NON-BBN CONSTRAINTS ON THE KEY COSMOLOGICAL PARAMETERS

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Abstract. Since the baryon-to-photon ratio $\eta_{10}$ is in some doubt at present, we ignore the constraints on $\eta_{10}$ from big bang nucleosynthesis (BBN) and fit the three key cosmological parameters ($h, \Omega_M, \eta_{10}$) to four other observational constraints: Hubble parameter ($h_0$), age of the universe ($t_0$), cluster gas (baryon) fraction ($f_0 \equiv f_G h^{3/2}$), and effective shape parameter ($\Gamma_0$). We consider open and flat CDM models and flat $\Lambda$CDM models, testing goodness of fit and drawing confidence regions by the $\Delta \chi^2$ method. CDM models with $\Omega_M = 1$ (SCDM models) are accepted only because we allow a large error on $h_0$, permitting $h < 0.5$. Open CDM models are accepted only for $\Omega_M > 0.4$. $\Lambda$CDM models give similar results. In all of these models, large $\eta_{10}$ ($\sim > 6$) is favored strongly over small $\eta_{10}$ ($\sim < 2$), supporting reports of low deuterium abundances on some QSO lines of sight, and suggesting that observational determinations of primordial $^4$He may be contaminated by systematic errors. Only if we drop the crucial $\Gamma_0$ constraint are much lower values of $\Omega_M$ and $\eta_{10}$ permitted.

Key words: Baryon-to-photon ratio, Universal matter density, Hubble parameter

1. Introduction

In the context of the hot big bang cosmology, if the number of light-neutrino species has its standard value $N_\nu = 3$, the predicted primordial abundances of four light nuclides (D, $^3$He, $^4$He, and $^7$Li) depend on only one free parameter, $\eta_{10}$, the universal ratio (at present) of nucleons (baryons) to photons (in units $10^{-10}$). In principle, $\eta_{10}$ is overdetermined by the observed or inferred primordial abundances of the four light nuclides. Indeed, Steigman, Schramm, and Gunn (1977) have exploited this fact to use big bang nucleosynthesis (BBN) to constrain $N_\nu$. The status quo ante is that observations, principally of D and $^4$He, have rendered $\eta_{10}$ one of the best known of the key cosmological parameters: $\eta_{10} = 3.4 \pm 0.3$ (Walker et al., 1991; the error bars being roughly “1σ”).

At present, when the microwave background temperature $T = 2.728$ K (Fixsen et al., 1996), the universal baryonic mass-density parameter $\Omega_B \equiv 8\pi G \rho_B / 3H_0^2$ is related to $\eta_{10}$ by

$$\Omega_B h^2 = 3.667 \times 10^{-3} \eta_{10} = 0.0125 \pm 0.0011. \quad (1)$$
However, recently there have emerged reasons to suspect that $\eta_{10}$ may not be so well determined, and even that the standard theory of BBN may not provide a very good fit to the current data (Hata et al., 1995). There are several options available for resolving this apparent conflict between theory and observation. Although some change in standard physics could offer resolution (e.g., a reduction in the effective value of $N_\nu$ during BBN below its standard value 3; cf. Hata et al., 1995), Hata et al. (1995) note that large systematic errors may compromise the abundance data (cf. Copi, Schramm, and Turner, 1995).

This controversy has been sharpened by new observations giving the deuterium abundances on various lines of sight to high-redshift QSOs. In principle, these data should yield the primordial D abundance, but current results span an order of magnitude. If the low value ($\text{D/H by number} \approx 2 \times 10^{-5}$; Tytler, Fan, and Burles, 1996; Burles and Tytler, 1996) is correct, then $\eta_{10} \approx 7$ in the standard model, but then it seems impossible to reconcile the inferred abundance of $^4\text{He}$ [Olive and Steigman, 1995 (OS)] with (standard) BBN for this value of $\eta_{10}$ unless there are large systematic errors in the $^4\text{He}$ data. If, instead, the high figures ($\text{D/H} \approx 2 \times 10^{-4}$; Carswell et al., 1994; Songaila et al., 1994; Rugers and Hogan, 1996) are correct, then D and $^4\text{He}$ are consistent with $\eta_{10} \approx 2$, but modellers of Galactic chemical evolution have a major puzzle: How has the Galaxy reduced D from its high primordial value to its present (local) low value without producing too much $^3\text{He}$ (Steigman and Tosi, 1995), without using up too much interstellar gas (Edmunds, 1994; Prantzos, 1996), and without overproducing heavy elements (cf. Tosi, 1996, and references therein)? It appears that $\eta_{10}$, though known to order of magnitude, may now be among the less well-known cosmological parameters. Despite this, large modern simulations which explore other cosmological parameters are often limited to a single value of $\eta_{10} = 3.4$ (e.g., Borgani et al., 1997).

Given this unsettled situation Steigman, Hata, and Felten (1997; hereafter SHF) have proposed that it may be constructive to abandon nucleosynthetic constraints on $\eta_{10}$ entirely and to put $\eta_{10}$ onto the same footing as the other cosmological free parameters, applying joint constraints on all these parameters based on other (non-BBN) astronomical observations and on theory and simulation. Armed with $\eta_{10}$ determined in this manner we may then “predict” the primordial abundances of the light nuclides and compare with the data to test the consistency of standard BBN. In this contribution to the proceedings of the ISSI Workshop on Primordial Nuclei and Their Galactic Evolution (Bern, Switzerland, 6–10 May 1997) we present a brief description of our approach along with a summary of our results for a “standard” (fiducial) choice of the observational constraints. For further details (especially of the many variations on the standard case to be described herein) and references the reader is encouraged to consult SHF.
2. The Method: An Overview

Our approach is to let the three key cosmological parameters \((h, \Omega_M, \eta_{10})\) range freely, fit the constraints (observables other than nucleosynthetic) to be described below, test goodness of fit by \(\chi^2\), and draw formal confidence regions for the parameters by the usual \(\Delta \chi^2\) method. Most of the SHF results are not surprising, and related work has been done before (White et al., 1996; Lineweaver et al., 1997; White and Silk, 1996; Blduman, 1997), but not with these three free variables and the full \(\chi^2\) formalism. Further, some recent cosmological observations and simulations, particularly those related to the “shape parameter” \(\Gamma\) and the cluster baryon fraction (CBF), seem to pose a challenge to popular models, and there is some doubt whether any simple model presently fits all data well. Our approach, which begins by discarding nucleosynthetic constraints, provides a new way of looking at these problems. For example, the CBF and \(\Gamma\) constraints have not been applied jointly in earlier work which often also adopts a precise value for \(\eta_{10}\) (or \(\Omega_B\)).

SHF find that, given their conservative (generous) choice of error bar on \(h\), the SCDM model is disfavored but by no means excluded. But even with this generous error bar, large values \((\gtrsim 6)\) of \(\eta_{10}\) \((\Omega_B h^2 \gtrsim 0.022)\) are favored strongly over low values \((\lesssim 2; \Omega_B h^2 \lesssim 0.007)\). This suggests that the low D abundances measured by Tytler et al. (1996) and by Burles and Tytler (1996) may be correct, and that the observed (extrapolated) primordial helium-4 mass fraction \([Y_P \approx 0.23; \text{cf. OS and Olive, Skillman, and Steigman, 1997 (OSS)}]\), thought to be well determined, may be systematically too low for unknown reasons.

3. CDM Models: Parameters and Observables

3.1. Parameters

The CDM models we consider are defined by three free parameters: Hubble parameter \(h\); mass-density parameter \(\Omega_M = 8\pi G \rho_M / 3 H_0^2\); and baryon-to-photon ratio \(\eta_{10}\), related to \(\Omega_B\) by equation \([\text{II}]\). Here \(\Omega_M\) by definition includes all “dynamical mass”: mass which behaves dynamically like ordinary matter in the universal expansion; \(\Omega_M\) is not limited to clustered mass only. Other free parameters having to do with structure formation, such as the tilt parameter \(n\), could be added (White et al., 1996; Kolatt and Dekel, 1997; White and Silk, 1996), but generally we have tried to avoid introducing many free parameters.
3.2. Observables

We consider four observables (constraints) with measured values and with errors which are assumed to be Gaussian: (1) Hubble parameter $h_0$; (2) age of the universe $t_o$; (3) gas-mass fraction $f_o \equiv f_G h^{3/2}$ in rich clusters; and (4) “shape parameter” $\Gamma_o$ from structure studies. In SHF we considered a fifth constraint: the dynamical mass-density parameter $\Omega_o$ as inferred from cluster measurements or from large-scale flows. Here, we ignore this constraint but we shall comment on its relation to our “standard” results.

3.2.1. Observed Hubble Parameter $h_0$

For the Hubble parameter the observable $h_o$ is simply fit with the parameter $h$. Measurements of $h$ still show scatter which is large compared with their formal error estimates (Bureau, Mould, and Staveley-Smith, 1996; Tonry et al., 1997; Kundić et al., 1997; Tammann and Federspiel, 1997). This indicates systematic errors. To be conservative (permissive), we adopt $h_o = 0.70 \pm 0.15$. Perhaps a smaller error could be justified; below we will comment on the consequences of shrinking the error bar.

3.2.2. Observed Age of the Universe $t_o$

The age for these $\Lambda = 0$ models is a function of $h$ and $\Omega_M$ given by: $t = 9.78 h^{-1} \times f(\Omega_M; \Lambda=0)$ Gyr [Weinberg, 1972, equations (15.3.11) & (15.3.20)]. We take the observed age of the oldest globular clusters as $t_{GC} = 14 \pm 2$ Gyr (Bolte and Hogan, 1995; Jimenez, 1997; D’Antona, Caloi, and Mazzitelli, 1997; Chaboyer et al., 1997; Cowan et al., 1997; cf. Nittler and Cowsik, 1997). The universe is older than the oldest globular clusters by an unknown amount $\Delta t$. Although most theorists believe that $\Delta t$ must be quite small (1 or 2 Gyr at most), we are unaware of any conclusive argument which guarantees this. To keep things simple, SHF introduced asymmetric error bars: $t_o = 14^{+7}_{-2}$ Gyr, allowing enough extra parameter space at large ages to accommodate a conservative range of $\Delta t$; extremely large ages will be eliminated by the $h_o$ constraint in any case.

3.2.3. Observed Gas Mass Fraction in Clusters $f_o$

As is suggested by simulations, we assume that rich clusters provide a fairly unbiased sample of the universal ratio of baryonic to dark matter. Thus, we use the cluster (hot) gas fraction, $f_G$, not as a constraint on $\Omega_M$, but as a constraint on the universal baryon fraction, the ratio $\Omega_B/\Omega_M$. We emphasize that the following argument assumes that rich clusters provide a fair sample of the universal baryon fraction but does not assume that most of the mass in the universe, or any specific fraction of it, is in rich clusters.

The measurement of $f_G$ poses some problems; for discussion and references, see SHF. We have followed the approach of Evrard, Metzler, and
Navarro (1996), who used gas-dynamical simulations to model the observations. They find that the largest contribution to the error in \( f_G \) arises from the measurement of the cluster’s total mass, and they suggest that this error can be reduced by using an improved estimator and by restricting the measurement to regions of fairly high overdensity. Evrard (1997) applies these methods to data for real clusters and finds \( f_G h^{3/2} = 0.060 \pm 0.003 \). To be conservative, we double his error bars and adopt for our constraint

\[
fo = f_G h^{3/2} = 0.060 \pm 0.006.
\]  

We are interested in the baryonic mass fraction, \( \Omega_B/\Omega_M \), but even in rich clusters not all baryons are in the form of gas, and selection factors may operate in bringing baryons and dark matter into clusters. White et al. (1993) introduced a “baryon enhancement factor” \( \Upsilon \) to describe these effects. \( \Upsilon \) may be defined by

\[
f_G^0 = \Upsilon \Omega_G/\Omega_M,
\]  

where \( \Omega_G \) is the initial contribution of gas to \( \Omega_M \) (note that \( \Omega_G \leq \Omega_B \)) and \( f_G^0 \) is the gas mass fraction in the cluster immediately after formation. \( \Upsilon \) is really the gas enhancement factor, because the simulations do not distinguish between baryonic condensed objects if any (galaxies, stars, machos) and non-baryonic dark-matter particles. All of these are lumped together in the term \( (\Omega_M - \Omega_G) \) and interact only by gravitation.

If all the baryons start out as gas (\( \Omega_G = \Omega_B \)), and if gas turns into condensed objects only after cluster formation, then equation (3) may be rewritten:

\[
f_G + f_{\text{GAL}} = \Upsilon \Omega_B/\Omega_M,
\]  

where \( f_G \) is the present cluster gas-mass fraction and \( f_{\text{GAL}} \) the present cluster mass fraction in baryonic condensed objects of all kinds (galaxies, stars, machos). White et al. (1993) took some pains to estimate the ratio \( f_G/f_{\text{GAL}} \) within the Abell radius of the Coma cluster, counting only galaxies (no stars or machos) in \( f_{\text{GAL}} \). They obtained

\[
f_G/f_{\text{GAL}} = 5.5 h^{-3/2}.
\]  

This is large, so unless systematic errors in this estimate are very large, the baryonic content of this cluster (at least) is dominated by the hot gas. Carrying \( f_{\text{GAL}} \) along as an indication of the size of the mean correction for all clusters, and solving equations (4) and (5) for \( f_G h^{3/2} \), we find

\[
f_G h^{3/2} = \left[ 1 + (h^{3/2}/5.5) \right]^{-1} (\Upsilon \Omega_B/\Omega_M) h^{3/2},
\]  

where \( \Omega_B \) is given from \( \eta_{10} \) and \( h \) by equation (1).
This is the appropriate theoretical function of the free parameters to fit to the observations. We set $\Upsilon = 0.9$ in our “standard” case. Although this is representative of results from simulations, Cen (1997) finds that the determination of $f_G$ from X-ray observations may be biased toward high $f_G$ by large-scale projection effects; i.e., the calculated $f_G$ exceeds the true $f_G$ present in a cluster by a bias factor which can be as large as 1.4. Although Evrard et al. (1996) and Evrard (1997) have not observed such a bias in their simulations, SHF explored its effect on our analysis by using for $\Upsilon$, instead of 0.9, an “effective value” $\Upsilon \approx 0.9 \times 1.4 \approx 1.3$.

3.2.4. Shape Parameter $\Gamma_o$ from Large-Scale Structure

The last observable we use is the “shape parameter” $\Gamma$, which describes the transfer function relating the initial perturbation spectrum $P_I(k) \propto k^n$ to the present spectrum $P(k)$ of large-scale power fluctuations, as observed, e.g., in the galaxy correlation function. When the spectral index $n$ of $P_I(k)$ has been chosen, $\Gamma$ is determined by fitting the observed $P(k)$.

Results of observations may be cast in terms of an “effective shape parameter” $\Gamma$ (White et al., 1996) which we take as our observable. Studies show that for the usual range of CDM models, with or without $\Lambda$, the expression for $\Gamma$ is

$$\Gamma \approx \Omega_M h \exp \left[ -\Omega_B - (h/0.5)^{1/2} (\Omega_B/\Omega_M) \right] - 0.32 (n^{-1} - 1)$$

(7)

(Peacock and Dodds, 1994; Sugiyama, 1995; Liddle et al., 1996a,b; White et al., 1996; Liddle and Viana, 1996; Peacock, 1997). For $n \approx 1$, if $\Omega_B$ and $\Omega_B/\Omega_M$ are small, we have $\Gamma \approx \Omega_M h$. The Harrison-Zeldovich (scale-invariant, uniltled) case is $n = 1$, which we adopt for our standard case.

In contrast to the “standard” case in SHF, here we adopt the more conservative choice (larger error bars) for the observed value of $\Gamma$,

$$\Gamma_o = 0.25 \pm 0.05$$

(8)

(cf. Peacock and Dodds, 1994; Maddox, Efstathiou, and Sutherland, 1996). This is based on the galaxy correlation function, and it assumes that light traces mass. Equations (7) and (8) imply, very roughly, that $\Omega_M h \approx 0.25$.

The shape-parameter constraint is in a sense the least robust of the constraints we have discussed since it is not part of the basic Friedmann model. Rather, it depends on a theory for the primordial fluctuations and how they evolve. If the Friedmann cosmology were threatened by this constraint, we believe that those who model large-scale structure would find a way to discard it. Therefore SHF have also explored the consequences of removing this constraint and replacing it with one on $\Omega_M$ derived from the $M/L$ ratio in clusters and the luminosity density of the universe (Carlberg, Yee, and Ellingson, 1997) or one based on studies of large-scale flows around voids (Dekel and Rees, 1994; cf. Dekel, 1997).
4. CDM Models: Results

4.1. Standard Constraints

For our standard case we have four observational constraints: $h_0 = 0.70 \pm 0.15$, $t_0 = 14^{+7}_{-2}$ Gyr, $f_0 \equiv f_G h^{3/2} = 0.060 \pm 0.006$, and $\Gamma_0 = 0.25 \pm 0.05$. For this standard case we assume $n = 1$ and $\Upsilon = 0.9$. The results for our three cosmological parameters are displayed in Figures 1 and 2 where the 68% and 95% confidence regions (“CRs”) are shown. Also shown are the projected CRs obtained by computing $\chi^2$ for single observables alone, or for pairs of observables. These are not true CRs but are intended to guide the reader in understanding how the various constraints influence the closed contours which show our quantitative results.

Figure 1. 68% (shaded) and 95% (dotted) confidence regions (“CRs”) in the $(H_0, \Omega_M)$ plane for CDM models with our four standard constraints. The CRs are closed curves. Individual constraints in this plane are also shown schematically.
Our best-fit values for the three key cosmological parameters are: $\eta_{10} = 8.2^{+0.2}_{-0.2}$, $\Omega_M = 0.48^{+0.22}_{-0.15}$ and $h = 0.58 \pm 0.22$. Although the condition $\Omega_M h \approx 0.25$ poses some threat to the SCDM ($\Omega_M = 1$) model, Figure 1 shows that this threat is far from acute given our more accurate form of the $\Gamma$ constraint in equation (5), as long as the error on $h$ is large (0.15) and BBN constraints are discarded. The exponential term in equation (5) becomes significant because the $f_G$ constraint forces $\Omega_B$ to increase with $\Omega_M$ allowing the product $\Omega_M h$ to exceed 0.25. This has been noted before (White et al., 1996; Lineweaver et al., 1997). The SCDM model with $\Omega_M = 1$ and $h \approx 0.45$ is acceptable but the high value for the baryon-to-photon ratio, $\eta_{10} \approx 13$, is in conflict with the inferred primordial abundances of all the light nuclides. Note that, although the uncertainties are large, low values of $\eta_{10}$ are disfavored (see Figure 2).
If we add the Dekel-Rees estimate of $\Omega_M$ ($\Omega_o \gtrsim 0.4$), the five-constraint fit favors somewhat higher values of $\Omega_M$ and $\eta_{10}$ and slightly lower values of $h$. In contrast, if instead we include the cluster estimate ($\Omega_o = 0.2 \pm 0.1$; Carlberg, 1997; cf. Carlberg, Yee, and Ellingson, 1997), we find a barely acceptable fit ($\chi^2_{\text{min}} = 5.0$ for 2 DOF, 92% CL), which favors lower values of $\Omega_M$ and $\eta_{10}$ and slightly higher values of $h$.

4.2. Variations

Tilt in the primordial spectrum has been investigated in many papers (Liddle et al., 1996a,b; White et al., 1996; Kolatt and Dekel, 1997; White and Silk, 1996; Liddle and Viana, 1996). We considered the effect of a moderate “red tilt” ($n = 0.8$ instead of $n = 1$). This has the effect (see equation [4]) of raising slightly the 68% and 95% contours in Figure 1. With this tilt the $\Gamma$ constraint favors higher $\Omega_M$, so that the SCDM model is allowed for $h$ up to nearly 0.5. The favored likelihood range for $\eta_{10}$ is now also higher, though $\eta_{10} \approx 7$ is still allowed. However, the higher allowed range for $\eta$ does threaten the consistency of BBN. Conversely, a “blue” tilt, $n > 1$ (Hancock et al., 1994), would move the CR downward and allow models with $\Omega_M \leq 0.3$ at high $h$.

Changing to a gas enhancement factor $\Upsilon = 1.3$ (modest positive enhancement of gas in clusters) instead of 0.9 does not change the contours in Figure 1 by much since $\Gamma$ is only weakly coupled to $\Omega_B$ through the exponential term in $\Gamma$. Although the effect is to lower the contours in Figure 1 slightly and to move downward the acceptable range for $\eta_{10}$, $\eta_{10} \leq 4$ is still excluded, disfavoring the low D abundance inferred from some QSO absorbers and favoring a higher helium abundance than is revealed by the H II-region data.

The possibility that the fraction of cluster mass in baryons in galaxies, isolated stars, and machos ($f_{\text{CAL}}$) might be larger – even much larger – than implied by equation [3] would affect the CRs in much the same way as a small $\Upsilon$, favoring even higher values of $\Omega_M$ and $\eta_{10}$.

The $\Gamma$ constraint is crucial for our standard results favoring high $\Omega_M$ and high $\eta$. If, for example, we drop the $\Gamma$ constraint and in its place use the cluster estimate $\Omega_o = 0.2 \pm 0.1$, low $\Omega_M$ and low $\eta$ are now favored (see SHF).

The acceptability – or not – of the SCDM model depends crucially on the choice of Hubble parameter. SHF have experimented with replacing the standard constraint on $H_0$ with $h_o = 0.70 \pm 0.07$. Now, the SCDM model is strongly excluded.
4.3. \( \Lambda \)CDM MODELS

SHF have also considered models with nonzero \( \Lambda \), limiting their investigation to the popular flat \((k = 0)\) \( \Lambda \)CDM models with \( \Omega_\Lambda = 1 - \Omega_M \), where \( \Omega_\Lambda \equiv \Lambda/(3H_0^2) \). For these models there are still only three free parameters and the four constraints discussed earlier are still in force, except that the product of the age and the Hubble parameter is a different function of \( \Omega_M < 1 \): \( t = 9.78 h^{-1} f(\Omega_M; k = 0) \) Gyr [Carroll, Press, and Turner, 1992, equation (17)]. For a given \( \Omega_M < 1 \), the age is longer for the flat \((k = 0)\) model than for the \( \Lambda = 0 \) model. The results differ very little from those in Figures 1 and 2. The longer ages do allow the CRs to slide farther down toward large \( h \) and small \( \Omega_M \). Because of the longer ages at low \( \Omega_M \) (high \( \Omega_\Lambda \)), \( \Omega_o \) from clusters can now be accepted as a fifth constraint. In this case (see SHF) large \( \Omega_M \) and small \( h \) are now excluded while \( \eta_{10} > 4 \) is still favored strongly.

5. Conclusions

If BBN constraints on the baryon density are removed (or relaxed), the interaction among the shape-parameter (\( \Gamma \)) constraint, the cluster baryon fraction \( (f_G) \) constraint, and the value of \( \eta_{10} \) assumes critical importance. These constraints still permit a flat CDM model, but only as long as \( h < 0.5 \) is allowed by observations of \( h \). The \( f_G \) constraint means that large \( \Omega_M \) implies fairly large \( \Omega_B \). Therefore the exponential term in \( \Gamma \) becomes important allowing \( \Omega_M = 1 \) to satisfy the \( \Gamma \) constraint. However, values of \( \eta_{10} \approx 8 - 15 \) are required (see Figures 1 and 2). The best-fit SCDM model has \( h \approx 0.45 \) and \( \eta_{10} \approx 13 \), which is grossly inconsistent with the predictions of BBN and the observed abundances of \(^4\)He, and \(^7\)Li. For \( h > 0.5 \) a fit to SCDM is no longer possible. The SCDM model is severely challenged.

The \( \Gamma \) and age constraints also challenge low-density CDM models. The \( \Gamma \) constraint permits \( \Omega_M < 0.4 \) only for high \( h \), while the age constraint forbids high \( h \), so \( \Omega_M \gtrsim 0.4 \) is required. The bound \( \Omega_M \gtrsim 0.4 \) conflicts with the added cluster constraint \( \Omega_o = 0.2 \pm 0.1 \) at the 98% CL, suggesting strongly that there is additional mass not traced by light.

Although a few plausible variations on the CDM models do not affect the constraints very much, removing the \( \Gamma \) constraint would have a dramatic effect. Both high and low values of \( \Omega_M \) would then be permitted. The \( \Gamma \) constraint plays a crucial role in our analysis.

At either low or high density, the situation remains about the same for the \( \Lambda \)CDM models. Because the ages are longer, we can tolerate \( \Omega_M \approx 0.3 \) for \( h = 0.85 \). The \( \Lambda \)CDM model therefore accepts more easily the added constraint \( \Omega_o = 0.2 \pm 0.1 \). Improved future constraints on \( \Omega_\Lambda \) will come into play here.
Having bounded the baryon density using data independent of constraints from BBN, we may explore the consequences for the light-element abundances. In general, our fits favor large values of $\eta_{10}$ ($\gtrsim 6$) over small values ($\lesssim 2$). While such large values of the baryon density are consistent with estimates from the Ly-$\alpha$ forest, they do create some tension for BBN. For deuterium there is no problem, since for $\eta_{10} \gtrsim 6$ the BBN-predicted abundance, $(D/H)_{P} \lesssim 3 \times 10^{-5}$ ($2\sigma$), is entirely consistent with the low abundance inferred for some of the observed QSO absorbers (Tytler et al., 1996; Burles and Tytler, 1996). Similarly, the BBN-predicted lithium abundance, $(Li/H)_{P} \gtrsim 2.5 \times 10^{-10}$ ($2\sigma$), is consistent with the observed surface lithium abundances in the old, metal-poor stars (allowing, perhaps, some minimal destruction or dilution of the prestellar lithium). However, the real challenge comes from $^4$He where the BBN prediction for $\eta_{10} \gtrsim 6$, $Y_{P} \gtrsim 0.248$ ($2\sigma$), is to be contrasted with the H II-region data which suggest $Y_{P} \lesssim 0.238$ (OS, OSS).

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