1 Introduction

This manuscript is the written version of the material I attempted to cover at “Critical Dialogues in Cosmology”. My position is that although BBN is inevitable in an expanding universe filled with radiation and baryons, at present there is a conflict between the abundances of the light nuclides predicted by standard, big bang nucleosynthesis (SBBN) and those inferred from current observational data. This challenge to SBBN provides opportunities for astronomy/astrophysics, cosmology and particle physics. Perhaps there are unaccounted-for errors in passing from the observational data to the derived abundances (astronomy/astrophysics). Perhaps there are unaccounted-for systematic corrections in translating the derived abundances from “here and now” to “there and then” (astrophysics/cosmology). Or perhaps the tension between theory and observations is offering us a hint of new physics beyond the standard model (cosmology/particle physics).

1.1 The Basics

Which nuclei may be synthesized during BBN, and in what relative abundances, depends on the interplay among the nucleon density, the radiation temperature and the early expansion rate. For example, if the nucleon density were very small and/or the universe were expanding very rapidly when thermal energies were comparable to nuclear binding energies, few complex nuclei would have emerged from the big bang. In SBBN (isotropy, homogeneity, three flavors of light neutrinos, etc.) the yields depend on only one “free” parameter, $\eta$, the ratio (at present) of nucleons to photons ($\eta = n_B/n_\gamma$; $\eta_{10} = 10^{10}\eta$). In Figure 1 are shown the predicted SBBN yields ($Y_P$ is the $^4$He mass fraction and $y_2, y_3, y_7$ are the ratios by number to H of D, $^3$He and $^7$Li) as a function of $\eta$. The present contribution of baryons to the total density, in units of the critical
density, is directly proportional to $\eta$. For a present cosmic background radiation temperature of $T_{\text{CBR}} = 2.73K$,

$$\Omega_B = 0.0146\eta_{10}h_{50}^{-2},$$

(1)

where the Hubble constant is $H_0 = 50h_{50}$ km/sec/Mpc. As may be seen in Figure 1, the relative abundances vary considerably with $\eta$ so that SBBN is an overdetermined system in the sense that fixing one of the primordial abundances fixes $\eta$ and leads to predictions of the abundances of the three other nuclides. SBBN is an eminently testable theory! Consistency demands that the value of $\eta$ determined by, for example, the primordial abundance of D lead to predictions for the primordial abundances of $^3$He, $^4$He and $^7$Li consistent with the observational data.

1.2 Status Quo Ante

Until recently, the program of confronting the predictions of SBBN with the observational data had led to increasing confidence in the consistency of the standard model (e.g., WSSOK [1]). For example, solar system and interstellar (ISM) observations of D and $^3$He have been used in concert with Galactic evolution models [2, 3, 4, 5] (or, nearly model-independent “inventories” [1, 6, 7, 8]) to bound the primordial D abundance from above, leading to a lower bound to $\eta$ ($\eta_{10} \geq 2.8$) [1]. At the same time, observations of $^4$He in low-metallicity, extragalactic HII regions [9, 10, 11, 12] and of $^7$Li in very metal-poor halo stars [13, 14, 15] have led to upper bounds on their primordial abundances, providing an upper bound to $\eta$ ($\eta_{10} \leq 4.0$) [1]. This quantitative agreement between theory and observations for the abundances of the light nuclides, covering some nine orders of magnitude, provides strong support for the consistency of SBBN. Furthermore, it should be emphasized that the inferred value (range) of $\eta$ is in reasonable agreement with estimates of the baryon density derived from the dynamics of “luminous” (i.e., baryonic) matter (see, e.g., [16] and references therein) thus providing support for the extrapolation from the present universe to its earliest epochs. However, lest we fly too high on the sweet smell of success, it is sobering to recount the suggestions of problems with this quantitative comparison [17].

1.3 Hints Of A Crisis

For SBBN the primordial abundances of D and $^3$He decrease and that of $^4$He increases with increasing nucleon-to-photon ratio (see Fig. 1), so that the lower bound to $\eta$ inferred from observational upper bounds to D and $^3$He leads to a predicted lower bound to the primordial $^4$He mass fraction. Alternatively, the upper bound on $Y_P$ from the observational data leads to an upper bound to $\eta$ and a lower bound to the primordial abundance of D (or D+$^3$He). Observations of D
and $^3\text{He}$ “prefer” a relatively large lower bound to $\eta$ while those of $^4\text{He}$ “favor” a relatively small upper bound to $\eta$. This “tension” between $D$ and $^3\text{He}$ on the one hand, and $^4\text{He}$ on the other, provides a hint of a problem (e.g., [1, 6, 17]). In Figure 2 this “crisis” is displayed. Superposed on the SBBN predictions for the abundances of $D$, $^4\text{He}$ and $^7\text{Li}$ are the 68% and 95% confidence level bands inferred from the observational data [15]. Notice that the range of $\eta$ delimited by $D$ has (at 95%) no overlap with that inferred from $^4\text{He}$. This is the “crisis” [17]. Another way to visualize the crisis is provided by Figure 3 where the 68% and 95% CL ranges for $\eta$ have been fixed by the inferred primordial abundances of $D$, $^3\text{He}$ and $^7\text{Li}$, leading to predicted ranges for $Y_p$ which are to be compared to the upper bound derived from the HII region data [12]. Impressive as is the approximate consistency of SBBN, the standard model is seriously challenged.

2 Three Possible Solutions

The hint of a crisis outlined above bears some similarities to several crises which challenged the 19th century “standard model” (Newtonian mechanics/gravity) when solar system observations appeared to disagree with theoretical predictions. The “Uranus crisis” was real (accurate data) and was resolved in favor of the standard model leading to the discovery of something new: Neptune. The “Neptune crisis” was illusory (inaccurate data), the standard model remained consistent, and the discovery of Pluto was an “accident”. Most exciting, of course, was the resolution of the “Mercury crisis”. The crisis was real (the data accurate) and the standard model was superseded by General Relativity. Similar options appear available for the resolution of the current crisis. Perhaps the data used to derive the abundances of one or more of the light nuclides are tainted by unrecognized statistical or systematic errors (the Neptune crisis). Or perhaps the data are accurate but there are unforeseen astrophysical effects, unaccounted for in our extrapolation from the derived abundances to their inferred primordial values (the Uranus crisis). We would, however, be remiss to ignore the possibility (the Mercury crisis) that this conflict may be revealing evidence for new physics (cosmology and/or particle physics). Although the ultimate resolution of the current crisis may require some combination of the above suggestions, here I will consider them separately and identify possible examples of each.

2.1 Inaccurate Data: $^4\text{He}$

Once the number of light neutrino flavors is fixed ($N_\nu = 3$ for SBBN), the predicted $^4\text{He}$ mass fraction is a relatively insensitive function of $\eta$ (see, e.g., Figs. 1-3). However, as $^4\text{He}$ is the second most abundant nuclide, $Y$ may be determined very accurately in a variety of environments spread throughout the universe. One source of the current crisis is the relatively low upper bound
to $\eta$ inferred from the primordial abundance ($Y_P = 0.232 \pm 0.003 \pm 0.005$) derived from observations of recombination emission from hydrogen and helium in extragalactic HII regions [8, 11, 12]. Although there are large numbers of low metallicity HII regions which have been observed carefully, minimizing the extrapolation to the primordial abundance and leading to a very small statistical uncertainty in $Y_P$ (0.003), perhaps there are large systematic corrections along the path from the observed equivalent widths to the derived abundances which exceed the estimate of 0.005 [12]. For example, since neutral helium is unobservable, perhaps there is hidden neutral helium in regions where hydrogen is fully ionized. If unaccounted for, this would bias the results to abundances which are systematically low. The observers (clever as they are) have anticipated this possibility and have restricted attention to “high excitation” HII regions where observations of other ions and comparisons with models suggest this ionization correction is negligible. Indeed, for the low metallicity HII regions observed, the hard radiation spectrum from the very hot stars may even reverse this effect (neutral H where He is fully ionized) [11]. Such an effect might even correlate with metallicity (downward correction to $Y$ for low metallicity, upward correction for higher values), leading to a reduction in the derived value of $Y_P$. Collisional excitation (especially from the metastable level in HeI) could enhance the helium emission leading to an overestimate of $Y$. Most estimates suggest this effect is small, and the observers do, in one of several ways, try to correct for it. Perhaps they have overcorrected, leading to an abundance which is systematically too low. Again, since collisional excitation is temperature-dependent and metal-poor HII regions might be hotter, this systematic effect might correlate with metallicity.

The bottom line here is that if $Y_P = 0.246$ (rather than 0.232; see, e.g., [18]), the crisis would be resolved (in favor of a relatively higher value of $\eta$ and relatively lower values of primordial D and $^3$He and a higher value for primordial $^7$Li).

2.2 Uncertain Extrapolation: D?

Until recently, deuterium had only been observed “here and now” in the solar system [19] and the (very local) ISM [20, 21]. The older Copernicus UV data and the newer HST data lead to a reasonably accurate value for the abundance of ISM D ($D/H = 1.6 \pm 0.2 \times 10^{-5}$). Solar system data (meteoritic $^3$He abundances, deuterated molecules in the giant planets, etc.) lead to a slightly larger (and slightly less accurate) abundance [19]. So far, so good. Although these data are local (in space and in time), they are still of great value since the evolution of deuterium is simple. Other than the big bang, there are no astrophysical sites for the production of significant abundances of D [22], and D is destroyed whenever gas forms stars. Thus, $y_2$ (actually $X_2$, the deuterium mass fraction) has only decreased since primordial nucleosynthesis ended ($y_{2P} \geq y_{2ISM}$; actually, $X_{2P} \geq X_{2ISM}$). As a result, observations of deuterium anywhere, anytime provide a
lower bound to its primordial abundance and, therefore, an upper bound to $\eta$.

The bad news is that both the present ISM and the presolar nebula are evolved; they contain gas which has been processed through stars (where D is destroyed). To bound $\eta$ from below requires that we bound $y_{2P} (X_{2P})$ from above and this requires knowledge of Galactic chemical evolution. For a wide assortment of independent (but similar) chemical evolution models [2, 3, 5, 23], designed to account for the observed age-metallicity relation, the observed gas/stars ratio, various abundance ratios (e.g., secondary to primary nuclei), etc., it is predicted that D is destroyed by a factor of 2 – 3 [5]. Given the strong dependence of $y_{2P}$ on $\eta$ (see, e.g., Figs. 1 & 2), such a modest destruction factor coupled with the accurate ISM abundance leads to a reasonably narrow range for $\eta$ which, however, corresponds to a SBBN predicted abundance for $^4$He larger than that inferred from the HII region data (the “crisis”). Although reasonable, these upper bounds to primordial D are model-dependent. Could “designer” models for Galactic evolution be found which, while maintaining consistency with the wealth of observational data, nonetheless permit much larger D destruction? Without detailed models which have actually been confronted with the data, it is difficult to answer this question. Nonetheless, there are reasons to believe it will not be easy to find such models based on several nearly model-independent approaches which have been explored previously.

### 2.2.1 The D+$^3$He Inventory

One such approach to bounding D destruction has been to exploit the fact that when D is incorporated into stars and burned, it is first burned to $^3$He [24, 25]. The more resilient $^3$He burns at a higher temperature than D, and so, while all the D is destroyed, some $^3$He survives stellar processing. Indeed, in stars of all masses there are interior zones where hydrogen burning results in the production of new $^3$He. Thus, in general, the more gas cycled through stars (and the more D destroyed), the more $^3$He might be expected [1, 6, 26, 27]. Unfortunately, the evolution of $^3$He is very complex involving a competition between new production and the destruction and survival of the prestellar D+$^3$He. New production of $^3$He is uncertain. If it is ignored current observations (ISM and/or solar system) of D and $^3$He [19, 20, 21] may be used to provide upper bounds on primordial D and $^3$He, nearly independent of the details of Galactic chemical evolution [1, 6]. All the unknown model-dependence of stellar and Galactic chemical evolution is contained in $\langle g_{3} \rangle$, the average $^3$He “survival fraction”.

Such an approach was pioneered by Yang et al. [6] and has been refined and updated by Steigman & Tosi [6] and Hata et al. [8]. For $\langle g_{3} \rangle \geq 1/4$ and employing solar system D and $^3$He and ISM D data, Hata et al. [8] derive for SBBN the best fit values (95% CL): $(D/H)_P = 3.5^{+2.7}_{-1.8} \times 10^{-5}$ and $\eta_{10} = 5.0^{+2.9}_{-1.5}$. This 95% CL range for $\eta_{10}$ derived from D and $^3$He alone, is considerably higher than the previously preferred range (WSSOK), exacerbating the tension between D and $^4$He since it predicts (for SBBN) $Y_P = 0.247 \pm 0.004$, far in excess of the value in-
ferred from the HII region observations [12]. This strong disagreement could be ameliorated if \( g_3 \) is smaller than the value \((1/4)\) usually adopted [1, 6, 7, 8, 27]. For \( g_3 \leq 0.1 \), considerably less \(^3\)He survives, permitting more destruction of D, consistent with a larger primordial abundance (corresponding to lower values of \( \eta \) and \( Y_p \)). Production of new \(^3\)He, if any, would have an effect similar to that of increasing \( g_3 \), restricting primordial D and \(^3\)He to lower abundances leading to higher values of \( \eta \). There are reasons to suspect that current stellar models may overestimate the production of \(^3\)He [3, 28, 29, 30, 31]. But, even if total destruction in stars less massive than \( 2.5M_\odot \) is assumed, \( g_3 \geq 0.3 \) for gas which has been cycled through one (and only one) generation of stars [3]. Thus to reduce \( g_3 \) would seem to require a model where gas was efficiently cycled through several generations of stars. As outlined in the next section, there may be problems with such models.

### 2.2.2 Constraints On D Depletion From Metallicity And Gas/Stars

As mentioned above, to relax the upper bound on the primordial abundance of D (and, correspondingly, the lower bounds on \( \eta \) and \( Y_p \)) seems to require chemical evolution models which are efficient in cycling gas through stars. \(^3\)He provides one possible constraint on such models which, however, may be plagued by uncertainties in stellar modelling. The observed metallicity provides another such constraint [32, 33]. The more gas cycled through stars, the higher the metallicity in young stars and newly returned gas. It will be a challenge for “designer” models of Galactic evolution to accommodate large D destruction while avoiding overproduction of the heavy elements. Perhaps this might be accomplished by expelling (via winds or superbubbles?) the metal-enriched gas while retaining the D-depleted gas; it remains to be seen whether realistic models of this type can be found.

Another challenge to such models is the observed ratio of mass in gas to that in stars (e.g., [34]). Is the relatively high observed gas/stars ratio consistent with models which efficiently cycle the gas through stars (e.g., see [22])? Such models might require infall to replenish the gas supply, but if the infalling gas consists largely of unprocessed material, the ISM D abundance is driven back towards its primordial value.

Nonetheless, given our ignorance of Galactic chemical evolution, we cannot dismiss the possibility that D has been destroyed by a large factor \((\sim 5 - 10)\) between the big bang and the present epoch. If so, lower values of \( \eta \) might be compatible with ISM and solar system observations of D (and \(^3\)He), leading to lower predicted values for \( Y_p \), consistent with the HII region data. Perhaps the astrophysics is at fault. Recent data from high redshift (\( z \)), low metallicity (\( Z \)) QSO absorbing clouds present ambiguous support for this possibility (see Sec. 3).
2.3 New Physics: A Massive Tau Neutrino?

Due to the gap at mass-5 and the strong binding of $^4$He, once BBN begins most available neutrons are burned to helium-4. As a result, although $Y_P$ is relatively insensitive to $\eta$, it is closely tied to the neutron-to-proton ratio at BBN. In turn, $n_n/n_p$ is regulated by the competition between the weak interaction rates ($n \leftrightarrow p$) and the universal expansion rate ($H$). $H$ is fixed by the total energy density at BBN and, for SBBN, is dominated by the contribution from the extremely relativistic particles present ($\gamma, e^\pm, \nu_e, \nu_\mu, \nu_\tau$). In units of the photon density, for SBBN, $\rho_{TOT}^{SBBN}/\rho_\gamma = 43/8$. If, due to “new physics”, $H$ is changed from its SBBN value, $n_n/n_p$ at BBN will be modified leading to a different $Y_P$ versus $\eta$ relation. One such possibility is that the standard cosmology may be modified due to a variation in $G$, the Newtonian gravitational “constant”. Another is that the particle physics content of the early universe could change due to the presence of additional light neutrinos or light scalars, or if the tau neutrino were very massive ($> \sim 10$ MeV) and unstable [35]. It is convenient to parameterize such changes by $N_\nu$ [36], the “effective number of equivalent light neutrinos” (complementary to the number of standard model neutrinos probed by collider experiments) where $N_\nu$ is defined by,

$$\frac{\rho_{TOT}/\rho_{TOT}^{SBBN}}{\rho_{TOT}^{SBBN}/\rho_\gamma} = 1 + 7(N_\nu - 3)/43$$

For $N_\nu > 3$, the early universe expands more quickly, leaving behind more neutrons to be incorporated into $^4$He during BBN, and vice-versa. To a good first approximation, $\Delta Y_P \approx 0.01(N_\nu - 3)$. Since one aspect of the crisis is that SBBN consistent with the inferred primordial abundances of D, $^3$He and $^7$Li predicts a value for $Y_P$ which is larger than that derived from the extragalactic HII regions by $\Delta Y_P \approx 0.01$, $N_\nu \approx 2$ could reestablish consistency [37, 42]. Of the myriad possibilities, a massive (unstable) tau neutrino provides one option for reducing $N_\nu$ from its SBBN value of 3 to one closer to 2 [35]. Current collider experiments are capable of exploring the interesting mass range ($> \sim 10$ MeV) and either ruling out this option or confirming it.

3 High-z, Low-Z Deuterium

As noted earlier, the relatively strong dependence of the SBBN predicted abundance of D on $\eta$, coupled with the simple evolution of deuterium, identifies D/H as the ideal baryometer. It has been anticipated that observations of deuterium in high redshift (nearly primordial), low metallicity (nearly unevolved) QSO absorption systems would resolve the current confusion, relieving the tension between theory and observations. Unfortunately, the few such cases identified to date have added to the confusion, and rather than relieving the tension, have led to a rupture. As described eloquently by Hogan [37], he favors the “high-D” results ($y_{2P} = 19 \pm 4 \times 10^{-5}$) [35, 38] while I’m sure Tytler [40, 41] would argue
for the “low-D” values ($y_{2P} = 2.4 \pm 0.3 \pm 0.3 \times 10^{-5}$). As may be seen from Figure 4 [42], if either of these values is correct (rather than something between the two) then the “true” value of $\eta$ is actually outside the old concordance range ($2.8 \leq \eta_{10} \leq 4.0$). For example, for “high-D”, $1.3 \leq \eta_{10} \leq 2.7$ (95%CL), while for “low-D”, $5.1 \leq \eta_{10} \leq 8.2$ (95%CL) [42]. For “high-D” the SBBN crisis dissipates, since the predicted abundances of $^4$He and $^7$Li ($Y_P = 0.234 \pm 0.002$, $y_{7P} = 1.5 \pm 0.6 \times 10^{-10}$) are in excellent agreement with their inferred primordial values [43]. In this case the challenge is in the chemical evolution court since the comparison of the high primordial D abundance with the low ISM value requires that deuterium should have been destroyed by a factor of $\sim 13$. In contrast, for “low-D”, the SBBN crisis is exacerbated [42] ($Y_P = 0.249 \pm 0.001$, $y_{7P} = 4.7 \pm 0.7 \times 10^{-10}$), while the D evolution (destruction by a factor of $\sim 1.6$) is consistent with “normal” Galactic chemical evolution models (e.g., [2, 3, 8]). As always (and as it should be) we await more data to resolve the current conundrum.

4  A Different Path To The Baryon Density

Given the current ambiguous state of affairs it may be of some value to explore non-BBN pathways to the baryon density. Here x-ray clusters may play a valuable role. To the extent that rich clusters of galaxies provide a “fair sample” of the universal baryon fraction, the cluster baryon fraction may be used in concert with dynamical determinations of the total density (in clustered matter) to infer the baryon density.

$$\Omega_B = f_B \Omega ; \quad \eta_{10} = 273f_B\Omega h^2 \quad (3)$$

In equation (3), $H_0 = 100h = 70 \pm 10$ [44] and $\Omega$ is the density of clustered matter ($= \Omega_B + \Omega_{CDM}$ for “open” and “lambda” CDM models) in units of the critical density. Within the context of “open” and “lambda” CDM models observations of large scale clustering constrain the combination $\Omega h \approx \Gamma \approx 0.25 \pm 0.05$ [45]. From x-ray, optical and “mini-lensing” studies of rich clusters, $f_B^{\text{Cl}} \approx f_{\text{HG}} + f_{\text{GAL}} \approx (0.07 \pm 0.01)h^{-3/2} + (0.02 \pm 0.01)$ so that $\eta_{10} \approx 6.7 \pm 1.6$. Actually, further bounds on $\Omega$ and $H_0$ from large scale velocity flows [17] and the age of the Universe [48] tend to increase $\Omega$ and reduce $H_0$ from the rough estimate presented here, leading to a somewhat higher range for $\eta$ [46]. This is true also for “mixed” hot plus cold dark matter models where $\Omega \geq 1 - \Omega_{HDM} \geq 0.7$; even for $H_0 = 55 \pm 10$ [15], $\eta_{10} \geq 11 \pm 2$. Thus, in the context of a variety of CDM models, the preliminary results of this “dynamical” approach to the baryon density suggest a high value for $\eta$, consistent with that inferred from solar system and ISM D and $^3$He [8], favoring the low-D/high-$^4$He option.
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Figure Captions

Figure 1. SBBN predicted primordial abundances of $^4$He (mass fraction $Y_P$), D ($y_{2P} = (D/H)_P$), $^3$He ($y_{3P} = (^3\text{He}/H)_P$) and $^7$Li ($y_{7P} = (^7\text{Li}/H)_P$) as a function of $\eta$, the nucleon-to-photon ratio. This graph has been provided by D. Thomas.

Figure 2. SBBN predictions (solid lines) for $Y_P$, $y_{2P}$ and $y_{7P}$ along with their theoretical uncertainties (1$\sigma$) estimated via Monte Carlos (dashed lines) [17]. Also shown are the regions constrained by the observations at 68% and 95% (shaded regions and dotted lines respectively).

Figure 3. Theoretical (SBBN) predictions for the primordial helium-4 mass fraction ($Y_{th}$) at 68% (shaded region) and 95% (dotted curve) for $\eta$ constrained by the inferred primordial abundances of D, $^3$He and $^7$Li. Also shown are the 68% and 95% bounds to $Y_P$ inferred from observations of low-metallicity, extragalactic HII regions ($Y_{obs}$). The absence of overlap between $Y_{obs}$ and $Y_{th}$ is the “crisis”.

Figure 4. As for Figure 2 but, with the deuterium abundance inferred from the two sets of QSO absorption data [42].
$\eta_{10}$

BBN constraints 68, 95% C.L.

$Y_{BBN}$ 68, 95% C.L.

$Y_{th}$ 68, 95% C.L.

$Y_{obs}$ 68, 95% C.L.
