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PRIMORDIAL NUCLEOSYNTHESIS FOR THE NEW MILLENNIUM

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Primordial Nucleosynthesis For The New Millennium

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Abstract. The physics of the standard hot big bang cosmology ensures that the early Universe was a primordial nuclear reactor, synthesizing the light nuclides (D, ^{3}He, ^{4}He, and ^{7}Li) in the first 20 minutes of its evolution. After an overview of nucleosynthesis in the standard model (SBBN), the primordial abundance yields will be presented, followed by a status report (intended to stimulate further discussion during this symposium) on the progress along the road from observational data to inferred primordial abundances. Theory will be confronted with observations to assess the consistency of SBBN and to constrain cosmology and particle physics. Some of the issues/problems key to SBBN in the new millenium will be highlighted, along with a wish list to challenge theorists and observers alike.

1. Introduction

Among the quantitative, "hard" sciences, astronomy has traditionally been scorned, with particular disdain reserved for cosmology. No more. In the decade of the nineties the combination of an avalanche of high quality observational data and theoretical advances driven by enhaced computer (and brain) power, have succeeded in transforming cosmology to a precise science. In this introductory lecture to IAU Symposium 198 on The Light Elements and Their Evolution it is my intent to describe primordial nucleosynthesis in this precision era of cosmology and to highlight the challenges, along with some goals, for the new millennium. After a brief review of the important physics during the era of primordial nucleosynthesis in the standard, hot big bang cosmological model (SBBN), I will present an overview of the predicted primordial abundances, emphasizing the generally very small theoretical uncertainties. These will then be compared to the present best estimates (including their uncertainties) of the primordial abundances inferred from current observational data. After assessing the consistency of SBBN, I will explore what SBBN has to offer to Cosmology and to Particle Physics and, what Cosmology may teach us about SBBN. I will conclude with a summary of the key issues/problems confronting SBBN and with a wish list of topics I hope will be addressed during this meeting – and beyond.

2. An Early Universe Chronology

Our story begins when the Universe is a few tenths of a second old and the temperature of the cosmic background radiation has dropped to a few MeV as the Universe expanded and cooled from its denser, hotter infancy. At this time (and earlier) the density and average energy of colliding particles is so high that even the weak interactions occur sufficiently rapidly to establish equilibrium. In particular, at this stage all flavors of neutrinos (e, μ, τ) are in thermal equilibrium with the cosmic background radiation (CBR) photons and with the copius electron-position pairs present $(\nu_i + \bar{\nu}_i \leftrightarrow e^+ + e^- \leftrightarrow \gamma + \gamma)$. However, as the Universe ages beyond a few tenths of a second and the temperature drops below a few MeV, these weak interactions become too slow to keep pace with the rapid expansion of the Universe and the neutrinos decouple from the CBR. The electron-type neutrinos continue to play a role in transforming neutrons into protons and, vice-versa $(p + e^- \leftrightarrow n + \nu_e,\ n + e^+ \leftrightarrow p + \bar{\nu}_e,\ n \leftrightarrow p + e^- + \bar{\nu}_e)$. As the temperature continues to drop, less massive protons are favored over the more massive neutrons and the n/p ratio falls (roughly as $e^{-\Delta m/kT}$, where Δm is the neutron – proton mass difference ~ 1.3 MeV). After the temperature drops below 800 keV or so, when the Universe is a few seconds old, even these weak interactions become too slow to keep pace with the expansion and the neutron-to-proton ratio "freezes out" (in fact, the ratio continues to decrease, albeit very slowly). All the while, neutrons and protons have been colliding, occasionally forming deuterons $(p + n \rightarrow D + \gamma)$. However, the deuterons find themselves bathed in a high density background of energetic CBR photons which quickly photodissociate them $(D + \gamma \rightarrow p + n)$ before they can find a proton or neutron and form the more tightly bound, less fragile, ^{3}H or ^{3}He nuclei. Since, as we shall see, there are roughly nine to ten orders of magnitude more CBR photons than nucleons in the Universe, the deuteron "stepping-stone" to further nucleosynthesis is absent until the temperature drops sufficiently low so that even in the high-energy tail of the black-body spectrum there are too few photons to prevent the deuteron from acting as a catalyst for primordial nucleosynthesis. This critical temperature, which is weakly (logarithmically) dependent on the nucleon abundance (the nucleon-to-photon ratio η), is roughly 80 keV. Now, at last, when the Universe is a few minutes old, Big Bang Nucleosynthesis finally commences. However, the Universe was a fatally flawed nuclear reactor, cooling and diluting rapidly as it aged. When the Universe is some 10 – 20 minutes old ($\sim$ 1000 sec) and the temperature has dropped below 30 keV or so, the coulomb barriers preventing nuclear reactions between charged nuclei and protons and among charged nuclei become insurmountable (in the short amount of time available) and primordial nucleosynthesis comes to an abrupt end. In this all too brief but shining era there has been time to synthesize (in abundances comparable to those observed or observable) only the lightest nuclides: D, ^{3}He, ^{4}He, and ^{7}Li. In "standard" (a homogeneous Universe, expanding isotropically with the particle content of the standard model of particle physics in which there are three flavors of light ($m \ll$ MeV) or massless neutrinos) big bang nucleosynthesis (SBBN) the abundances (relative to protons $\equiv$ hydrogen) of these four nuclides are determined by only one free parameter, the present epoch nucleon-to-photon ratio η $(\eta \equiv (n_{\rm N}/n_\gamma)_0,\ \eta_{10} \equiv 10^{10}\eta)$.

3. SBBN-Predicted Primordial Abundances

Once the deuterium photodissociation bottleneck is breached primordial nucleosynthesis begins in earnest, quickly burning D to ^{3}H, ^{3}He and ^{4}He. The higher the nucleon density, the faster D is destroyed. The same is true of ^{3}H (which, if it survives will decay to ^{3}He) and ^{3}He. Thus, the primordial abundances of D and ^{3}He are determined by the competition between the nuclear reaction rates and the universal expansion rate. The former rate depends on the overall density of the reactants – the nucleon density. Since all densities decrease as the Universe expands, it is convenient to quantify the nucleon density by specifying the *ratio* of the nucleon density to the photon density (measured after e^+e^- annihilation which enhances the Universe's photon budget) η. Since observations of the cosmic background radiation (CBR) temperature (T = 2.73 K) determine the present density of CBR photons, a knowledge of η is equivalent to a determination of the present mass density in nucleons ("baryons" $\equiv$ B). In terms of the density parameter $\Omega_{\rm B}$ (the ratio of the mass density to the critical mass density) and the present value of the Hubble parameter ($H_0 \equiv 100h$ km/s/Mpc), $\eta_{10} = 273\Omega_{\rm B}h^2$. As η increases the surviving abundances of D and ^{3}He decrease; since the ^{3}He nucleus is more tightly bound than the deuteron, the decrease of the ^{3}He/H ratio with η is less rapid than that of D/H.

In contrast to D and ^{3}He, the primordial abundance of ^{4}He is not reaction rate limited since the nuclear reactions building helium-4 are so rapid that virtually all neutrons available when BBN commences are incorporated into ^{4}He. As a result the ^{4}He abundance, conventionally presented as the mass fraction of all nucleons which are in ^{4}He, $Y_{\rm P}$, is *neutron limited.* Since the neutron-to-proton ratio is determined by the competition between the (charged-current) weak interactions which mediate the transformation of neutrons into protons (and, vice-versa) and the universal expansion rate, $Y_{\rm P}$ is sensitive to the universal expansion rate at the time the n/p ratio "freezes" and when the deuterium photodissociation barrier disappears. Since the universal expansion rate is controlled by the total energy density, $Y_{\rm P}$ provides an important test of cosmology and of particle physics in the early Universe (Steigman, Schramm & Gunn 1977). It should be noted that $Y_{\rm P}$ is not entirely insensitive to the nucleon density since the higher η, the earlier the photodissociation barrier is overcome. At earlier times when the temperature is higher, fewer neutrons have been transformed into protons and are available for incorporation into ^{4}He. As a result, $Y_{\rm P}$ increases logarithmically with η.

There is no stable nucleus at mass-5 and this presents a gap in the road to the synthesis of nuclei heavier than ^{4}He. In order to bridge the gap nuclear reactions must occur among nuclei with two or more nucleons. But, the abundances of D, ^{3}H, and ^{3}He are small and the coulomb barriers (especially between ^{3}He and ^{4}He and between ^{4}He and ^{4}He) suppress these reactions as the Universe expands and cools. As a result, there is very little "leakage" to nuclei beyond mass-4; as a corollary, virtually all the ^{4}He formed, survives. The only heavier nucleus produced primordially in an abundance comparable to that observed (or, even, observable with current technology) is ^{7}Li, whose BBN abundance is some 4 – 5 orders of magnitude smaller than that of D and ^{3}He. The absence of a stable nucleus at mass-8 provides another gap preventing the production of astrophysically interesting abundances of any heavier nuclei.

As will become clear in our subsequent discussion, the "interesting" range of η is $\eta_{10} = 1 - 10$ ($\Omega_B h^2 = 0.004 - 0.037$), so we focus our discussion here on values of η in this range. In the current precision era of BBN *most* of the nuclear reactions relevant to the synthesis of the light elements have been measured to reasonable accuracy at energies directly comparable to the thermal energies at the time of primordial nucleosynthesis (*e.g.*, see Nollett, this volume). As a result, the theoretical uncertainties in the BBN-predicted abundances are generally quite small. For η in the above range, the 1σ uncertainties in D/H and ^{3}He/H vary from 8 – 10%. Since ^{4}He is most sensitive to the very well measured weak interaction rates, the error in SBBN-predicted Y_P is very small (0.2 – 0.5% or, $\sigma_Y = 0.0005 - 0.0011$). In contrast, larger uncertainties, of order 12 – 21%, afflict the predicted primordial abundance of ^{7}Li.

Since this Symposium devoted much discussion to ^{7}Li, and space-limitations here prevent me from discussing all the light elements in detail, I will concentrate in the following on the two key light elements, deuterium and helium-4. In Figure 1 is shown the relation between the BBN-predicted abundances of D and ^{4}He. The band going from upper left to lower right represents the $\pm 2\sigma$ range of uncertainties in the primordial abundances ($(D/H)_P$ and Y_P). Low D/H (high η) corresponds to high Y_P and high D/H (low η) corresponds to low Y_P. This anticorrelation will be very important when we confront the predictions of SBBN with the observational data.

4. Precise (Accurate?) Primordial Abundances

To test SBBN and fully exploit the opportunities it offers to constrain cosmology (e.g., the baryon density) and particle physics (e.g., new particles with weak or weaker-than-weak interactions) requires that observational data be used to pin down the primordial abundances of the light elements to precisions as good as (or, better than) those of the SBBN predictions. As we approach the new millennium there is good news along with some bad news. The good news is that new detectors on ever larger telescopes which cover the spectrum from radio to x-ray energies and beyond are providing very high quality data, leading to inferred abundances of high statistical accuracy. Furthermore, the abundances of the light elements are determined from observations which differ from element to element in the telescopes and techniques employed as well as in the astrophysical sites explored. As a result, insidious correlated errors between and among the various element abundances are unlikely to be a problem. The good news is also responsible for the bad news. Since the statistical errors have become so small, systematic errors now tend to dominate the uncertainties in the derived primordial abundances. As Bob Rood has said during this Symposium, estimating systematic errors is an oxymoron. When a potential source of systematic error is identified, observations can (and should) be designed to eliminate or bound its contribution to the error budget. It is a pointless and potentially misleading exercise to "estimate" the magnitude of unidentified systematic errors. In part to remind us that our precise abundance determinations may not be accurate, and in part to challenge our observational colleagues who have done such a magnificent job of reducing the statistical errors, I will try to focus on the potential sources of systematic uncertainty (when I can identify them) in the following overview of the current observational status.

4.1. Deuterium

As J. Linsky (this volume) has reminded us, the deuterium abundance in the local interstellar medium (the local interstellar cloud: LIC) is known very accurately: $(D/H)_{LIC} = 1.5 \pm 0.1 \times 10^{-5}$ (Linsky 1998). Since deuterium is only destroyed during the evolution of the Galaxy (Epstein, Lattimer & Schramm 1976), the LIC abundance provides a lower bound to its primordial (pre-Galactic) value. This bound is strong enough to bound the nucleon density from above ($\eta_{10} \lesssim 10$; $\Omega_B h^2 \lesssim 0.04$), ensuring that baryons cannot "close" the Universe ($\Omega_B \ll 1$), nor even dominate its present mass density ($\Omega_B \ll \Omega_M \approx 0.3 - 0.4$). Thus, local observations of deuterium, combined with the *assumption* of the correctness of SBBN (which we must test), already reaps great rewards: the mass-energy density of the Universe must be dominated by unseen ("dark") non-baryonic matter. To go beyond (in the quest for the primordial deuterium abundance) we must look for observing targets which are less evolved than the LIC. The presolar nebula is one such site. From solar system observations of ^{3}He reported by G. Gloeckler (this volume), it is possible to infer the presolar deuterium abundance (Geiss & Reeves 1972; Geiss & Gloecker 1998): $(D/H)_\odot = 1.9 \pm 0.5 \times 10^{-5}$. Although marginally higher than the LIC abundance, the larger errors prevent us from using this determination to improve on our previous bounds from the LIC. What this result does indicate is that there has been very little (if any) evolution in the D-abundance in the solar vicinity of the Galaxy in the last 4.5 Gyr. This is consistent with a large class of Galactic chemical evolution models discussed by M. Tosi (this volume) which point to only a modest overall destruction of primordial deuterium by a factor of 2 – 3 (Tosi et al. 1998). If this theoretical estimate is combined with the LIC abundance, we may estimate the primordial abundance: $(D/H)_P \approx 2.6 - 5.1 \times 10^{-5}$ ($\sim 2\sigma$). Although possibly model dependent, this estimate is in remarkable agreement with the 2 – 3 determinations of D/H in high-redshift, low-metallicity (hence very nearly primordial) Ly-α absorbers illuminated by background QSOs described by D. Tytler and S. Levshakov (this volume). The data and analysis of Burles & Tytler (1998a,b: BT) suggests that $(D/H)_P = 2.9 - 4.0 \times 10^{-5}$ ($\sim 2\sigma$). Notice that the 1σ uncertainty in the observationally determined primordial abundance, $\sim 8\%$, is impedance-matched to the $\sim 8\%$ SBBN theoretical uncertainty cited earlier. However, lest we risk dislocating a shoulder while patting ourselves on the back at the triumph of such wonderful data, we should not ignore the claim (Webb et al. 1997; Tytler et al. 1999) that the deuterium abundance in at least one Ly-α absorption system may be much higher. This is a reminder that while any determination of the deuterium abundance anywhere in the Universe (LIC, solar system, Ly-α absorbers, etc.) provides a *lower* bound to primordial deuterium, finding an upper bound is more problematic. Indeed, in some absorbing systems it may be impossible to distinguish D-absorption from that due to hydrogen in an interloping, low column density, "wrong-velocity" system. Thus, the deuterium abundance inferred from absorption-line data may only provide an *upper* bound to the true deuterium abundance. Since the low-Z, high-z QSO absorbing systems hold the greatest promise of revealing for us nearly unevolved, nearly primordial material, we look forward to the time when we can use the *distribution* of D/H values from more than a handful of such systems to eliminate – statistically – the uninvited contribution to the inferred primordial deuterium abundance from such interlopers. Keeping this in mind, in the following I will, nevertheless, use the BT determination when confronting theory with data.

4.2. Helium-4

In contrast to deuterium whose primordial abundance only decreases as pristine gas is incorporated into stars, stars burn hydrogen to helium. As a result, the ^{4}He observed anywhere in the Universe is an unknown mixture of primordial and stellar-produced helium. It has long been appreciated that to minimize the uncertain correction due to the debris of stellar evolution, it is best to concentrate on ^{4}He abundance determinations in the lowest-metallicity regions available. These are the low-Z, extragalactic H II regions which have been discussed by K. Olive, T. Thuan, and S. M. Viegas at this Symposium (this volume). The reader is urged to consult their papers for details; here I will merely summarize my view of the current status of the determination of the primordial ^{4}He mass fraction Y_P. Several years ago Olive & Steigman (1995: OS) gathered together the data from the literature (dominated by the data assembled by Pagel et al. 1992). More recently Olive, Skillman & Steigman (1997: OSS) supplemented this with newer data (some of it, unfortunately, still unpublished). Using a variety of approaches such as the regression of Y on the oxygen and/or nitrogen abundances and the weighted means of Y in the lowest metal-abundance H II regions, OSS concluded that $Y_P = 0.234 \pm 0.003$ (note that, in contrast to the published (OSS) result, this value is obtained when the NW region of IZw18, suspected of being contaminated by underlying stellar absorption, is excluded from the fit, and the newer data of Izotov, Thuan and collaborators is not included). Izotov, Thuan and their collaborators (Izotov, Thuan, & Lipovetsky 1994, 1997; Izotov & Thuan 1998(IT); Thuan, this volume) have been systematically observing a mostly independent set of H II regions. Although, as with the data employed in the OS and OSS studies, they ignore the ionization correction ($icf \equiv 1$), they take special care with the correction for collisional excitation. IT (also Thuan, this volume) find $Y_P(\text{IT}) = 0.244 \pm 0.002$. Comparing the IT and OSS estimates of Y_P we find that difference between the two Y_P estimates far exceeds the statistical errors, suggesting systematic differences in the acquisition and/or analysis of the data samples. In a recent discussion which attempted to account for these unidentified systematic differences, Olive, Steigman & Walker (1999: OSW) combined the 2σ ranges for each determination to conclude: $Y_P = 0.238 \pm 0.005$; at the 2σ level, $Y_P \leq 0.248$. Note, that this is also the 2σ upper bound to the IT data alone. Since, as we shall see shortly, it is the upper bound which is crucial to testing the consistency of SBBN, in the following we shall adopt the IT value (and error estimate) for the primordial abundance of ^{4}He.

Recently, Viegas, Gruenwald & Steigman (1999: VGS; see Viegas & Gruenwald, this volume) have emphasized the importance of the ionization correction which has heretofore been ignored. VGS suggest that the IT helium abundance (Y_P) should be reduced by 0.003 to account for unseen neutral hydrogen in regions where the helium is still ionized in H II regions ionized by young, hot, metal-poor stars. In subsequent comparisons I shall explore the implications of adopting $Y_P(VGS) = 0.241 \pm 0.002$.

4.3. Helium-3 and Lithium-7

The cosmic history of the two other light nuclides produced in astrophysically interesting abundances during SBBN, ^{3}He and ^{7}Li, is considerably more complex than that of D or ^{4}He, which limits their utility as probes of the consistency of SBBN. ^{3}He is destroyed in the hotter interiors of all stars, but some ^{3}He does survive in the cooler, outer layers. For lower mass stars this ^{3}He survival layer increases and, indeed, newly synthesized ^{3}He is produced by incomplete hydrogen burning. The competition between destruction, survival, and synthesis complicates the Galactic history of the ^{3}He abundance. Nonetheless, since any deuterium incorporated into stars is first burned to ^{3}He, the apparent lack of enhanced ^{3}He (see Bania & Rood, this volume) argues against a very large pre-Galactic abundance of deuterium (Steigman & Tosi 1995). For further discussion of the evolution of ^{3}He see Bania & Rood (this volume).

As with ^{3}He, any ^{7}Li incorporated into stars is quickly burned away. However, fusion and spallation reactions between cosmic ray nuclei and those in the interstellar medium are a potent source of ^{7}Li (as well as of ^{6}Li, ^{7}Be, ^{10}B, and ^{11}B). It is also likely that there are stellar sources of ^{7}Li as indicated by the sample of lithium-rich red giants (V. Smith, this volume). Since the abundance of lithium in the solar system and in the interstellar medium ("here and now") greatly exceeds that in the very metal-poor halo stars (T. Beers & S. Ryan, this volume), the latter likely provide the closest approach to a nearly primordial sample. Since a significant fraction of this Symposium is devoted to lithium, I will defer here to those other discussions except to comment that, within the theoretical and observational uncertainties, the primordial abundances inferred from the observational data are consistent with SBBN constrained by the confrontation with D and ^{4}He.

5. Confrontation Of SBBN With Data

Although SBBN does lead to the prediction of the abundances of D, ^{3}He, ^{4}He, and ^{7}Li, the currently best-constrained primordial abundances are those of deuterium and helium-4 which we are concentrating on in this status report. For each value of η, SBBN predicts a pair of $(D/H)_P$ and Y_P values. Therefore, in SBBN there is a unique connection between $(D/H)_P$ and Y_P which, allowing for the theoretical uncertainties discussed above, is shown as the band (solid lines) in Figure 1 going from the upper left to the lower right (2σ uncertainties). Note that high-helium correlates with low-deuterium and, vice-versa. Also shown as the dotted ellipse in Figure 1 is the contour of the (independent) 2σ uncertainties in the BT deuterium abundance and the IT helium-4 mass fraction.

Although the overlap between theory and data is not complete, Figure 1 shows that, at the $\sim 2\sigma$ level, the predictions of SBBN are consistent with current observational data. This is a dramatic success for the standard hot, big bang cosmological model. Of course it is not at all surprising that some value of η may be found to provide consistency with the inferred primordial deuterium abundance. But there was no guarantee at all that the helium-4 abundance

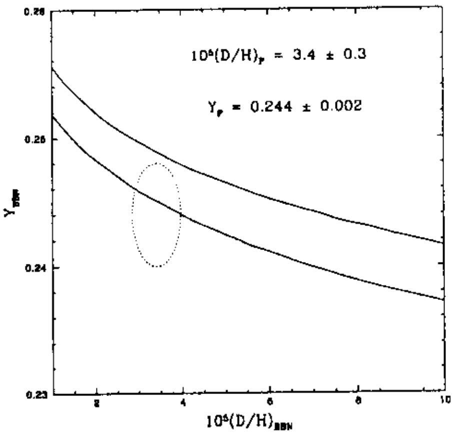

Figure 1. The SBBN-predicted ^{4}He mass fraction Y_P as a function of the SBBN-predicted primordial deuterium-to-hydrogen ratio D/H is shown (at the $\pm 2\sigma$ level) by the solid lines. The dotted ellipse is the 95% contour of the BT deuterium abundance and the IT ^{4}He mass fraction (see the text).

corresponding to this choice would bear any relation to its inferred primordial value. Consistency with the BT D-abundance limits the nucleon abundance to the range (2σ) $\eta_{10} = 4.4 - 5.9$ or, $\Omega_B h^2 = 0.016 - 0.022$. For η in this range there is consistency, within the theoretical and observational uncertainties, between the SBBN-predicted and observationally inferred primordial abundances of ^{3}He and ^{7}Li as well. Four for the price of one! There is, of course, one more test – and opportunity – offered by this result. This SBBN-inferred nucleon abundance must also be consistent with present epoch estimates of the baryon density. Indeed, the SBBN-determined value of Ω_B is *larger* than estimates (Persic & Salucci 1992) of the "luminous" matter in the Universe suggesting that the majority of baryons are "dark". This is good ($\Omega_B > \Omega_{LUM}$); the opposite would have been a disaster. This early-Universe estimate of the baryon density is in good agreement with that inferred from the X-ray cluster baryon fraction (Steigman, Hata & Felten 1999) and with the independent estimate from the Ly-α forest (Weinberg et al. 1997) discussed below.

5.1. What BBN May Do For Cosmology

X-ray clusters likely provide a "fair" sample of the universal baryon *fraction* f_B (White et al. 1993; Steigman & Felten 1995; Evrard, Metzler, & Navarro 1996) which, when combined with the SBBN-inferred baryon density Ω_B, leads to a "clean" prediction, independent of detailed cosmological models, of the overall matter density Ω_M. If the results presented here are combined with the determination of f_B from Evrard (1997), and with a Hubble parameter $h = 0.70 \pm 0.07$ (Mould et al. 1999), we predict $\Omega_M = 0.35 \pm 0.08$, in excellent agreement with several other recent, independent determinations. For example, a lower bound to the cosmic baryon density follows from the requirement that the high-redshift intergalactic medium contain enough neutral hydrogen to produce the Ly-α absorption observed in quasar spectra. According to Weinberg et al.

(1997), depending on estimates of the quasar UV background intensity, this lower bound corresponds to $\eta_{10} \gtrsim 3.4 - 4.9$, in excellent agreement with the SBBN prediction based on the BT deuterium determination. Note that this lower bound from the Ly-α absorption forbids (in the context of SBBN) the primordial deuterium abundance to be any larger than $\sim 8 \times 10^{-5}$, largely excluding the one surviving claim of high D (Webb et al. 1997).

Indeed, if the SBBN results are combined with the magnitude-redshift data from surveys of high-redshift Type Ia supernovae (Garnavich et al. 1998; Perlmutter et al. 1999) which bound a linear combination of $\Omega_{\rm M}$ and the cosmological constant $\Omega_\Lambda \equiv \Lambda/3{\rm H}_0^2$, we may also constrain the cosmological constant ($\Omega_\Lambda = 0.80 \pm 0.20$), the curvature ($\Omega_k \equiv 1 - (\Omega_{\rm M} + \Omega_\Lambda) = -0.15 \pm 0.25$), and the deceleration parameter ($q_0 = \Omega_{\rm M}/2 - \Omega_\Lambda = -0.62 \pm 0.18$).

5.2. What Cosmology May Do For BBN

As we have just seen, the SBBN-determined baryon density is consistent with that determined or constrained by observations of the Universe during its present or recent evolution. We may turn the argument around and ask what baryon density is suggested by non-BBN contraints, and then compare the light element abundances which correspond to that density with those inferred from the observational data. As an exercise of this sort, suppose (for reasons of "naturalness" or inflation) that the Universe is "flat": $\Omega_{\rm M} + \Omega_\Lambda = 1$. When combined with the SN Ia magnitude-redshift data (Perlmutter et al. 1999), this suggests that $\Omega_{\rm M} = 0.29 \pm 0.07$ (and $\Omega_\Lambda = 0.71 \pm 0.07$). Now, if this mass density estimate ($\Omega_{\rm M}$) is combined with with the X-ray determined cluster baryon fraction $f_{\rm B}$ (Evrard 1997; Steigman, Hata & Felten 1999), the resulting nucleon abundance is $\eta_{10} = 4.5 \pm 1.5$. Although the uncertainty is large, it is reassuring that this non-BBN estimate has significant overlap with our SBBN estimate. Indeed, for the baryon density in this range SBBN predicts: $({\rm D/H})_{\rm P} = 4.3 \pm 2.3 \times 10^{-5}$ and $Y_{\rm P} = 0.245 \pm 0.004$.

5.3. What SBBN May Do For Particle Physics

The expansion rate of the early Universe is controlled by the density of the relativistic particles present. In the standard model at the time of BBN these are: photons, electron-positron pairs (when $T \gtrsim m_e$) and three "flavors" of neutrinos (ν_e, ν_μ, ν_τ) which, if "light" ($m_\nu \ll 1$ MeV), are relativistic at BBN even if one or more of them may contribute to the present density of non-relativistic ("hot") dark matter. If "new" particles were to contribute to the energy density at BBN, the increase in the density would result in an increase in the universal expansion rate, leaving less time for neutrons to transform into protons. The higher n/p ratio at BBN would result in the production of more primordial ^{4}He (Steigman, Schramm & Gunn 1977). It is convenient (and conventional) to characterize such additional contributions to the energy density by comparing their effects to that of an additional "flavor" of (light) neutrino: $\Delta\rho \equiv \Delta N_\nu \rho_\nu$. For ΔN_ν small, $\Delta Y \approx 0.01 \Delta N_\nu$. Notice in Figure 1 that the predicted ^{4}He abundance is a little high for perfect overlap with the observations. If ΔN_ν were < 0, ($N_\nu \approx 2.8$) the overlap would improve (e.g., Hata et al. 1995), while if $\Delta N_\nu > 0$, the overlap would be reduced until it disappeared. This is illustrated in Figure 2 which shows the Y versus D/H BBN band that would result if $\Delta N_\nu = 0.2$

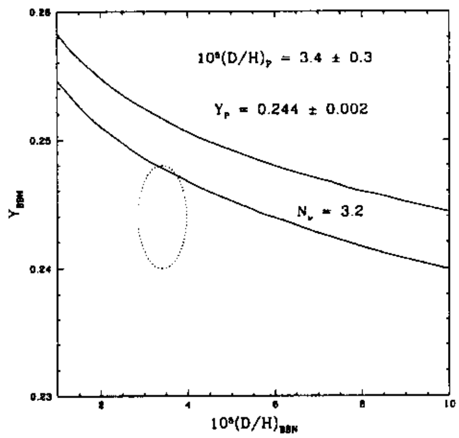

Figure 2. As Figure 1, but for $N_\nu = 3.2$

(i.e., $N_\nu = 3.2$, in contrast to the SBBN value of 3.0). Notice that due to the faster expansion, more deuterium survives being burnt away so that, for fixed η, the D-abundance also increases; however since D/H is a much more sensitive function of η, this has a much smaller effect on the Y versus D/H relation than does the increase in Y.

6. Conclusions And Outlook

The study of the early evolution of the Universe and, in particular primordial nucleosynthesis, has truly entered the precision era of cosmology. Precise abundances of the light nuclides are predicted and inferred from observations and the two are – apparently – in excellent agreement. As pleased as we may be at this success, it behooves us to avoid the temptation to rest on our laurels and to test this consistency ever more carefully. To this end, it doesn't take much contemplation to identify several clouds looming on the horizon. What follows is my personal list of some problems/issues I would like to see addressed at this Symposium and beyond.

6.1. Problems/Issues

First consider deuterium. On the one hand, any determination of the D/H ratio anywhere, anytime provides a *lower* bound to the primordial abundance. On the other hand, since "wrong" velocity hydrogen can masquerade as deuterium, any observation of "deuterium" is really an *upper* bound to its true abundance. More data tracking the velocity structure of the absorbing features used to identify D and H and exploring variations in D/H in material with similar histories will be very valuable. More data at high-redshift and low-metallicity will be very valuable. After all, at present we are drawing profound conclusions on the basis of only two such systems.

Much remains to be done concerning the primordial abundance of ^{4}He. For the most part, the H II regions from which the helium abundance is inferred have been modelled as homogeneous spheres or plane-parallel slabs. A glance at the beautiful HST images of real H II regions reveals that they are anything but such idealizations. What are the effects of temperature and/or density inhomogeneities, and how large may they be? What of underlying stellar absorption which, if present but neglected, would lead to an *under*estimate of the helium abundance. And, what of the usually neglected ionization correction for neutral hydrogen and helium (Viegas, Gruenwald & Steigman 1999; see Viegas & Gruenwald, this volume)? Considering this latter work, where models of H II regions ionized by realistic spectra of young star clusters were used in a reanalysis of the IT data, a *reduction* in Y_P of order 0.003 was suggested. A comparison with Figure 1 shows that if Y_P were reduced by this amount, the overlap between theory and data would, in fact, disappear.

6.2. Wish List

Given the setting of this Symposium (Natal) and the proximity to the Christmas season, I'd like to conclude with my personal wish list. To avoid being greedy, I'll only ask for two gifts.

A half-dozen or so observations of deuterium in high-z, low-Z systems along the lines-of-sight to distant quasars, with D/H determined in each (on average) to 10% or better. With such a gift, I could determine η to better than 4%, predict Y_P to $\lesssim 0.0007$, and constrain ΔN_ν to an uncertainty less than $\pm$ 0.05. I'd be a very happy cosmologist indeed.

My second wish is for ^{4}He measured to 3% accuracy (or better) in each of about a dozen low-metallicity, extragalactic H II regions, with care taken to address the several problems outlined above. With such data, Y_P could be fixed to better than the current level of ± 0.002, permitting ^{4}He to be used as a baryometer ($\Delta\eta/\eta \lesssim 20\%$).

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References

Burles, S., & Tytler, D. 1998a, ApJ, 499, 699 (BT)

Burles, S., & Tytler, D. 1998b, ApJ, 507, 732 (BT)

Epstein, R. Lattimer, J., & Schramm, D. N. 1976, Nature, 263, 198

Evrard, A. E. 1997, MNRAS, 292, 289

Evrard, A. E., Metzler, C. A., & Navarro, J. F. 1996, ApJ, 469, 494

Garnavich, P. M. et al. 1998, ApJ, 509, 74

Geiss, J., & Reeves, H. 1972, A&A, 18, 126

Geiss, J., & Gloeckler, G. 1998, Space Sci.Rev., 84, 239

Hata, N., Scherrer, R. J., Steigman, G., Thomas, D., Walker, T. P., Bludman, S., & Langacker P. 1995, Phys.Rev.Lett, 75, 3977

Linsky, J. L. 1998, Space Sci.Rev., 84, 285

Izotov, Y. I., Thuan, T. X., & Lipovetsky, V. A. 1994, ApJ, 435, 647

Izotov, Y. I., Thuan, T. X., & Lipovetsky, V. A. 1997, ApJS, 108, 1

Izotov, Y. I., & Thuan, T. X. 1998, ApJ, 500, 188 (IT)

Mould, J. R. et al. 1999, ApJ, submitted (astro-ph/9909260)

Olive, K. A., Skillman, E., & Steigman, G. 1997, ApJ, 483, 788 (OSS)

Olive, K. A., &, Steigman, G. 1995, ApJS, 97, 49 (OS)

Olive, K. A., &, Steigman, G., & Walker, T. P. 1999, Physics Reports, in press (astro-ph/9905320) (OSW)

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

Perlmutter, S. et al. 1999, ApJ, 517, 565

Persic, M., & Salucci, P. 1992, MNRAS, 258, 14P

Steigman, G., Schramm, D. N., & Gunn, J. E. 1977, Phys. Lett., B66, 202

Steigman, G., & Felten, J. E. 1995, Space Sci.Rev., 74, 245

Steigman, G., Hata, N., & Felten, J. E. 1999, ApJ, 510, 564

Steigman, G., & Tosi, M. 1995, ApJ, 453, 173

Tosi, M., Steigman, G., Matteucci, F., & Chiappini, C. 1998, ApJ, 498, 226

Tytler, D., Burles, S., Lu, L., Fan, X. M., Wolfe, A., & Savage, B. D. 1999, AJ, 117, 63

Viegas, S.M., Gruenwald, R., & Steigman, G. 1999, ApJ, 532 (in press, March 20, 2000; astro-ph/9909213)

Webb, J. K., Carswell, R. F., Lanzetta, K. M., Ferlet, R., Lemoine, M., Vidal-Madjar, A., & Bowen, D. V. 1997, Nature, 388, 250

Weinberg, D. H., Miralda-Escudé, J., Hernquist, L., & Katz, N. 1997, ApJ490, 564

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