RevMexAA (Serie de Conferencias), **12**, 265–271 (2002)

CMB (AND OTHER) CHALLENGES TO BBN

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RESUMEN

La nucleosíntesis primordial proporciona una medida de la abundancia universal de bariones cuando el Universo tenía sólo unos minutos de edad. Las observaciones recientes de la anisotropía en el fondo cósmico de radiación de microondas (CMB) dan una medida de la abundancia de bariones cuando el Universo tenía varios cientos de miles de años de edad. Las observaciones de supernovas tipo Ia y de cúmulos de galaxias en el pasado muy reciente, cuando el Universo tiene una edad de varios miles de millones de años y mayor, proporcionan una medida complementaria de la densidad de bariones en excelente concordancia con los valores del Universo temprano. La concordancia general entre las tres mediciones representa una notable confirmación del modelo estándar de la cosmología. Sin embargo, hay indicaciones de que las observaciones CMB pueden estar en desacuerdo con aquellas de nucleosíntesis de la Gran Explosión (BBN). Si esta "tensión" persiste entre BBN y CMB, el modelo estándar de la cosmología pude requerir una modificación. Aquí, en una contribución dedicada a Silvia Torres-Peimbert y Manuel Peimbert, describimos cómo una asímetria entre neutrinos y antineutrinos (la "degeneración de neutrinos") tiene el potencial para resolver este *posible* conflicto entre BBN y CMB.

ABSTRACT

Primordial nucleosynthesis provides a probe of the universal abundance of baryons when the universe was only a few minutes old. Recent observations of anisotropy in the cosmic microwave background (CMB) probe the baryon abundance when the universe was several hundred thousand years old. Observations of type Ia supernovae and clusters of galaxies in the very recent past, when the universe is several billion years old and older, provide a complementary measure of the baryon density in excellent agreement with the early universe values. The general agreement among the three measurements represents an impressive confirmation of the standard model of cosmology. However, there is a hint that the CMB observations may not be in perfect agreement with those from big bang nucleosynthesis (BBN). If this "tension" between BBN and the CMB persists, the standard model of cosmology may need to be modified. Here, in a contribution dedicated to Silvia Torres-Peimbert and Manuel Peimbert, we describe how an asymmetry between neutrinos and antineutrinos ("neutrino degeneracy") has the potential for resolving this *possible* conflict between BBN and the CMB.

Key Words: **COSMIC MICROWAVE BACKGROUND — COSMOLOGICAL PARAMETERS — EARLY UNIVERSE**

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Editors: William Henney, José Franco, Marco Martos, & Miriam Peña

1. INTRODUCTION

Even though diamonds may not be forever, experimental constraints on proton stability are very strong ($\tau_{\rm N} > 10^{25}$ yr) and baryon (nucleon) number should be preserved during virtually the entire evolution of the universe. If so, then in the standard theories of particle physics and cosmology the baryon density at very early epochs is simply related to the baryon density throughout the later evolution of the universe. In particular, the nucleon-to-photon ratio ($\eta \equiv n_{\rm N}/n_\gamma$) during primordial nucleosynthesis when the universe is only minutes old should be identical to η measured when the universe is several hundred thousand years old and the cosmic microwave background (CMB) photons last scattered, as well as to η in the present universe billions of years after the "bang". Probing η at such widely separated epochs in the evolution of the universe is a key test of the consistency of the standard models of particle physics and cosmology.

The current status of this confrontation between theory and observations is reviewed here and our key results appear in Figure 1 where estimates of the universal baryon abundance at widely separated epochs are compared. In § 2 the predicted BBN abundance of deuterium is compared with the primordial value inferred from observational data to derive the early-universe value of η. After testing

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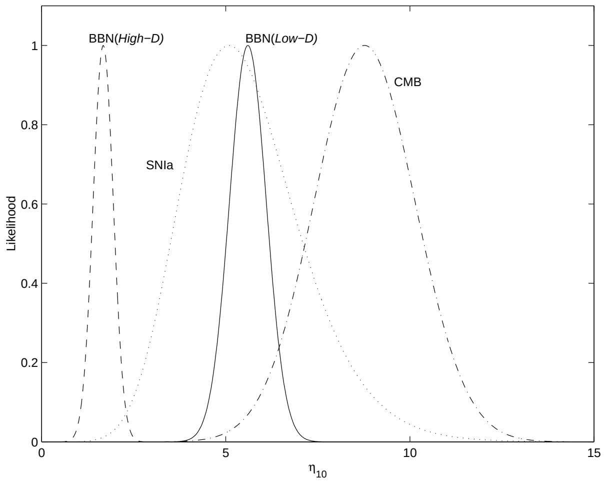

Fig. 1. The likelihood distributions, normalized to unit maximum, for the baryon-to-photon ratio $\eta_{10} = 274\Omega_{\rm B}h^2$. The solid curve is the early universe value for low-D BBN while the dashed curve is for high-D BBN; the dotted curve (SNIa) is the present universe estimate; the dot-dashed curve shows the CMB inferred range.

for the internal consistency of the standard model of Big Bang Nucleosynthesis (SBBN) by comparing the BBN-predicted and observed abundances of the other light elements (^{4}He, ^{7}Li), an independent estimate of η in the present (recent) universe is derived in § 3 utilizing observations of clusters of galaxies and of type Ia supernovae (SNIa). These *independent* estimates of η are compared to each other and, in § 4 to that from observations of the CMB anisotropy spectrum, a probe of η in the several hundred thousand year old universe. Having established that some "tension" exists between $\eta_{\rm BBN}$ and $\eta_{\rm CMB}$, in § 5 a modification of SBBN involving "degenerate" neutrinos is introduced and its consequences for the CMB anisotropies is explored. In § 6 we summarize our conclusions. The material presented here is extracted from our recent work (Steigman, Walker, & Zentner 2000; Kneller et al. 2001) where further details and more extensive references may be found.

An alternate measure of the baryon abundance is the baryon density parameter, $\Omega_{\rm B}$, the ratio of the baryon mass density to the critical mass density. In terms of the present value of the Hubble parameter h ($H_0 \equiv 100h$ km s^{-1} Mpc^{-1}), and for a present CMB temperature of 2.725 K (Mather et al. 1999), $\eta_{10} \equiv 10^{10}\eta = 274\Omega_{\rm B}h^2$.

2. THE EARLY UNIVERSE BARYON DENSITY

During its early evolution the universe is too hot to allow the presence of astrophysically interesting abundances of bound nuclei and primordial nucleosynthesis doesn't begin in earnest until the temperature drops below $\approx$ 80 keV, when the universe is a few minutes old (for a recent review and further references see Olive et al. 2000). Prior to this time neutrons and protons have been interconverting, at first rapidly, but more slowly after the first few seconds, driven by such "charged-current" weak interactions as: $p + e^- \longleftrightarrow n + \nu_e$, $n + e^+ \longleftrightarrow p + \bar{\nu}_e$, and $n \longleftrightarrow p + e^- + \bar{\nu}_e$ (β-decay). Once BBN begins neutrons and protons quickly combine to form deuterium which, in turn, is rapidly burned to ^{3}H, ^{3}He, and ^{4}He. There is a gap at mass-5 which, in the expanding, cooling universe, is difficult to bridge. As a result, most neutrons available when BBN began are incorporated in the most tightly bound light nuclide, ^{4}He. For this reason, the ^{4}He abundance (by mass, Y) is largely independent of the nuclear reaction rates but does depend on the neutron abundance at BBN which is determined by the competition between the weak interaction rates and the universal expansion rate (the early universe Hubble parameter, H). In contrast, the abundances of D and ^{3}He (^{3}H is unstable, decaying to ^{3}He) depend on the competition between the expansion rate and the nuclear reaction rates and, hence, on the baryon abundance η. As a result, while D (and to a lesser extent, ^{3}He) can provide a baryometer, ^{4}He offers a test of the internal consistency of SBBN. Although the gap at mass-5 is a barrier to the synthesis of heavier nuclides in the early universe, there is some production of mass-7 nuclei (^{7}Li and ^{7}Be), albeit at a much suppressed level. The second mass gap at mass-8 eliminates (within SBBN) the synthesis of any astrophysically interesting abundances of heavier nuclides. The abundance of lithium (after BBN, when the universe is sufficiently cool, ^{7}Be will capture an electron and decay to ^{7}Li) is rate driven and can serve as a complementary baryometer to deuterium.

SBBN is overdetermined in the sense that for one adjustable parameter η, the abundances of four light nuclides (D, ^{3}He, ^{4}He, ^{7}Li) are predicted. Here we concentrate on D and ^{4}He. Deuterium is an ideal baryometer candidate (Reeves et al. 1976) since it is only **destroyed** (by processing in stars) in the post-BBN universe (Epstein, Lattimer, & Schramm 1976). Deuterium is observed in absorption in the spectra of distant QSOs and its abundance in these high-redshift (relatively early in the star-forming history of the universe), low-metallicity (confirming that very little stellar processing has occurred) systems should represent the primordial value. For three, high-z, low-Z QSO absorption-line systems a

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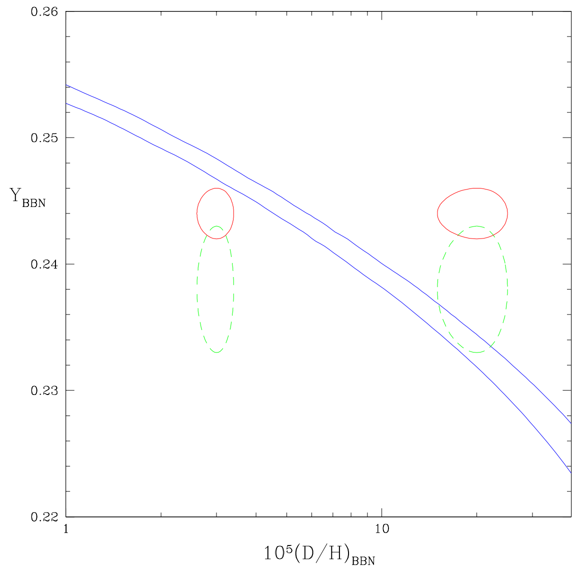

Fig. 2. Comparison of the SBBN-predicted relation between the primordial abundances of helium-4 (mass fraction, Y) and deuterium (ratio by number to hydrogen, D/H) and four sets of observationally inferred abundances. The SBBN prediction, including uncertainties, is shown by the solid band. The "low-D" deuterium abundance is from O'Meara et al. (2000); the "high-D" value is from Webb et al. (1997). The solid ellipses reflect the Izotov & Thuan (1998) helium abundance, while the dashed ellipses use the Olive, Steigman, & Walker (2000) value.

"low" value of the deuterium abundance is found (Burles & Tytler 1998a,b; O'Meara et al. 2001), from which O'Meara et al. (2001) derive: $\mathrm{D/H} = 3.0 \pm 0.4 \times 10^{-5}$. Given the steep dependence of $(\mathrm{D/H})_{\mathrm{BBN}}$ on η ($\propto \eta^{-1.6}$), this leads to a reasonably precise prediction for the baryon abundance at BBN: $\eta_{10} = 5.6 \pm 0.5$ ($\Omega_{\mathrm{B}} h^2 = 0.020 \pm 0.002$). The likelihood distribution for this BBN-determined baryon density is shown in Figure 1 by the curve labeled "BBN(Low-D)".

Although any deuterium, observed anywhere (and at any time) in the universe, provides a *lower* limit to its primordial abundance, not all absorption identified with deuterium need actually be due to deuterium. The absorption spectra of hydrogen and deuterium are identical, save for the wavelength/velocity shift (81 km s^{-1}) due to the very slightly different reduced masses. Thus, any "observed" deuterium can only provide an *upper* bound to the true deuterium abundance. It is dismaying that such crucial implications for cosmology rely at present on only three pieces of observational data. Indeed, the most recently determined deuterium abundance (O'Meara et al. 2001) is somewhat more than 3σ lower than the previous primordial value based on the first two systems. In fact, there is a fourth absorption-line system for which it has been claimed that deuterium is observed (Webb et al. 1997). The deuterium abundance derived for this system is very high ("high-D"), nearly an order of magnitude larger than the low-D value, leading to a considerably smaller baryon abundance estimate. This determination suffers from a lack of sufficient data on the velocity structure of the absorbing cloud(s) and is a likely candidate for confusion with a hydrogen interloper masquerading as deuterium. Nonetheless, for completeness, this estimate of the baryon density is included in Figure 1 by the curve labeled "BBN(High-D)". We believe that the low-D value provides a better estimate of the true primordial abundance and, use it in the following for our "preferred" estimate of the SBBN baryon density.

In Figure 2 the band extending from upper left to lower right shows the relation between the SBBN-predicted abundances of D and ^{4}He; the width of the band represents the (1σ) uncertainties in the predictions due to uncertainties in the nuclear and weak interaction rates. Note that while D/H changes by an order of magnitude, Y hardly changes at all ($\Delta Y \approx 0.015$). Figure 2 exposes the first observational challenge to SBBN. For the observed (low-D) deuterium abundance (including its uncertainty), the SBBN-predicted helium abundance is $Y = 0.248 \pm 0.001$. This is in disagreement with several determinations of the primordial helium abundance derived from observations of low-metallicity, extragalactic H II regions. From their survey of the literature Olive & Steigman (1995) find $Y_{\mathrm{P}} = 0.234 \pm 0.003$ (see also Olive, Skillman, & Steigman 1997 and Olive et al. 2000), while from their own, independent data set Izotov & Thuan (1998) derive $Y_{\mathrm{P}} = 0.244 \pm 0.002$. It is clear that these results are in conflict and it is likely that unaccounted for systematic errors dominate the error budget. For this reason a "compromise" was advocated in Olive et al. (2000): $Y_{\mathrm{P}} = 0.238 \pm 0.005$. Recently, in an attempt to either uncover or avoid some potential systematic errors, Peimbert, Peimbert, & Ruiz (2000) studied the nearby, albeit relatively metal-rich, H II region NGC 346 in the SMC. They found $Y = 0.2405 \pm 0.0018$ and, correcting for the evolution of Y with metallicity, derived $Y_{\mathrm{P}} = 0.235 \pm 0.003$. It is clear (see Fig. 2) that *none* of these observational estimates is in agreement with the predictions of SBBN (low-D), although the gravity of the disagreement may be in the eye of the beholder. The observationally inferred primordial helium abundance is "too small" for the observationally determined deuterium abundance. Either one (or both) of the abundance determinations is inaccurate at the level claimed, or some interesting physics (and/or cosmology) is missing from SBBN. Notice that if the high-D abundance is the true primordial value there is no conflict between SBBN and the Olive et al. (2000) helium abundance, while the Izotov & Thuan (1998) abundance is now too high. Before addressing the role of possible non-standard BBN in relieving the tension between D and ^{4}He, other, non-BBN, bounds on the baryon abundance are considered and compared to $\Omega_{\rm BBN}$.

3. THE PRESENT UNIVERSE BARYON DENSITY

It is notoriously difficult to inventory baryons in the present universe. Persic & Salucci (1992) have attempted to find the density of those baryons which reveal themselves by shining (or absorbing!) in some observationally accessible part of the electromagnetic spectrum: "luminous baryons". It is clear from Persic & Salucci (1992) that most baryons in the present universe are "dark" since they find $\Omega_{\rm LUM} \approx 0.0022 + 0.0006h^{-1.3} \ll \Omega_{\rm BBN}$. At the very least this lower bound to $\Omega_{\rm B}$ is good news for SBBN, demonstrating that the baryons present during BBN *may* still be here today. In a more recent inventory which includes some estimates of dark baryons, Fukugita, Hogan, & Peebles (1998) find a larger range ($0.007 \lesssim \Omega_{\rm B} \lesssim 0.041$) that has considerable overlap with $\Omega_{\rm BBN}$.

A complementary approach to the present universe baryon density is to combine an estimate of the *total* mass density, baryonic plus "cold dark matter" (CDM), $\Omega_{\rm M}$, with an independent estimate of the universal baryon *fraction* $f_{\rm B}$ to find $\Omega_{\rm B} = f_{\rm B}\Omega_{\rm M}$. Recently, we (Steigman et al. 2000) imposed the assumption of a "flat" universe and used the SNIa magnitude-redshift data (Perlmutter et al. 1997; Schmidt et al. 1998; Perlmutter et al. 1999) to find $\Omega_{\rm M}$ ($0.28^{+0.08}_{-0.07}$), which was combined with a baryon fraction estimate ($f_{\rm B}h^2 = 0.065^{+0.016}_{-0.015}$) based on X-ray observations of rich clusters of galaxies (Mathiesen, Evrard, & Mohr 1999; Mohr, Mathiesen, & Evrard 1999) and the *HST* Key Project determination of the Hubble parameter ($h = 0.71 \pm 0.06$; Mould et al. 2000) to derive $\eta_{10} = 4.8^{+1.9}_{-1.5}$ ($\Omega_{\rm B}h^2 = 0.018^{+0.007}_{-0.005}$). Subsequently Grego et al. (2001), utilizing observations of the Sunyaev-Zeldovich effect in X-ray clusters, have reported a very similar value for the cluster hot gas fraction to that adopted in Steigman et al. (2000). For the Grego et al. (2001) value for $f_{\rm B}$, which may be less vulnerable to systematics, the present universe baryon density is, $\eta_{10} = 5.1^{+1.8}_{-1.4}$ ($\Omega_{\rm B}h^2 = 0.019^{+0.007}_{-0.005}$). This distribution is shown in Figure 1 by the curve labeled SNIa. Although the uncertainties in this estimate at $z \approx 0$ are large, the excellent overlap lends support to the low-D SBBN baryon abundance. The poor overlap with the high-D SBBN baryon density argues against the high D/H being representative of the primordial deuterium abundance.

4. THE BARYON DENSITY AT $z \sim 1000$

At redshift $z \sim 1000$, when the universe is several hundred thousand years old, the temperature of the CMB radiation has cooled sufficiently for neutral hydrogen (and helium) to form. The CMB photons are now freed from the tyranny of electron scattering and they propagate freely carrying the imprint of cosmic perturbations as well as encoding the parameters of the cosmological model, in particular the baryon density. Observations of the CMB anisotropies therefore provide a probe of $\Omega_{\rm B}$ at a time in the evolution of the universe intermediate between BBN and the present epoch.

Recent observations of the CMB fluctuations by the BOOMERANG (de Bernardis et al. 2000; Lange et al. 2001) and MAXIMA (Hanany et al. 2000) experiments have provided a means for constraining the baryon density at $z \sim 1000$. The relative height of the first two "acoustic peaks" in the CMB anisotropy spectrum is sensitive to the baryon density. Although the precise value of $\Omega_B h^2$ depends on the choice of "priors" for the other cosmological parameters which must be included in the analysis, the CMB-inferred baryon density exceeds that derived from BBN (low-D) by $\sim 50\%$, $\Omega_B h^2 \sim 0.03$ ($\eta_{10} \sim 8$). The baryon density likelihood distribution shown in Figure 1 is based on the combined Boomerang and Maxima analysis of Jaffe et al. (2001) who find $\Omega_B h^2 = 0.032 \pm 0.005$ ($\eta_{10} = 8.8 \pm 1.4$).

It is clear from Figure 1 that while there is excellent overlap between the low-D SBBN and SNIa baryon density estimates, the high-D SBBN value is discordant. Furthermore, there is a hint that the CMB value may be too large. Note that the apparent "agreement" (or, minimal apparent disagreement) in Figure 1 is an artifact of normalizing each likelihood function to unit maximum. In fact, the CMB data excludes the central value of low-D SBBN at greater than 98% confidence. Although it may well be premature to take this "threat" to SBBN seriously, this potential discrepancy has led to the suggestion that new physics may need to be invoked to reconcile the

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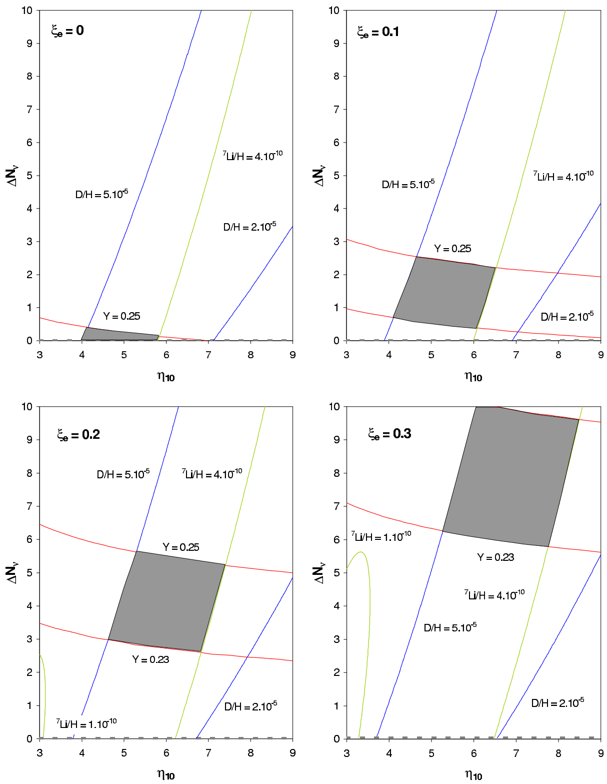

Fig. 3. Iso-abundance contours for deuterium (D/H), lithium (Li/H) and helium (mass fraction, Y) in the ΔN_ν–η_{10} plane for four choices of ν_e degeneracy (ξ_e). The shaded areas highlight the range of parameters consistent with the adopted abundance ranges.

BBN and CMB predictions for $\Omega_B h^2$. This possibility is discussed next.

5. BEYOND SBBN

Observations of deuterium and helium (and, perhaps lithium) offer the first challenge to SBBN and the baryon density derived from it (see § 2). Setting aside the very real possibility of errors in the observationally derived abundances, how might SBBN be modified to account for a helium abundance which is (predicted to be) too large? Not surprisingly, the options are manifold. One possibility is to modify the expansion rate of the early universe. If for some reason the universe were to expand more slowly than in the standard model, there would be more time for neutrons to convert to protons, resulting in a lower primordial helium abundance. In addition, a slower expansion would leave more time for deuterium to be destroyed resulting in a lower D-abundance. To compensate for this, the BBN baryon density would need to be *reduced*. This has the further beneficial effect of reducing the predicted lithium abundance, as well as reducing (very slightly) the predicted helium abundance. Thus, a *slower* expansion rate in the early universe can reconcile the predicted and observed deuterium and helium abundances (cf. Chen, Scherrer, & Steigman 2001; Ziaeepour 2001). But, since this "solution" requires a *lower* baryon density, it exacerbates the tension between BBN and the CMB.

Although a *speed up* in the expansion rate offers the possibility of reconciling the observed deuterium abundance with the high baryon density favored by the CMB, it greatly exacerbates the helium abundance discrepancy and increases the tension between the predicted and observed lithium abundances. To reconcile the BBN and CMB estimates of the baryon density, while maintaining (or, establishing!) consistency between the predicted and observed primordial abundances, additional "new physics" needs to be invoked.

The simplest possibility for reducing the BBN-predicted helium abundance is a non-zero chemical potential for the electron neutrinos. An excess of ν_e over $\bar{\nu}_e$ can drive down the neutron-proton ratio, leading to reduced production of helium-4. Thus, one path to reconciling BBN with a high baryon density is to "arrange" for a faster than standard expansion rate ($S \equiv H'/H > 1$) *and* for degenerate ν_e. Although these two effects need not be related, neutrino degeneracy can, in fact, provide an economic mechanism for both since the energy density contributed by degenerate neutrinos exceeds that from non-degenerate neutrinos, leading to an enhanced expansion rate during radiation-dominated epochs ($H'/H = [\rho'/\rho]^{1/2} > 1$). Thus, one approach to non-standard BBN is to introduce two new parameters, the speed up factor S and the electron neutrino degeneracy parameter ξ_e, where $\xi_e = \mu_e/T_\nu$ is the ratio of the electron neutrino chemical potential μ_e to the neutrino temperature T_ν. For degenerate neutrinos the energy density, $\rho_\nu(\xi)$, exceeds the non-degenerate energy density, ρ_ν^0:

$$\Delta\rho_\nu/\rho_\nu^0 = \frac{15}{7}\left[(\xi/\pi)^4 + 2(\xi/\pi)^2\right]. \qquad (1)$$

Thus, neutrino degeneracy has the same effect (on the early universe expansion rate) as would additional species of light, non-degenerate neutrinos. In terms of the equivalent number of "extra", non-degenerate, two-component neutrinos ΔN_ν, the speed up factor is

$$S = (1 + 7\Delta N_\nu/43)^{1/2}. \qquad (2)$$

To facilitate comparison with the published literature, ΔN_ν is used in place of S. Since ΔN_ν =

$\Delta\rho_\nu/\rho_\nu^0$, ΔN_ν accounts for the additional energy density contributed by all the degenerate neutrinos, see eq. (1), *as well as any other energy density not accounted for in the standard model of particle physics* (e.g., additional relativistic particles) expressed in terms of the equivalent number of extra, non-degenerate, two-component neutrinos. However, our results are independent of whether ΔN_ν (or the corresponding value of S) arises from neutrino degeneracy, from "new" particles, or from some other source. Note that a non-zero value of ξ_e implies a non-zero contribution to ΔN_ν from the electron neutrinos alone. This contribution has been included in our calculations. However, for the range of ξ_e which proves to be of interest ($\xi_e \lesssim 0.5$; see Fig. 3), the degenerate electron neutrinos contribute only a small fraction of an additional neutrino species to the energy density ($\Delta N_\nu \lesssim 0.1$). As Kang & Steigman (1992) and Olive et al. (1991) have shown, the observed primordial abundances of the light nuclides can be reconciled with very large baryon densities provided that $\xi_e > 0$ and ΔN_ν is sufficiently large.

The parameter space Kneller et al. (2001) investigated is three-dimensional: η, ξ_e, and ΔN_ν. Generous ranges for the primordial abundances were chosen which are large enough to encompass systematic errors in the observations, as well as to account for the BBN uncertainties due to imprecisely known nuclear and/or weak reaction rates: $0.23 \le Y_{\rm P} \le 0.25$, $2\times10^{-5} \le {\rm D/H} \le 5\times10^{-5}$, $1\times10^{-10} \le {}^7{\rm Li/H} \le 4\times10^{-10}$. Since we wish to compare to the predictions of the CMB, which are sensitive to η and ΔN_ν, but independent of ξ_e, the allowed BBN region is projected onto the η–ΔN_ν plane. The BBN results are shown in the four panels of Figure 3 where, for four choices of ξ_e the iso-abundance contours for $Y_{\rm P}$, D/H and Li/H are shown. The shaded areas highlight the acceptable regions in our parameter space. As ξ_e increases, the allowed region moves to higher values of η and ΔN_ν, tracing out a BBN-consistent band in the η–ΔN_ν plane. This band is shown in Figure 4 where the CMB constraints on the same parameters (under the assumption of a flat universe; for details and other cases, see Kneller et al. 2001) are shown. The trends are easy to understand: as the baryon density increases the universal expansion rate (measured by ΔN_ν) increases to keep the deuterium and lithium unchanged, while the ν_e degeneracy (ξ_e) increases to maintain the helium abundance at its (correct!) BBN value.

The CMB anisotropy spectrum depends on the baryon density and on the universal expansion rate (through the relativistic energy density as measured

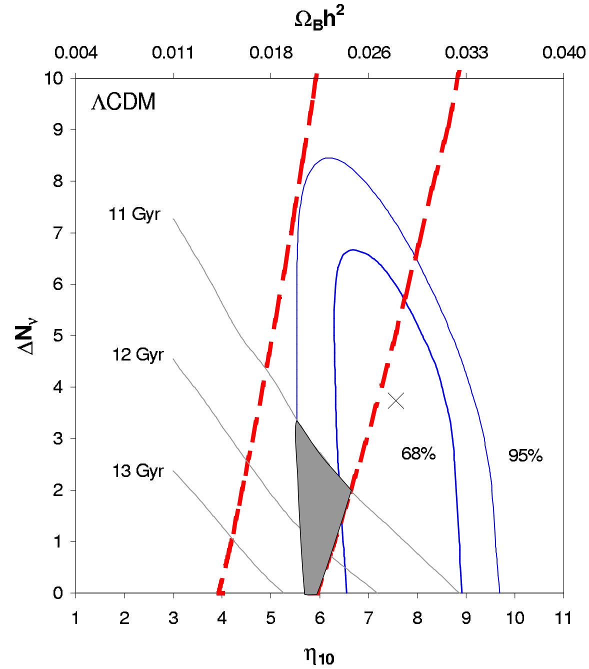

Fig. 4. The BBN (dashed) and CMB (solid) contours (flat, ΛCDM model) in the ΔN_ν–η_{10} plane. The corresponding best fit iso-age contours are shown for 11, 12, and 13 Gyr. The shaded region delineates the parameters consistent with BBN, CMB, and $t_0 > 11$ Gyr.

by ΔN_ν) as well as on many other cosmological parameters which play no role in BBN. But, in fitting the CMB data, choices must be made ("priors") of the values or ranges of these other parameters. In Kneller et al. (2001) several cosmological models and several choices for the "priors" were explored. Figure 4 shows the BBN/CMB comparison for the "flat, ΛCDM" model (Case C of Kneller et al. 2001). The significant overlap between the BBN-allowed band and the CMB contours, confirms that if we allow for "new physics" ($\xi_e > 0$ and $\Delta N_\nu > 0$), the tension between BBN and the CMB can be relieved.

Since the points in the η–ΔN_ν plane are projections from a multi-dimensional parameter space, the relevant values of the "hidden" parameters may not always be consistent with other, independent observational data which could provide additional constraints. As an illustration, three iso-age contours (11, 12, and 13 Gyr), are shown in Figure 4. The iso-age trend is easy to understand since as ΔN_ν increases, so too do the corresponding values of the matter density (Ω_M) and the Hubble parameter (H_0) which minimize χ^2. Furthermore, since $\Omega_{\rm M} + \Omega_\Lambda = 1$, Ω_Λ decreases. All of these lead to younger ages for larger values of ΔN_ν. Note that if an age constraint is imposed (e.g., that the universe today is *at least* 11 Gyr old, Chaboyer 2000; Chaboyer & Krauss 2002), then the BBN and CMB overlap is considerably restricted (to the shaded region in Fig. 4). Even with this constraint it is clear that for modest "new physics" ($\Delta N_\nu \lesssim 4$; $\xi_e \lesssim 0.3$) there is a small range of baryon density ($0.020 \lesssim \Omega_{\rm B} h^2 \lesssim 0.026$) which is concordant with both the BBN and CMB constraints, as well as the present universe baryon density.

6. SUMMARY AND CONCLUSIONS

According to the standard models of cosmology and particle physics, as the universe evolves from the first few minutes to the present, the ratio of baryons (nucleons) to photons, η, should be unchanged. The abundance of deuterium, a relic from the earliest epochs, identifies a nucleon abundance $\eta_{10} \sim 5.6$. The CMB photons, relics from a later, but still distant epoch in the evolution of the universe suggest a somewhat higher value, $\eta_{10} \sim 8.8$. Although most baryons in the present universe are dark and the path to the current nucleon-to-photon ratio is indirect, our estimates suggest $\eta_{10} \sim 5.1$. That these determinations are all so close to one another is a resounding success of the standard model. The possible differences may either reflect the growing pains of a maturing field whose predictions and observations are increasingly precise, or perhaps, be pointing the way to new physics. Exciting times indeed!

We are pleased to acknowledge Bob Scherrer and Terry Walker for their contributions to the work reviewed here. Financial support for this research at OSU has been provided by the DOE (DE-FG02-91ER-40690).

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Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
Editors: William Henney, José Franco, Marco Martos, & Miriam Peña