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COSMOLOGICAL IMPLICATIONS OF THE FIRST MEASUREMENT OF THE LOCAL ISM ABUNDANCE OF ^{3}He

MICHAEL S. TURNER,[1,2,3] JAMES W. TRURAN,[3] DAVID N. SCHRAMM,[1,2,3] AND CRAIG J. COPI[1,2]
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ABSTRACT

Deuterium plays a crucial role in testing big bang nucleosynthesis. However, its chemical evolution is intertwined with that of ^{3}He. Gloeckler & Geiss's new measurement of the ^{3}He abundance and the *Hubble Space Telescope* measurement of D, both in the local ISM today, can be compared to the presolar nebula abundances of D and ^{3}He. Within the uncertainties, the sum of D + ^{3}He relative to hydrogen is unchanged. This indicates that over the past 4.5 Gyr there has been at most modest stellar production of ^{3}He, in contradiction with stellar modeling, or modest stellar destruction of ^{3}He, in contradiction with efficient "solar spoons." The constancy of D + ^{3}He alleviates some of the cosmic tension between the big bang ^{4}He abundance and those of D and ^{3}He.

Subject headings: cosmology: theory — galaxy: abundances — galaxy: evolution — ISM: abundances — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

Much of the current controversy concerning the consistency (Copi, Schramm, & Turner 1995a, 1995b) or inconsistency (Hata et al. 1995a) of standard big bang nucleosynthesis revolves around the chemical evolution of ^{3}He. In fact, ^{3}He is involved indirectly. Deuterium plays the crucial role in testing big bang nucleosynthesis, as its abundance is the most sensitive to the baryon density, decreasing rapidly with increasing baryon density, and its chemical evolution brings in ^{3}He. The chemical evolution of D is straightforward: it is readily burned to ^{3}He, but it is not produced in Galactic environments (Epstein, Lattimer, & Schramm 1976). This means that the present deuterium abundance can be used to place an upper limit to the baryon density. This upper limit, $\eta \lesssim 9 \times 10^{-10}$, which implies $\Omega_B \lesssim 0.03\ h^{-2} \lesssim 0.2$, provides the linchpin in the two-decade–old argument that baryons cannot close the universe (Reeves et al. 1973). This argument is not questioned in the current controversy. (As usual, η is the present ratio of baryons to photons, Ω_B is the fraction of critical density contributed by baryons, and the Hubble constant $H_0 = 100\ h$ km s^{-1} Mpc^{-1} with $0.4 < h < 1$. The baryon-to-photon ratio and fraction of critical density contribution by baryons are related by, $\Omega_B h^2 = 3.63 \times 10^7\ \eta$.)

Using deuterium to precisely determine the baryon density, or even to set a lower limit to it, is more difficult. Because deuterium is so easily destroyed in passing through stars, the former is only possible if the deuterium abundance can be measured in a very primitive sample of the universe. There has been progress toward this goal (Adams 1976), with three claimed and three tentative detections of the D Lyα feature in high redshift ($z \sim 2.5$–4.5), quasar absorption-line systems (Songaila et al. 1994; Carswell et al. 1994, 1996; Tytler, Fan, & Burles 1996; Burles & Tytler 1996; Rugers & Hogan 1996; Wampler et al. 1996). The inferred abundances are in the anticipated range, 2×10^{-5} to 2×10^{-4}; however, the results are not yet definitive (Schramm & Turner 1996).

[1] Department of Physics, Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637-1433.

[2] NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510-0500.

[3] Department of Astronomy and Astrophysics, The University of Chicago, Chicago, IL 60637-1433.

Deriving a lower limit to the baryon density hinges upon the chemical evolution of ^{3}He. Since D is burned to ^{3}He and ^{3}He is far more difficult to burn, Yang et al. (1984) proposed using the sum of D + ^{3}He for this purpose. Based upon stellar modeling (Iben & Truran 1978), they assumed that at least 25% of the primordial D + ^{3}He survives stellar processing, which led to the lower limit $\eta \gtrsim 2.5 \times 10^{-10}$ and $\Omega_B \gtrsim 0.009\ h^{-2}$. This, together with the upper limit that follows from ^{7}Li ($\eta \lesssim 6 \times 10^{-10}$ and $\Omega_B \lesssim 0.02\ h^{-2}$), provides the best determination of the baryon density—between about 1% and 15% of critical density (allowing $0.4 < h < 1$; see Copi et al. 1995a)—and establishes the two dark-matter problems central to cosmology: most of the baryons are dark (since $\Omega_{\rm lum} \simeq 0.003\ h^{-1} < \Omega_B$) and most of the dark matter must be nonbaryonic, if, as several measurements indicate, $\Omega_0 \gtrsim 0.2$.

Beyond pinning down the baryon density, there is a more fundamental issue: the consistency of the standard model of primordial nucleosynthesis itself and the validity of the hot big bang model at times as early as 0.01 s. (By standard model of big-bang nucleosynthesis we mean: FRW cosmology, uniform distribution of baryons, three light neutrino species, and small neutrino chemical potentials.) The ^{7}Li abundance measured in almost 100 old, Population II halo stars is consistent ("at 2 σ") with the big bang prediction provided that $\eta \simeq (1$–$6) \times 10^{-10}$, which overlaps the D + ^{3}He consistency interval (Copi et al. 1995a). Of some concern is the primeval ^{4}He abundance: If one accepts at face value the analysis of Olive & Steigman (1995), based upon metal-poor, extragalactic H II regions, then $Y_P = 0.232 \pm 0.003$ (stat) ± 0.005 (sys), which implies $\eta \simeq (1$–$4) \times 10^{-10}$ (at "2 σ"), which is only marginally consistent with D + ^{3}He. It should be noted, however, that other authors (see, e.g., Skillman et al. 1994; Sasselov & Goldwirth 1995; and B. Pagel, private communication) have argued that the systematic uncertainties are at least a factor of 2 larger, which, owing to the logarithmic dependence of Y_P upon η, would enlarge the concordance interval to $\eta \simeq (0.6$–$10) \times 10^{-10}$.

For some time, there has been tension between the measured abundances of ^{4}He and D + ^{3}He (see, e.g., Yang et al. 1984; Copi et al. 1995a; Walker et al. 1991; Olive et al. 1995; Scully et al. 1996). The resolution could involve a revision of our understanding of the evolution of ^{3}He: more stellar destruction than standard stellar models predict would lead to a lower value of η as inferred from D + ^{3}He and lessen the tension. Alternatively, the resolution could involve a systematic underestimation of the primeval ^{4}He abundance, by an amount $\Delta Y_P \sim 0.01$ (Copi et al. 1995b); this would raise the value of η inferred from ^{4}He, making it consistent with that inferred from D + ^{3}He and conventional stellar evolution of ^{3}He. Hata et al. (1995) have argued that the discrepancy is real and is evidence for new physics, e.g., an unstable tau neutrino of mass around 10 MeV or large neutrino chemical potentials.

Eventually the deuterium abundance in high redshift Lyα clouds will be decisive; e.g., a value $(D/H)_P \sim 10^{-4}$ implies $\eta \sim 2 \times 10^{-10}$ and would implicate the chemical evolution of ^{3}He, while $(D/H)_P \sim 3 \times 10^{-5}$ implies $\eta \sim 6 \times 10^{-10}$ and would implicate the primeval ^{4}He abundance. Until a definitive determination is forthcoming, continued scrutiny of ^{3}He offers a means of addressing this important issue. Because previous measurements of the abundance of ^{3}He have raised as many questions as they have answered—variations in the abundance measured in H II regions of more than a factor of 5 (Bania, Rood, & Wilson 1987; Wilson & Rood 1994) with some values *lower than that in the presolar nebula* (Black 1972; Geiss & Reeves 1972)—the measurement of the ^{3}He abundance in the local ISM by Gloeckler & Geiss (1996) is an important development. We will use it to derive a lower bound to the baryon density, which is more empirically rooted and less sensitive to the questionable aspects of ^{3}He evolution.

2. THE EVOLUTION OF D + ^{3}He

According to conventional stellar modeling, low-mass stars ($M \lesssim 2\ M_\odot$) are net producers of ^{3}He and high-mass stars preserve at least 20% of their ^{3}He. Integrating over a Salpeter mass function, Dearborn, Schramm, & Steigman (1986) found a mean ^{3}He survival fraction of 0.8. The arguments of Yang et al. (1984) and others since (see, e.g., Steigman & Tosi 1992, 1995) have been predicated upon this "conventional wisdom."

As mentioned above, there are reasons to remain skeptical. Most importantly, there is precious little observational evidence to support this picture, with some recent observations apparently contradicting it, cf. Scully et al. (1996). A number of authors (e.g., Dilke & Gough 1972; Schmitt, Rosner, & Bohn 1984; Zahn 1992; Hogan 1995; Wasserburg, Boothroyd, & Sackmann 1995; Charbonnel 1994, 1995; W. Haxton, private communication) have discussed mixing mechanisms by which ^{3}He would be brought deep enough to be burned and become depleted (to which we will refer collectively as a "solar spoon"). Wasserburg et al. (1995) have emphasized how such a mixing mechanism might explain carbon and oxygen isotopic anomalies seen in certain AGB stars and in some meteoritic grains (also see, Charbonel 1994, 1995; Weiss, Wagenhuber, & Denissenkov 1996; Boothroyd & Malaney 1996) and Haxton has suggested that such a mechanism could lessen or even alleviate the solar neutrino problem.

Finally, Copi, Schramm, & Turner (1995c) have emphasized how the heterogeneity of Galactic abundances complicates attempts to infer primeval D and ^{3}He abundances. Heterogeneity arises because the Galaxy is not necessarily well mixed and material in different regions has experienced different histories of stellar processing. Starting with the same primordial abundances, present local abundances can vary by a factor of as much as two (see Fig. 1). While the most recent HST observations (Linsky et al. 1993, 1996) now show at most a 10% variation in D/H within the local ISM, earlier *Copernicus* and *IUE* observations showed a larger variation in the local

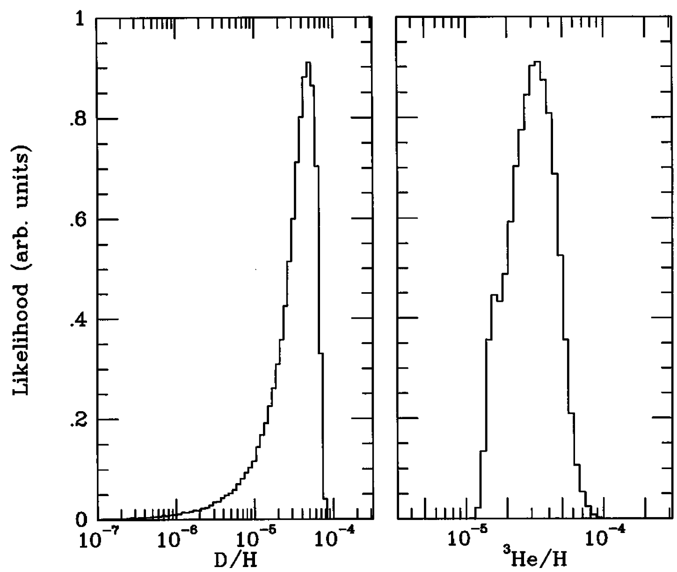

FIG. 1.—The variation in present D and ^{3}He abundances expected today due to differing histories. Here we have assumed $\eta = 3.2 \times 10^{-10}$ to fix the primordial values.

ISM (for a discussion of this point see Ferlet & Lemoine 1996). And of course, the local ISM could be relatively homogeneous with the Galaxy inhomogeneous on larger scales.

The observational situation has its share of vagaries. The deuterium abundance has only been measured in nearby regions of the Galaxy, along several lines of sight in the local ISM and in the presolar nebula. For the presolar nebula, a deuterium abundance, $(D/H)_\odot = (2.7 \pm 0.5\ \text{sys} \pm 1\ \text{stat}) \times 10^{-5}$, is inferred from the difference of two measurements, the ^{3}He abundance in the solar wind, which reflects the sum of the presolar D + ^{3}He (Geiss & Reeves 1972; Bodmer et al. 1995), and the ^{3}He abundance measured in gas rich meteorites (Black 1972), which reflects the presolar ^{3}He abundance. The higher presolar deuterium abundance is consistent with its expected decline with time due to stellar processing. (Measurements of the deuterium abundance using deuterated molecules, both in the solar system and throughout the Galaxy, shed little light as the effects of chemical fractionation are expected to be very significant and are difficult to disentangle.)

As mentioned above, the presolar abundance of ^{3}He has been measured in primitive meteorites, $(^3He/H)_\odot = (1.5 \pm 0.2 \pm 0.3) \times 10^{-5}$. The present ^{3}He abundance has also been measured within the Galaxy, in a number of H II regions and in a planetary nebula by means of the $^3He^+$ hyperfine line (Rood, Bania, & Wilson 1992, 1995) and in a HB star by Hartoog (1979). The abundances in H II regions range from $(^3He/H)_{H\,II} = 10^{-5}$ to 6×10^{-5}, suggesting a wide variation in the present abundance. On the face of it, the planetary nebula measurement, $(^3He/H)_{PN} \sim 10^{-3}$ and the HB star measurement are consistent with the notion that low-mass stars produce significant amounts of ^{3}He. However, only a few objects have been studied, and these objects represent a biased sample, optimized for the detection of ^{3}He (R. T. Rood, private communication).

Heterogeneity aside, the existing Galactic ^{3}He measurements do not provide a representative sample of material. The H II regions probably preferentially sample material that has been processed through high-mass stars which destroy ^{3}He (Olive et al. 1995), while the planetary nebulae and HB star represent objects with sufficiently large ^{3}He abundance to detect.

Finally, Gloeckler & Geiss (1996) have used the Solar Wind Ion Composition Spectrometer (SWICS) on the *Ulysses* spacecraft to determine the abundance of ^{3}He in the local ISM. To be specific, they measured the ^{3}He/^{4}He ratio of slowly moving, singularly ionized helium atoms—so-called pick-up ions—which entered the solar system as neutral atoms, were photoionized, and were swept back out by the solar wind (see Geiss, Gloeckler, & von Steiger 1994). Using $(^4\mathrm{He/H})_{\mathrm{ISM}} = 0.095 \pm 0.01$ leads to $(^3\mathrm{He/H})_{\mathrm{ISM}} = (2.1^{+0.9}_{-0.8}) \times 10^{-5}$, where the error is the sum of statistical + systematic uncertainties. This measurement is important because the deuterium abundance in the ISM is also known. Together they imply $[(\mathrm{D} + {}^3\mathrm{He})/\mathrm{H}]_{\mathrm{ISM}} = (3.7 \pm 0.9) \times 10^{-5}$, which is essentially identical to the pre-solar value, $[(\mathrm{D} + {}^3\mathrm{He})/\mathrm{H}]_{\odot} \simeq (4.2 \pm 0.7 \pm 1) \times 10^{-5}$ (see Copi et al. 1995c). The constancy of the D + ^{3}He abundance over the past 4.5 Gyr is striking and provides general confirmation of the cosmological utility of D + ^{3}He as proposed by Yang et al. (1984), though one must be mindful of the details of its implementation.

3. DISCUSSION

Gloeckler & Geiss' measurement is noteworthy because it allows the evolution of D + ^{3}He to be addressed empirically for the first time. The message is simple: over the past 4.5 Gyr it has not changed dramatically. This is not a trivial fact; the increase in ^{3}He and the decline in D over this time (almost a factor of 2) indicate substantial stellar processing.

(There is a possible loophole in this interpretation. The presolar value of D + ^{3}He is obtained from the abundance of ^{3}He in the solar wind today, which should reflect the presolar D + ^{3}He abundance. If for some reason the ^{3}He abundance in the solar surface has been depleted, the solar wind value of ^{3}He could be lower than the presolar value of D + ^{3}He. We do not believe that this is an important concern because none of the solar spoon mechanisms predict such a depletion in the sun, and more importantly, the abundance of ^{3}He in the solar wind 4.5 Gyr ago determined from meteoritic studies is consistent with the present value [Black 1972; Weiler et al. 1991].)

According to chemical-evolution models, low-mass stars ($\sim 1\,M_{\odot}$–$1.5\,M_{\odot}$) have made the dominant contribution to the ISM over the past 4.5 Gyr (Truran & Cameron 1971; Rood, Steigman & Tinsley 1976; see also the recent discussion by Scully et al. 1996). The constancy of D + ^{3}He implies that low-mass stars cannot be significant producers of ^{3}He, which is at variance with the predictions of standard stellar models. Likewise, there is no evidence to support significant destruction of ^{3}He by low-mass stars as predicted with an efficient solar spoon at work (see e.g., Hogan 1995). However, D. Dearborn (private conversation) has shown that the slow mixing models that fit the oxygen and carbon isotopic anomalies do not completely deplete ^{3}He; they reduce the amount of ^{3}He that would have been returned to the ISM by at most 80%. If this is indeed the case, a solar spoon could be consistent with the ISM value of D + ^{3}He.

Gloeckler & Geiss's result does little to directly constrain the earlier evolution of D + ^{3}He. The stellar mass function at earlier times is expected to favor more massive stars, which deplete ^{3}He. Since the Gloeckler & Geiss result constrains the destruction of ^{3}He by low-mass stars, massive stars are the only possible way to greatly deplete ^{3}He. Massive stars produce heavy elements, and thus there is a limit to the amount of material that could have been processed through massive stars.

In particular, the ejecta of Type II supernovae are about 10% oxygen by mass, which implies that only a small fraction of the material in the local ISM—roughly 10%—could have been processed through massive stars. Taken together with the apparent constancy of D + ^{3}He over the last 4.5 Gyr, this suggests that the primordial value of D + ^{3}He cannot differ greatly (about a factor of 2 for simple closed galaxy models) from the present value. This leads to the upper bound, $[(\mathrm{D} + {}^3\mathrm{He})/\mathrm{H}]_P \lesssim 10^{-4}$, which is almost identical to that used by Yang et al. (1984), but with firmer empirical roots.

An important assumption underlies the above argument, that all the metals ejected by massive stars make their way back into the ISM. It is possible that metals produced in the early supernova-active phase of the proto-Galaxy (or the proto-galactessimals that merged to form the Galaxy) were ejected into the surrounding IGM. There is some evidence for this; observations of the X-ray emitting gas in rich clusters show metallicities that are slightly less than solar, distributed in a gas mass that is roughly 10 times that in galaxies. If the Galaxy ejected a comparable amount of metals, 10 times more material could have been processed through massive stars, depleting ^{3}He dramatically. (Note, material depleted in ^{3}He is still returned to the ISM in a presupernova stellar wind.)

Finally, let us use the information gleaned from this first measurement of the ^{3}He abundance in the ISM to make more quantitative statements about the value of the baryon density and the consistency of standard big bang nucleosynthesis. The stochastic history approach of Copi et al. (1995c) allows one to use the presolar values of ^{3}He and D + ^{3}He to infer both their primordial values and η, while allowing for the heterogeneity of Galactic abundances. The physical input needed is the mean properties of stellar processing. Based upon Gloeckler & Geiss's measurement, we consider two possibilities for the evolution of ^{3}He in low-mass stars, (1) low-mass stars preserve their ^{3}He, but do not produce ^{3}He and (2) low-mass stars destroy 80% of the ^{3}He they would have returned to the ISM, and two possibilities for metal ejection by massive stars, (1) massive stars return most of the metals they make to the ISM and (2) massive stars only return 10% of the metals they make to the ISM (the rest ejected into the IGM). For these four possibilities, 1a, 1b, 2a, and 2b, we have constructed Monte Carlo likelihood functions for the baryon-to-photon ratio η, which are shown in Figure 2. The 95% credible intervals are $\eta_{1a} = (4–7) \times 10^{-10}$; $\eta_{2a} = (3–6) \times 10^{-10}$; $\eta_{1b} = (2–5) \times 10^{-10}$; and $\eta_{2b} = (2–5) \times 10^{-10}$. For reference, the naive assumption that D + ^{3}He has remained unchanged since primordial nucleosynthesis implies $\eta \sim 5 \times 10^{-10}$ and a primeval D abundance $(\mathrm{D/H})_P \sim 4 \times 10^{-5}$; the 95% credible interval for the joint likelihood function based upon ^{7}Li and ^{4}He alone is $\eta_{\mathrm{He-Li}} \simeq (1.5–2.5) \times 10^{-10}$.

Regarding the consistency of big bang nucleosynthesis, model 1a continues to implicate ^{4}He as the culprit (or the standard model of big bang nucleosynthesis itself). Models 1b, 2a, and 2b lessen the tension between ^{4}He and ^{3}He and D, with models 1b and 2b essentially eliminating the tension all together. The full range for the baryon density based upon

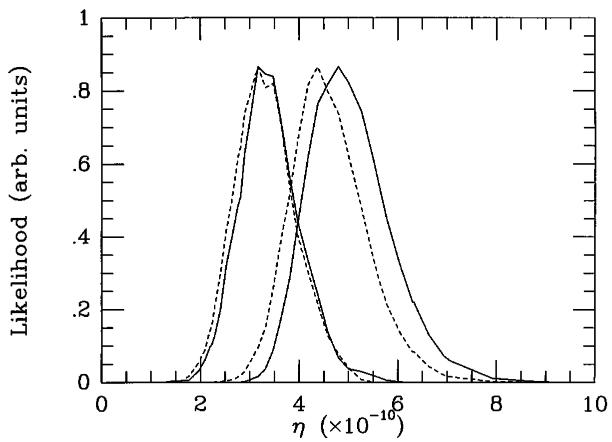

FIG. 2.—Monte Carlo likelihood functions for the baryon-to-photon ratio based upon D and ^{3}He for models 1a (*right solid curve*), 2a (*right dashed curve*), 1b (*left solid curve*), and 2b (*left dashed curve*).

these models, $\eta \simeq (2\text{–}7) \times 10^{-10}$, is essentially the same as that found previously by Copi et al. (1995a). We note that the models that lessen the tension, lead to a stronger upper limit to η, and strengthen the case for nonbaryonic dark matter. For example, for models 1b and 2b the 95% credible region based upon all the light-element abundances corresponds to $\Omega_B = (0.007\text{–}0.015)h^{-2}$, which allows Ω_B as large as 0.1 only if $h \leq 0.37$.

In sum, the measurement of the interstellar ^{3}He abundance by Gloeckler & Geiss (1996) allows the chemical evolution of D + ^{3}He to be addressed empirically for the first time, and in turn, tests primordial nucleosynthesis and its prediction for the baryon density. Their measurement indicates little evolution of D + ^{3}He over the past 4.5 Gyr, generally confirming the the argument of Yang et al. (1984), suggesting that low-mass stars are not significant producers or destroyers of ^{3}He, and calling into question standard stellar models as well as efficient solar spoons. Little can be learned directly from their result about the earlier evolution of D + ^{3}He, which is likely to be dominated by high-mass stars. However, the fact that high-mass stars also produce metals limits the amount of ^{3}He depletion, even if 90% of the metals they produce are ejected from the Galaxy. We have used this fact together with Gloeckler & Geiss's result to establish a more empirically based lower bound to the baryon-to-photon ratio, $\eta \gtrsim 2 \times 10^{-10}$. While only slightly less stringent than the bounds of Yang et al. (1984) and Copi et al. (1995a), it suggests the apparent tension between the big bang abundance of ^{4}He and those of D and ^{3}He involves the chemical evolution of ^{3}He.

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