the standard models of particle physics ($N_\nu = 3$) and cosmology ($S = 1$) and it fixes the baryon abundance to an accuracy of $\pm 7\%$ during the first few minutes of the evolution of the Universe. At the same time this comparison sets constraints on possible deviations from these standard models (e.g., $N_\nu \neq 4$). How do these BBN results compare with what the CBR reveals about the Universe some 400 thousand years later?

**CONFRONTATION WITH THE CBR**

The angular spectrum of CBR temperature fluctuations depends on several key cosmological parameters, including the baryon density and the relativistic energy density (for further discussion and references, see Hu and Dodelson 2002 [10] and Barger *et al.* 2003 [11]), thereby providing a probe of $\eta_{10}$ and $N_\nu$ some 400 kyr after BBN. With $N_\nu$ allowed to depart from the standard model value, Barger *et al.* [11] found the first year WMAP data [12] is best fit by $\Omega_B h^2 = 0.0230$ and $N_\nu = 2.75$, in excellent agreement with the purely BBN results above. In fact, the CBR is a much better baryometer than it is a chronometer, so that while the $2\sigma$ range for the baryon density is limited to $0.0204 \leq \Omega_B h^2 \leq 0.0265$, the corresponding $2\sigma$ range for $N_\nu$ was found to be $0.9 \leq N_\nu \leq 8.3$ [11].

Quite recently the WMAP team released (and analyzed) their 3-year data. For $N_\nu = 3$, Spergel *et al.* 2006 [13] find $\Omega_B h^2 = 0.0223^{+0.0007}_{-0.0009}$. With $N_\nu$ free to vary, V. Simha
and the current author, in preliminary work in progress, find a similar result for the baryon density (not unexpected since in fitting to the CBR data the contributions from the baryon density and the relativistic energy density (or, $S$) are largely uncorrelated),

$$\Omega_B h^2 = 0.0222 \pm 0.0007,$$

along with a 2σ range for $N_\nu$ ($0.7 < N_\nu < 6.0$) which is somewhat smaller than the previous WMAP-based result [11]. However, this result is preliminary and should be regarded with a very large grain of salt (caveat emptor!).

**SUMMARY**

Comparison between the BBN predictions and relic abundance observations of deuterium and helium-4 reveals consistency with the standard models of particle physics and cosmology and constrains the value of the baryon abundance during the first few minutes of the evolution of the Universe. This comparison also enables quantitative constraints on possible deviations from these standard models, particularly in the neutrino sector. Some 400 thousand years later, when the CBR photons are set free, the angular spectrum of temperature fluctuations encodes information about several key cosmological parameters, including $N_\nu$ and $\Omega_B h^2$. The present data reveal consistency (at 2σ) between the values of $\Omega_B h^2$ and $N_\nu$ inferred from the first few minutes of the evolution of the Universe and from a snapshot of the Universe some 400 kyr later. While there is still room for surprises, at present the standard models appear robust.

**ACKNOWLEDGMENTS**

The author’s research is supported at The Ohio State University by a grant (DE-FG02-91ER40690) from the US Department of Energy.

**REFERENCES**

1. G. Steigman, *Int. J. Mod. Phys.* E 15, 1 (2006).
2. J. P. Kneller and G. Steigman, *New J. Phys.* 6, 117 (2004).
3. D. Kirkman, D. Tytler, N. Suzuki, J. O’Meara and D. Lubin, *ApJS* 149, 1 (2003).
4. J. M. O’Meara, S. Burles, J. X. Prochaska, G. E. Frochter, R. A. Bernstein and K. M. Burgess, (2006).
5. I. T. Izotov and T. X. Thuan, *ApJ* 500, 188 (1998); I. T. Izotov and T. X. Thuan, *ApJ* 602, 200 (2004).
6. K. A. Olive, G. Steigman and T. P. Walker, *Phys. Rep.* 333-334, 389 (2000).
7. B. D. Fields and K. A. Olive, *ApJ* 506, 177 (1998).
8. K. A. Olive and E. D. Skillman, *New Astron.* 6, 119 (2001); K. A. Olive and E. D. Skillman, *ApJ* 617, 29 (2004).
9. M. Peimbert, A. Peimbert and M. T. Ruiz, *ApJ* 541, 688 (2000); A. Peimbert, M. Peimbert and V. Luridiana, *ApJ* 565, 668 (2002).
10. W. Hu W and S. Dodelson, *Ann. Rev. Astron. & Astrophys.* 40, 171 (2002)
11. V. Barger, J. P. Kneller, H-S Lee, D. Marfatia and G. Steigman, *Phys. Lett. B* 569, 123 (2003).
12. D. N. Spergel et al., *ApJ Suppl.* 148, 175 (2003).
13. D. N. Spergel et al., *astro-ph/0603449* (2006); U. Seljak, A. Slosar and P. McDonald, *astro-ph/0604335* (2006).