Big-Bang Nucleosynthesis in Light of Discordant Deuterium Measurements

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ABSTRACT

Two dimensional concordance plots involving the baryon-to-photon ratio, $\eta$, and an effective number of light neutrinos, $N_\nu$, are used to discuss the overall consistency of standard big-bang nucleosynthesis in light of recent determinations of the primordial deuterium ($^2$H) abundance. Observations of high-redshift Ly-\(\alpha\) clouds have provided discordant $^2$H/H determinations: one cloud with $^2$H/H high compared with the previously accepted upper limit on ($^2$H + $^3$He)/H; and one system with a significantly lower upper bound on $^2$H/H than those previously obtained. The high value of $^2$H/H agrees well with the current observationally-inferred primordial abundances of $^4$He and $^7$Li for $N_\nu = 3$. The low value of $^2$H/H does not fit well with the current observationally-inferred primordial abundance of $^4$He for $N_\nu = 3$. In addition, if the low value of $^2$H/H is indicative of the primordial deuterium abundance, then significant depletion of $^7$Li in old, hot Pop II halo stars is probably required to obtain a concordant range of $\eta$, for any effective number of neutrino flavors. The use of conservative ranges for the primordial abundances of $^2$H, $^4$He, and $^7$Li allow success of the standard picture for $N_\nu = 3$.

Subject headings: cosmology: early universe — cosmology: observations — nuclear reactions, nucleosynthesis, abundances

Considerations of big bang nucleosynthesis (BBN) comprise our best probe of the physics of the early universe. Primordial nucleosynthesis calculations successfully predict the relative abundances of the lightest elements over some ten orders of magnitude. However, as claimed determinations of primordial abundances have grown in precision in the recent past, a number of different points of view have arisen regarding the overall consistency of the standard big-bang nucleosynthesis picture. The fact that proponents of these different points of view sometimes ascribe high confidence levels to their conclusions makes the situation all the more confusing.

Recent deuterium measurements in high-redshift Ly-\(\alpha\) clouds (Tytler, Fan, & Burles 1996; Rugers & Hogan 1996; see also Songaila et al. 1994; Carswell et al. 1994; Hogan 1995b) prompt a reexamination of the problem.

Though we recognize the basic success of the theory of BBN, we have little confidence that the commonly assigned uncertainties in the observationally-inferred primordial abundances of the light elements reflect the potentially large systematic errors in these quantities. Sasselov & Goldwirth...
(1995), for example, have emphasized how systematic errors in the observationally-inferred primordial $^4$He abundance conceivably can be much larger than the well-determined statistical errors (Olive & Steigman 1995; Olive & Scully 1995) in this measurement. Arguably, the primordial $^7$Li abundance can also be statistically well determined from the so-called “Spite plateau” (Spite & Spite 1982; Molaro, Primas, & Bonifacio 1993; Ryan et al. 1996), but significant depletion and/or production of $^7$Li may have occurred (Deliyannis, Boesgaard, & King 1995; Vanclain & Charbonnel 1995; Chaboyer & Demarque 1994). Any inference of the primordial $^3$He abundance is heavily dependent on models of stellar and galactic evolution (e.g., Dearborn, Steigman, & Tosi 1996; Hogan 1995a). As for $^2$H, at least three significantly different determinations of its primordial abundance exist, using two completely different methods.

Nevertheless, it is clearly desirable and possible to use BBN considerations to constrain $N_\nu$ and the baryon-to-photon ratio $\eta$. Here we follow common practice (e.g., Walker et al. 1991) and use $N_\nu$ to represent all relativistic particle degrees of freedom (except for photons and electrons) extant at the nucleosynthesis epoch. In this sense, $N_\nu$ parametrizes the expansion rate. Given our lack of precise knowledge of the primordial abundances at present, it is useful to explore the leverage each elemental abundance has on both “concordance” and the values of $N_\nu$ and $\eta$. A useful tool for this purpose is a two-dimensional concordance plot, in which abundance contours are plotted in the $\eta$-$N_\nu$ plane. (Similar plots have been used in the past in other contexts, for example by Kang & Steigman (1992) in a study of the effects of neutrino degeneracy on the outcome of BBN.) These plots give insight into both the degree of compatibility of determinations of the primordial abundances of $^2$H, $^4$He, and $^7$Li amongst themselves, and the compatibility of these abundances with the assumption of three families of light neutrinos and no additional relativistic degrees of freedom, i.e. $N_\nu = 3$.

In this work, the primordial abundances of $^4$He, $^2$H, and $^7$Li were computed with the Kawano (1992) update of the Wagoner (1969, 1972) code. We have used the world average neutron lifetime of 887.0 s (Montanet et al. 1994), and the reaction rates of Smith, Kawano, & Malaney (1993). In addition, we have employed a small correction to the $^4$He mass fraction (+0.0031, roughly independent of $\eta$) which arises from higher order effects in the weak rates and the use of a smaller time step (Kernan & Krauss 1994). We have not accounted for the reaction rate uncertainties in the calculated BBN yields (Krauss & Kernan 1993), except to consider the effect on the calculated abundance of $^7$Li, the element for which the theoretical uncertainty is by far the largest of any of the elements produced by BBN. However, given the potential systematic uncertainties in the inferred primordial abundances, we do not attempt to obtain precise numerical limits on $N_\nu$ or $\eta$ with associated statistically meaningful confidence levels. Our goal is simply to indicate the ranges of $N_\nu$ and $\eta$ suggested by various deuterium measurements.

Consider Fig. 1, in which the range of primordial $^2$H obtained by Hata et al. (1995b) is employed: $1.7 \leq d_5 \leq 6.2$, which is assigned a 95% C.L. (In our discussion of the primordial light element abundances, we use the following definitions: $d_5 \equiv ^2$H/H $\times 10^5$; $l_{10} \equiv ^7$Li/H $\times 10^{10}$; and $Y$ is the primordial mass fraction of $^4$He.) This range of $d_5$ is determined from solar system and
interstellar medium measurements, and models of chemical evolution. While this specific range was determined for \( N_\nu = 3 \), we will take it as representative of the most stringent inferences of the primordial deuterium abundance that can be obtained from “local” measurements. Recently adopted ranges for the observationally-inferred primordial abundances of \(^4\)He and \(^7\)Li are (Olive 1995) \( 0.223 \leq Y \leq 0.245 \) and \( 0.7 \leq l_{10} \leq 3.8 \), respectively. These ranges include \( \pm 2\sigma \) statistical and \( \pm 1\sigma \) systematic errors. Included in the systematic error in the range for \(^7\)Li/H is an allowance for a factor of two depletion to get from the primordial abundance to the measured value on the Spite plateau.

The primordial abundances of \(^4\)He, \(^2\)H, and \(^7\)Li will constrain bands in the \( \eta - N_\nu \) plane, whose overlap yields an ‘allowed region.’ For the range of primordial \(^2\)H/H adopted in Fig. 1, it is clear that the standard model value of \( N_\nu = 3 \) is only marginally compatible with the conventional \( 2\sigma \) upper limit of \( Y = 0.245 \). This is one of the central contentions of the Hata et al. (1995a) paper: they claim a best fit of \( N_\nu = 2.1 \pm 0.3 \), with \( N_\nu = 3 \) ruled out at 98.6% C.L. This potential conflict was noted earlier by Kernan & Krauss (1994). A philosophically different statistical approach, however, is taken by Copi et al. (1995b). In that work, a Bayesian analysis is employed in which it is taken as a prior assumption that there are at least three neutrino flavors. This procedure necessarily yields an upper limit on \( N_\nu \) which is greater than three. They then argue that the \(^4\)He abundance has been systematically underestimated.

Another method of measuring \(^2\)H involves the observation of Lyman-\( \alpha \) systems in the line of sight to QSOs via their absorption spectra. This method has the potential to more accurately determine the primordial \(^2\)H abundance, since the QSO absorption systems are at high redshift and have very low metallicity (Hogan 1995; Malaney & Chaboyer 1996; Jedamzik, Fuller, & Tytler 1996). Fig. 2 shows the range of primordial \(^2\)H inferred from the first such system in which \(^2\)H has been claimed to be detected (Hogan 1995; see also Songaila et al. 1994; Carswell et al. 1994; Rugers & Hogan 1996). We have used the latest range cited by Hogan (1995b): \( 1.5 \leq d_4 \leq 2.3 \). This reflects only \( 1\sigma \) errors; since statistical and systematic errors are combined in this range, we are not able to extend the statistical errors to the \( 2\sigma \) level. The adopted \(^4\)He and \(^7\)Li primordial abundance bands in Fig. 2 are the same as in Fig. 1. From this figure it is clear that \( N_\nu = 3 \) fits well with the adopted primordial abundance ranges of all three elements plotted. Interestingly, this range for deuterium is essentially that picked out if \( N_\nu = 3 \) is assumed, and only the conventional observationally-inferred ranges of primordial \(^4\)He and \(^7\)Li abundances are used to determine the appropriate range of \( \eta \) (Fields & Olive 1995; Olive 1995).

This high range of primordial \(^2\)H abundance is not without problems, however. Such a high value of \(^2\)H/H may be difficult to reconcile with local measurements of \(^3\)He. Since \(^2\)H burns to \(^3\)He, stellar and galactic evolution would have to destroy much more \(^3\)He than is sometimes thought possible to reduce its abundance to that observed today in the solar system. Whether enough \(^3\)He can be destroyed to accommodate high primordial \(^2\)H abundances is still a matter of current debate (e.g. Dearborn, Steigman, & Tosi 1996; Hogan 1995a). In addition, the lower cosmic baryon density implied by a higher \(^2\)H abundance aggravates the alleged "baryon
catastrophe.” The “catastrophe” is that cluster masses derived from X-ray measurements seem to imply a cosmic baryon density about a factor of three higher than that allowed by BBN, for a critical density universe \cite{White1993, White1995}. In addition, the existence of a significant baryonic component of the dark halos surrounding spiral galaxies is suggested by recent gravitational microlensing studies \cite{Griest1996}. This could also be a potential problem for this high range of D/H, because the low baryon density corresponding to high values of primordial deuterium leaves room for only a limited amount of baryonic dark matter, probably not enough to account for most of the halo mass \cite{Hogan1995b}.

Another detection of $^2$H in a QSO absorption system has been made by a separate group \cite{Tytler1996}. Compared with the high value of $^2$H/H determined from the Songaila et al. (1994) object, this measurement yields a low value of $^2$H/H: $^2$H/H = $1.5 - 3.4 \times 10^{-5}$, which represents a 2σ statistical plus 1σ systematic error range. As Fig. 3 shows, this range of $^2$H is inconsistent with $N_\nu = 3$ for the range of $^4$He used in Figs 1-2.

In addition, this range for $^2$H appears to be compatible with the $^7$Li abundance only when appeal is made to a factor of at least two or so depletion of primordial $^7$Li to arrive at the Spite plateau value of $^7$Li/H. This conclusion cannot be made with certainty, however, since the theoretical uncertainty in $^7$Li/H can allow for a marginal agreement between the Spite plateau value of $^7$Li/H and the new, low $^2$H/H value. In Fig. 4 the Tytler et al. (1996) range of $^2$H/H is plotted along with the upper limit on $\eta$ that arises from the upper limit on $^7$Li/H determined solely from the Spite plateau, without any allowance for depletion: $l_{10} \leq 2.2$ (Olive 1995). In this figure no concordance is obtained, for any effective number of neutrinos, for the central values of the reaction rates entering the calculation. The figure also shows, however, that the uncertainties in these rates allow for a sliver of a concordance. Nevertheless, it is clear that allowance for some $^7$Li depletion provides much better agreement between $^7$Li/H and the Tytler et al. (1996) measurement of $^2$H/H. Acceptance of the range of primordial deuterium shown in Figs. 3-4 would thus likely require rethinking of: (1.) our understanding of the $^4$He and $^7$Li primordial abundances, and/or: (2.) the simplifying assumptions of the standard BBN picture, including entropy homogeneity, three light ($\lesssim 1$ MeV) neutrinos, and negligible net lepton number. The potential conflict between the $^4$He abundance and $N_\nu = 3$ was previously noted based on “local” deuterium measurements alone \cite{Kernan1994, Hata1995a}, and solutions reflecting the two options above have already found expression. Krauss & Kernan (1995) emphasize the need for reconsideration of systematic uncertainties, and Copi et al. (1995b) suggest that the $^4$He abundance has been systematically underestimated. On the other hand, Hata et al. (1995a) hint at non-standard early universe neutrino physics.

Non-standard neutrino physics can “fix” the primordial $^4$He abundance rather easily in the case of the Hata et al. (1995b) range of the deuterium abundance. However, non-standard neutrino physics is less likely to be a solution to the conflict between the $^2$H/H and $^7$Li/H primordial abundances that arises if the Tytler, Fan, & Burles (1996) range of deuterium is adopted. This is because altering the neutrino physics affects the production of $^4$He much more strongly than
the production of the other light elements formed in the big bang. For example, consider the possibility that the cosmic neutrino seas contain net lepton number (i.e., the neutrinos have a nonzero chemical potential $\mu$). Calculations with the Kawano (1992) code reveal that an electron neutrino degeneracy parameter $\mu_e/kT \sim 0.03$ is sufficient to bring $^4\text{He}$, $^2\text{H}$, and $^7\text{Li}$ into good agreement for $N_{\nu} = 3$ if $d_5 \sim 5$. On the other hand, for $d_5 \lesssim 2.5$, an electron neutrino degeneracy parameter $\mu_e/kT \sim 0.4$ is required to bring $^2\text{H}$ and $^7\text{Li}$ into concordance for $N_{\nu} = 3$. However, $\mu/kT \sim 0.4$ yields $Y \approx 0.13$, which could only (maybe) be brought back up to the observed $^4\text{He}$ abundance with extreme fine tuning involving large values of the other neutrino degeneracy parameters (Kang & Steigman 1992).

Therefore, the acceptance of the low Tytler, Fan, & Burles (1996) value of $^2\text{H}/\text{H}$ would strongly suggest that significant ($\gtrsim$ factor of 2) depletion of $^7\text{Li}$ may be required to obtain concordance between the observationally-inferred primordial abundances of $^2\text{H}$, $^4\text{He}$, and $^7\text{Li}$. Two recent observations of $^6\text{Li}$ in old, hot Pop II halo stars (Smith, Lambert, & Nissen 1993; Hobbs & Thorburn 1994) have been cited as possible evidence against $^7\text{Li}$ depletion in this class of objects (Steigman et al. 1993; Copi et al. 1995a). This is because $^6\text{Li}$ is destroyed at considerably lower temperature than is $^7\text{Li}$. Therefore, if rotation-induced turbulent mixing is invoked to effect significant $^7\text{Li}$ depletion (Pinsonneault et al. 1993; Chaboyer & Demarque 1994), we would expect that $^6\text{Li}$ would suffer even greater, if not complete, depletion. If an appeal is made to turbulent mixing depletion of $^7\text{Li}$ in old halo stars, it would have to be argued that $^6\text{Li}$ is produced by galactic cosmic rays or in situ by stellar flares (Smith, Lambert, & Nissen 1993; Deliyannis & Malaney 1995). On the other hand, Vauclair & Charbonnel (1995) have claimed that another possible mechanism of $^7\text{Li}$ depletion—mass loss via stellar winds—would not destroy $^6\text{Li}$, and would thus be a “safe” method of $^7\text{Li}$ depletion. It is perhaps suggestive that the upper bound to the range of $^7\text{Li}/\text{H}$ obtained by Vauclair & Charbonnel (1995) with this mechanism is $4.0 \times 10^{-10}$, in reasonable agreement with what Fig. 3 would predict, given the new deuterium determinations.

Allowing the possibility of significant depletion of $^7\text{Li}$ brings to mind models of inhomogeneous BBN, in which $\eta$ is allowed to have spatial variations on scales either smaller or larger than the horizon scale at the epoch of BBN (Alcock, Fuller, & Meyer 1987; Applegate, Hogan, & Scherrer 1988; Mathews et al. 1993; Thomas et al. 1994; Jedamzik, Fuller, & Mathews 1994; Jedamzik & Fuller 1995; Copi, Olive, & Schramm 1993; Gnedin, Ostriker, & Rees 1995). Higher $^7\text{Li}$ abundance yields at a given $\eta$ compared with standard BBN are a usual feature of inhomogeneous schemes (but see Jedamzik et al. (1994)). However, a feature of almost all inhomogeneous models is a high average $^2\text{H}/\text{H}$ yield relative to a homogeneous model. Inhomogeneous models tuned to give low $^2\text{H}/\text{H}$ yields usually overproduce $^4\text{He}$ relative to a homogeneous case. An inference of a universally low primordial $^2\text{H}/\text{H}$ (in the range of Tytler et al. (1996)), which we have shown would imply a requirement for significant $^7\text{Li}$ depletion, would probably be incompatible with inhomogeneity, or would at least significantly narrow the allowed parameter range for inhomogeneous models. Should the Tytler et al. (1996) value of $^2\text{H}/\text{H}$ turn out to be close to the primordial value (e.g., only such a low $^2\text{H}/\text{H}$ is detected along many lines of sight and among many Ly-\(\alpha\) clouds), probably
we could conclude that the assumption of homogeneity is a good one, even though there is no face value concordance in $\eta$ and $N_\nu$ for the usually adopted $^4$He abundance and the Spite plateau $^7$Li abundance.

Of course, if both the Rugers and Hogan (1996) and Tytler et al. (1996) values of $^2$H/H are intrinsically primordial—the difference not being a result of differential chemical evolution or observational selection effects—then inhomogeneity in $\eta$ at the epoch of BBN is established. Indeed, just such intrinsic variations would be expected in inhomogeneous isocurvature models (Jedamzik & Fuller 1995).

The basic success of big-bang nucleosynthesis is remarkable. However, at present there are discordant determinations of the primordial deuterium abundance. As claimed inferences of primordial abundances have become more refined, some discomforts have surfaced. A two-dimensional concordance plot in the $\eta$-$N_\nu$ plane is a good tool to study these issues, as it clearly displays both the overall consistency of the theory and the leverage each element exerts on constraining $N_\nu$ and $\eta$. The high value of $^2$H/H $\approx 2 \times 10^{-4}$ (Rugers & Hogan 1996) measured in one QSO absorption system fits well with the currently popular observationally-inferred determinations of the $^4$He and $^7$Li abundances for $N_\nu = 3$. However, the low baryon density implied by this high range of $^2$H/H may conflict with determinations of the baryon content of x-ray clusters and the massive halos surrounding spiral galaxies. Should the low value $^2$H/H $= 1.5 - 3.4 \times 10^{-5}$ (Tytler, Fan, & Burles 1996) obtained from another QSO absorption system persist in future observations, it could require rethinking of: (1.) our understanding of the $^4$He and $^7$Li primordial abundances, and/or: (2.) the simplifying assumptions of the standard BBN picture, which include homogeneity, three light ($\lesssim 1$ MeV) neutrinos, and negligible net lepton number. In particular, it is unlikely that the incompatibility of the “Spite plateau” value of $^7$Li/H with $^2$H/H $\approx 1.5 - 3.4 \times 10^{-5}$ can be resolved in a believable way with non-standard early universe neutrino physics or inhomogeneous BBN. Instead, it would probably be necessary to invoke significant ($\gtrsim$ factor of two) depletion of $^7$Li in old, hot Pop II halo stars in order to obtain a concordant range of $\eta$, for any value of $N_\nu$.

The use of conservative ranges for the inferred primordial abundances of the light elements produced in the big bang confirms the basic success of the theory for $N_\nu = 3$, as is shown in Fig. 5. The abundance of primordial deuterium could be anywhere between the high and low values suggested by measurements of QSO absorption systems. Consideration of systematic effects may suggest that the upper limit on the $^4$He abundance could be as high as $Y = 0.255$ (Sasselov & Goldwirth 1995). If rotation-induced mixing has occurred in old, hot Pop II halo stars, primordial $^7$Li may have been depleted by a factor of ten (Pinsoneault et al. 1992; Chaboyer & Demarque 1994; Deliyannis, Boesgaard, & King 1995). Contours corresponding to the high value of primordial $^7$Li/H implied by such severe depletion do not even appear in the range of parameter space included in Fig. 5. Classic predictions of the theory remain essentially intact. For example, the effective number of light species present at nucleosynthesis is most likely less than four (especially if $^2$H/H turns out to be low), and the existence of both baryonic and non-baryonic
dark matter is suggested. Even with quite conservative ranges of the primordial abundances, big-bang nucleosynthesis retains predictive power.

Note Added. Another measurement of $^2\text{H}/\text{H}$ in a QSO absorption system has been made recently by Burles and Tytler (1996). They determine $^2\text{H}/\text{H}$ in this object to be $1.5 \leq d_5 \leq 4.2$, where this range includes $\pm 2\sigma$ statistical error $\pm$ systematic error. The range of $^2\text{H}/\text{H}$ implied by combining this measurement with the previous Tytler et al. (1996) measurement is $1.7 \leq d_5 \leq 3.5$ (Burles and Tytler 1996); therefore our conclusions regarding the impact of ‘low’ $^2\text{H}/\text{H}$ remain unchanged. Burles and Tytler (1996) argue that these two measurements taken together, along with observational difficulties in existing measurements of QSO absorption systems that could be interpreted as yielding ‘high’ $^2\text{H}/\text{H}$ (Rugers & Hogan 1996; Carswell et al. 1996; Wampler et al. 1996), indicate a low primordial deuterium abundance.

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Fig. 1.— The allowed region in the $\eta - N_{\nu}$ plane for the range of $^2$H (dotted lines) as determined by Hata et al. (1995b) from solar system and interstellar medium measurements: $1.7 \leq d_5 \leq 6.2$. This range is quoted as a 95% C. L. interval. For $^4$He (solid lines) and $^7$Li (dashed lines) we have used $2\sigma$ ranges on the quoted statistical error, plus or minus the quoted systematic error: $0.223 \leq Y \leq 0.245$, $0.7 \leq l_{10} \leq 3.8$ (Olive 1995). Both $^7$Li contours correspond to the upper bound; a sufficiently large lower bound would bifurcate the $^7$Li band, but this does not occur for the present lower bound. This range of $^7$Li allows for up to a factor of two depletion.
Fig. 2.— The allowed region in the $\eta - N_\nu$ plane for the range of $^2\text{H}$ (dotted lines) as determined from a QSO absorption system: $1.5 \leq d_4 \leq 2.3$ (Rugers & Hogan 1996). This is a 1$\sigma$ range. The ranges for $^4\text{He}$ (solid lines) and $^7\text{Li}$ (dashed lines) are as in Fig. 1.
Fig. 3.— The allowed region in the $\eta - N_\nu$ plane for the range of $^2\text{H}$ (dotted lines) as determined from a QSO absorption system: $1.5 \leq d_5 \leq 3.4$ (Tytler, Fan, & Burles 1996). This reflects $2\sigma$ ranges on the quoted statistical error, plus or minus the quoted systematic error. The ranges for $^4\text{He}$ (solid lines) and $^7\text{Li}$ (dashed lines) are as in Fig. 1.
Fig. 4.— The allowed region in the $\eta - N_\nu$ plane for $^2$H (dotted lines) as in Fig. 3, $^4$He (solid lines) as in Figs. 1-3, and the “Spite plateau” value of $^7$Li/H, with no allowance for depletion. Only the $^7$Li contour yielding the upper bound on $\eta$ is shown: $l_{10} \leq 2.2$ (Olive 1995). The dashed line indicates the $l_{10} = 2.2$ contour that arises from use of the central values of the reaction rates, and the dot-dashed lines indicate the range allowed by the uncertainties in these rates.
Fig. 5.— The allowed region in the $\eta - N_\nu$ plane for conservative estimates of the primordial abundances: $d_4 \leq 2.3$ (Rugers & Hogan 1996), $d_5 \geq 1.5$ (Tytler, Fan, & Burles 1996); $Y \leq 0.255$ (Sasselov & Goldwirth 1995), $Y \geq 0.223$ (Olive 1995).