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Authors

Fuller, George M
Cardall, Christian Y

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The Deuteron Confronts Big Bang Nucleosynthesis

George M. Fuller and Christian Y. Cardall ^a^aDepartment of Physics, University of California, San Diego, La Jolla, California 92093-0319

Recent determinations of the deuterium abundance, ${}^2\text{H}/\text{H}$, in high redshift Lyman limit hydrogen clouds challenge the usual picture of primordial nucleosynthesis based on “concordance” of the calculated light element (${}^2\text{H}$, ${}^3\text{He}$, ${}^4\text{He}$, ${}^7\text{Li}$) nucleosynthesis yields with the observationally-inferred abundances of these species. Concordance implies that all light element yields can be made to agree with the observationally-inferred abundances (within errors) for single global specifications of the baryon-to-photon ratio, η ; lepton number; neutron lifetime; and expansion rate (or equivalently, effective number of light neutrino degrees of freedom N_ν). Though one group studying Lyman limit systems obtains a high value of ${}^2\text{H}/\text{H}$ ($\sim 2 \times 10^{-4}$), another group finds consistently low values ($\sim 2 \times 10^{-5}$). In the former case, concordance for $N_\nu = 3$ is readily attained for the current observationally-inferred abundances of ${}^4\text{He}$ and ${}^7\text{Li}$. But if the latter case represents the primordial deuterium abundance, then concordance for *any* N_ν is impossible unless the primordial value of ${}^7\text{Li}/\text{H}$ is considerably larger than the abundance of lithium as measured in old, hot Pop II halo stars. Furthermore, concordance with $N_\nu = 3$ is possible for low ${}^2\text{H}/\text{H}$ only if either (1) the primordial ${}^4\text{He}$ abundance has been significantly underestimated, or (2) new neutrino sector physics is invoked. We argue that systematic underestimation of both the ${}^7\text{Li}$ and ${}^4\text{He}$ primordial abundances is the likely resolution of this problem, a conclusion which is strengthened by new results on ${}^4\text{He}$.

1. OVERVIEW

In this paper we assess primordial nucleosynthesis in light of the new Lyman limit system-derived deuterium abundance data [1–5]. Based on our analysis we adopt the view that currently we do not have a reliable handle on the primordial abundances of ${}^3\text{He}$, ${}^4\text{He}$, and ${}^7\text{Li}$; whereas, the Keck telescope may be providing us with a direct measurement of the abundance of the very fragile deuteron in relatively chemically-unevolved primordial material.

This is a somewhat radical view, given that much of the past discussion on big bang nucleosynthesis (BBN) has been predicated on the idea of “concordance”—where a single global specification of the parameters characterizing Nuclear Statistical Equilibrium (NSE) freeze-out nucleosynthesis can lead the calculated abundances to agree with their observationally-inferred primordial values within errors. In a computation of NSE freeze-out nucleosynthesis [6], it is necessary to specify: (1) either the entropy-per-baryon s (cosmic average $s \approx 2.63 \times 10^8 \Omega_b^{-1} h^{-2}$; where Ω_b is the baryon closure fraction and h is the Hubble parameter in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$),

or the baryon-to-photon ratio η (cosmic average $\eta \approx 2.68 \times 10^{-8} \Omega_b h^2$); (2) the spatial distribution of either of these quantities, both on scales smaller than the particle horizon at the epoch of NSE freeze-out and on super-horizon scales; (3) the three net lepton-to-photon numbers; (4) the ratio of the axial vector to vector weak interaction coupling constants (derived from the neutron lifetime); and (5) the expansion rate through the epoch of freeze-out. The expansion rate is determined by the energy density in the horizon. In turn, in the expected radiation-dominated conditions of BBN, the energy density is usually parametrized as an effective number of light neutrino species N_ν , representing all relativistic particle degrees of freedom beyond those contributed by photons, electrons and positrons.

The usual procedure has been to compute nucleosynthesis yields as a function of η , for specifications of N_ν and the neutron lifetime, *assuming* that the entropy is homogeneously distributed on all scales and *assuming* that all net lepton numbers are small ($\lesssim \eta$) and neutrino masses are small and there are no other relativistic degrees of freedom. These simple Occam’s razor assump-

tions are then “justified” by finding a concordant η where all the independently-determined primordial abundances line up with their values predicted in the calculations (*cf.* Refs. [7,8]). Such concordance-based justification has been touted as being all the more impressive and secure, given that the predicted and observationally-determined abundances range over some ten orders of magnitude.

2. THE “CRISIS”

The claimed precisions in the determinations of the primordial abundances of ^2H , ^3He , ^4He , and ^7Li have increased to the point where, if taken at face value, they invalidate the simple picture of concordance outlined above [9]. This is the recent so-called “Crisis” in BBN. In fact, there were even earlier hints at a potential problem with the standard picture of concordance [10,11].

With their adopted abundances of the ^2H and ^4He , the authors of Ref. [9] find no concordance for $N_\nu = 3$, and derive a best fit to concordance for $N_\nu \approx 2.1 \pm 0.3$ with $N_\nu = 3$ ruled out at the 98.6% C.L.. These authors have suggested that perhaps this discrepancy could be eliminated with the introduction of new neutrino physics, essentially relaxing the usual assumptions regarding the above-discussed parameters (3) and (5) in BBN.

This conclusion and interpretation has been disputed by Copi *et. al.* (Ref. [12]), who take as a prior assumption that $N_\nu = 3$ and then argue that ^4He has been underestimated. Cardall and Fuller (Ref. [13]) have done a re-analysis of this problem in light of the discordant determinations of ^2H in Ly- α clouds and with special attention to the dependence of the BBN yields on N_ν and to the ^7Li non-concordance problem (which they conclude cannot be rectified with new neutrino physics). This work tends to support the Copi *et al.* assessment. As we shall see, new work on the observationally-inferred abundances of ^2H and ^4He provides further support for this view and offers a hint of a new concordance.

3. DISCORDANT DEUTERIUM MEASUREMENTS

The deuteron is the most fragile of all nuclei, with a binding energy of only $E_B \approx 2.225$ MeV. As a result, the ^2H yield in BBN is exponentially sensitive to η , though only mildly sensitive to N_ν [6]. However, the fragile nature of the deuteron makes it extremely vulnerable to even small amounts of stellar processing and this, in turn, calls into question claims that we have a reliable handle on the primordial deuterium abundance. Direct measurements using the Keck telescope of isotope-shifted hydrogen lines in high redshift Ly-limit systems along lines of sight to distant QSO’s may completely circumvent these stellar processing issues [3]. This is because these systems have manifestly low metallicity and this argues against significant stellar processing-induced destruction of ^2H [14,15].

At present, however, there is no consensus on the primordial value of $^2\text{H}/\text{H}$ from this technique: the Seattle-Hawaii group [1–3] obtains a very high range for this quantity ($15 \lesssim d_5 \lesssim 23$ from Ref. [2]); whereas, the San Diego group [4,5] examining different clouds obtains a consistently much lower range ($1.7 \lesssim d_5 \lesssim 3.5$, combined results from Refs. [4] and [5] with $\pm 2\sigma$ statistical error and $\pm 1\sigma$ systematic error). Here $d_5 \equiv ^2\text{H}/\text{H} \times 10^5$.

An analysis of these discordant ranges is performed in Ref. [13]. In this analysis, we have adapted the Kawano BBN code (with neutron lifetime from Ref. [16], reaction rates from Ref. [8], and a small, nearly η -independent correction to the ^4He yield, +0.0031, from the time step and weak rate corrections of Ref. [11]). The BBN yields for ^2H , ^4He , and ^7Li are plotted as functions of N_ν and η . Such plots give insight into the leverage which each light element species has on concordance. Since, in contrary fashion to ^2H , the BBN ^4He yield is relatively sensitive to N_ν and much less sensitive to η , the tension between the overlap of these two species on our plots provides the most stringent criterion for concordance. This analysis shows that for the typically adopted range of the ^4He abundance [17] and the “Spite Plateau” ^7Li abundance measured in old, hot Pop

II halo stars [18–20], concordance is readily attained for the Seattle-Hawaii ^2H for $N_\nu = 3$. On the other hand, no concordance with these values of ^4He and ^7Li is possible for *any* N_ν with the San Diego deuterium determination.

Lack of concordance with the “Spite Plateau” ^7Li abundance may not be a serious problem: this determination of primordial ^7Li is fraught with potential systematic uncertainty, as ^7Li is destroyed readily by $^7\text{Li}(p, \alpha)\alpha$ at temperatures as low as $T \sim 0.1$ keV. Therefore, rotation-induced mixing and turbulent diffusion could have destroyed most of the original ^7Li on the surfaces of the old halo stars [21–23]. However, the issue is complicated by the claimed observation of the even more fragile species ^6Li in some of these objects [24,25]. If mixing-induced destruction (*depletion*) of ^7Li has indeed occurred, then the ^6Li could have been produced *in situ* [26]; alternatively, stellar wind-driven mass loss could deplete ^7Li while leaving some ^6Li present [27].

We here present plots showing the concordance situation when allowance is made for some ^7Li depletion. In Figure 1 we show the η - N_ν parameter space corresponding to the Seattle-Hawaii deuterium range (dotted lines), along with the ranges for ^4He ($0.223 \leq Y_p \leq 0.245$, solid lines) and ^7Li ($0.7 \leq l_{10} \leq 3.8$, dashed lines) taken from Ref. [17]. Here Y_p is the primordial mass fraction of ^4He , and $l_{10} \equiv ^7\text{Li}/\text{H} \times 10^{10}$. This range of l_{10} reflects $\pm 2\sigma$ statistical errors and $\pm 1\sigma$ systematic errors, and allows for a factor of 2 depletion (contained in the systematic error) on the Spite Plateau. Concordance of all of these species is apparent for $N_\nu = 3$ in Figure 1. However, if we adopt the San Diego deuterium range as primordial, with the same ranges adopted for the other species (Figure 2), then the “crisis” is evident, as there is no statistically significant overlap for $N_\nu = 3$.

The quality of the San Diego group’s data and the sophistication of their self-consistent analysis cannot be dismissed. Furthermore, there are a number of astrophysical problems which are partially or completely ameliorated if the San Diego group’s deuterium range is adopted as primordial. This range for $^2\text{H}/\text{H}$ would correspond to a range in baryonic closure fraction $0.016 \lesssim \Omega_b h^2 \lesssim 0.03$.

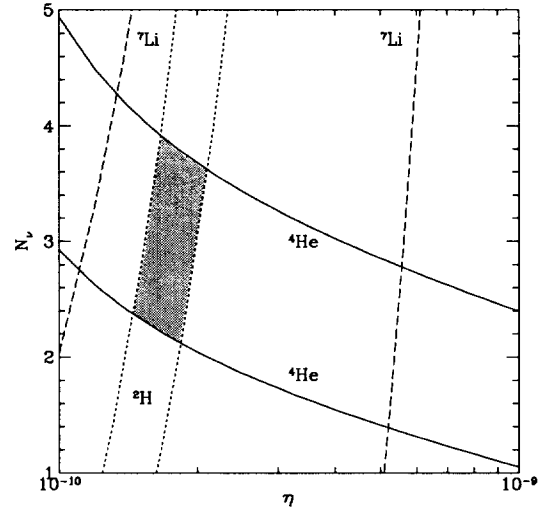


Figure 1. Concordance plot for the Seattle-Hawaii ^2H determinations ($15 \leq d_5 \leq 23$, dotted lines) and a typical ^4He range ($0.223 \leq Y_p \leq 0.245$, solid lines).

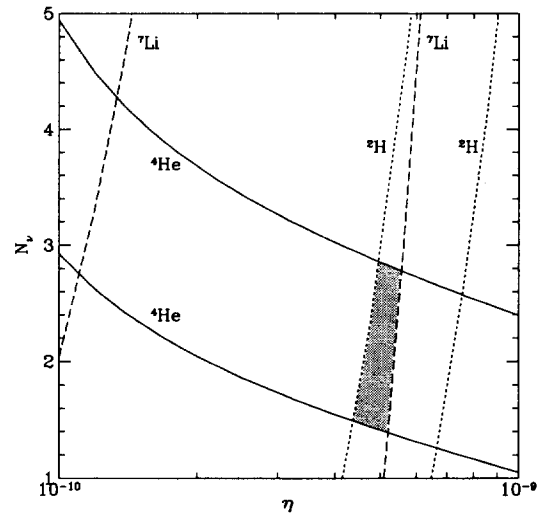


Figure 2. Concordance plot for the San Diego ^2H determinations ($1.7 \leq d_5 \leq 3.5$, dotted lines) and a typical ^4He range ($0.223 \leq Y_p \leq 0.245$, solid lines).

In contrast, adoption of the Seattle-Hawaii $^2\text{H}/\text{H}$ as primordial would imply the much smaller closure fraction $0.0056 \lesssim \Omega_b h^2 \lesssim 0.0075$. There are hints from the x-ray galaxy cluster problem [28,29] that the higher range for $\Omega_b h^2$ is to be preferred—*e.g.* the Coma cluster apparently has a fractional baryonic mass $f_b \approx 0.009 + 0.05h^{-3/2}$ or $f_b \approx 0.15$ for $h = 0.5$. Likewise, the MACHO project gravitational microlensing results [30,31] suggest that most or all of the galactic dark halo mass (corresponding to $\Omega \approx 0.02$ to 0.07) is composed of objects with masses in the range $\approx 0.2 M_\odot$ to $\approx 0.6 M_\odot$. It is clear that the Seattle-Hawaii deuterium range implies a baryonic closure fraction which is difficult to reconcile with these MACHO results if the lensing objects had baryonic progenitors. Finally, observation of the cosmic background radiation Doppler peaks may require a high range of $\Omega_b h^2$ [32].

An alternative to the adoption of the San Diego deuterium as primordial would be to invoke super-horizon scale entropy fluctuations at the epoch of BBN (*i.e.*, relax the homogeneity assumption of BBN parameter 2) [33–35]. Though such a scheme could give a comfortably high $\Omega_b h^2 \approx 0.05$ [33], it would require a fair degree of fine tuning of the fluctuation spectrum and would *demand* that the cosmic average primordial deuterium abundance be high $^2\text{H}/\text{H} \sim 10^{-4}$ [33]. Present statistics of Lyman limit systems and other uncertainties would have to improve significantly to establish such intrinsic inhomogeneity [14], so it seems reasonable to discount this scheme at present and see if a concordance can be found with adoption of the San Diego deuterium as a homogeneous primordial value.

4. NEW ^4HE : A NEW CONCORDANCE

A recent reinvestigation (with new data) of the linear regression method for estimating the primordial ^4He abundance has called into question the systematic uncertainties assigned to Y_p [36]. In fact, this study derives $Y_p \approx 0.243 \pm 0.003$, where the 1σ error is statistical. It is clear that the central value of this result is well above twice the systematic error assigned by Refs. [9,17], confirming the suspicion [13,37] that Y_p is not known

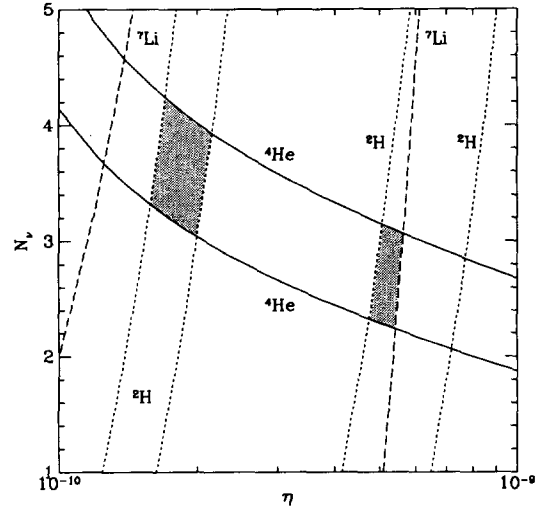


Figure 3. Concordance plot showing both the Seattle-Hawaii and San Diego ^2H ranges (dotted lines) and a new determination of the primordial ^4He abundance ($0.237 \leq Y_p \leq 0.249$, solid lines).

well enough to draw sweeping conclusions regarding a lack of concordance.

In Figure 3 we show both the San Diego and Seattle-Hawaii ^2H ranges (dotted lines), along with the same ^7Li range range (dashed lines) employed in Figure 1, but now with a band (solid lines) for ^4He ($0.237 \leq Y_p \leq 0.249$, reflecting $\pm 2\sigma$ statistical errors and no systematic uncertainty) meant to be representative of the Ref. [36] results. It is evident from this figure that there is now no statistically significant concordance between ^4He and the Seattle-Hawaii ^2H for $N_\nu = 3$, while there is now a hint of concordance for the San Diego ^2H range for $N_\nu = 3$. The new concordance engendered by the San Diego deuterium would be even better if allowance for systematic error were to be made in the ^4He range. Such a new concordance would probably still require significant depletion of ^7Li in old, hot Pop II halo stars [13], though the classic constraints on neutrino physics from BBN [38] would survive intact and could be strengthened [13].

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