Title
Is Deuterium in High-Redshift Lyman Limit Systems Primordial?

Journal
The Astrophysical Journal, 483(2)

ISSN
0004-637X

Authors
Jedamzik, Karsten
Fuller, George M

Publication Date
1997-07-10

DOI
10.1086/304288

Peer reviewed

THE ASTROPHYSICAL JOURNAL, 483:560–564, 1997 July 10

IS DEUTERIUM IN HIGH-REDSHIFT LYMAN LIMIT SYSTEMS PRIMORDIAL?

KARSTEN JEDAMZIK[1] AND GEORGE M. FULLER[2]

Received 1996 September 16; accepted 1997 January 13

ABSTRACT

Detections of deuterium in high-redshift Lyman limit absorption systems along the line of sight to QSOs promise to reveal the primordial deuterium abundance. At present, the deuterium abundances (D/H) derived from the very few systems observed are significantly discordant. Assuming the validity of all the data, if this discordance does not reflect intrinsic primordial inhomogeneity, then it must arise from processes operating after the primordial nucleosynthesis epoch. We consider processes that might lead to significant deuterium production or destruction and yet allow the cloud to mimic a chemically unevolved system. These processes include, for example, anomalous/stochastic chemical evolution and D/^{4}He photodestruction. In general, we find it unlikely that these processes could have significantly altered D/H in Lyman limit clouds. We argue that chemical evolution scenarios, unless very finely tuned, cannot account for significant local deuterium depletion since they tend to overproduce ^{12}C, even when allowance is made for possible outflow. Similarly, D/^{4}He photodestruction schemes engineered to locally produce or destroy deuterium founder on the necessity of requiring an improbably large γ-ray source density. Future observations of D/H in Lyman limit systems may provide important insight into the initial conditions for the primordial nucleosynthesis process, early chemical evolution, and the galaxy formation process.

Subject headings: cosmology: theory — nuclear reactions, nucleosynthesis, abundances — quasars: absorption lines

In this paper, we explore issues related to the interpretation of recent putative observations of deuterium in seemingly chemically unevolved hydrogen clouds along the line of sight to QSOs. These observations presently do not provide a consistent value for the deuterium abundance, D/H, in high-redshift Lyman limit systems. Measurements in several clouds suggest a "high" value, D/H $\sim 2 \times 10^{-4}$ (Songalia et al. 1994; Carswell et al. 1994; Rugers & Hogan 1996a, 1996b; Carswell et al. 1996; Wampler et al. 1996), while determinations in two systems yield a "low" value, D/H $\sim 2 \times 10^{-5}$ (Tytler, Fan, & Burles 1996; Burles & Tytler 1996a).

It is widely accepted that at least some of these observational inferences of D/H reflect the primordial value of this quantity at the conclusion of the big bang nucleosynthesis (BBN) epoch. This belief is founded on the absence of viable alternative sites or mechanisms that could produce significant amounts of deuterium without overproducing other light elements such as ^{6}Li, ^{7}Li, and ^{3}He (Epstein, Lattimer, & Schramm 1976; Sigl et al. 1995). It is also widely noted that the low metallicities inferred for hydrogen clouds at high redshift generally imply only negligible amounts of deuterium depletion by stars.

It is important to resolve which (if any) of the various inferred values of D/H represent the cosmic average primordial abundance (cf. Cardall & Fuller 1996; Hata et al. 1997). Here we use the term "average" since, in principle, there could exist intrinsic, primordial, super–horizon-scale inhomogeneity at the BBN epoch (e.g., isocurvature fluctuations; see Jedamzik & Fuller 1995). Such intrinsic inhomogeneity could give rise to the apparent discordance in observed D/H, but only if the cosmic average of this quantity was D/H $\sim 10^{-4}$ (Jedamzik & Fuller 1995). A real discordance in D/H is, however, not well established by the data. If the apparent discordance *is* established by future observations, and if it does not arise from intrinsic inhomogeneity, then it must result from processes operating after the BBN epoch.

It may be that the apparent discordance is simply a result of some subset of the data being wrong because, for example, hydrogen "interlopers" are mistaken for isotope-shifted Lyα lines (Songaila et al. 1994; Carswell et al. 1994; Steigman 1994). An erroneous (high) D/H would result if a low column density Lyα forest line by chance happened to reside at the position in velocity space where the deuterium isotope-shifted Lyα line is expected. From the observed frequency of Lyα forest lines in quasar spectra (Hu et al. 1995), one can estimate the a priori probability for any one Lyman limit system (LLS) to have such an interloper. This probability is given by

$$P \approx 9 \times 10^{-3}\left[\frac{(\mathrm{D/H})_p}{10^{-4}}\right]^{-0.46}\left(\frac{N_{\mathrm{H\,I}}}{3 \times 10^{17}\ \mathrm{cm}^{-2}}\right)^{-0.46} \times \left(\frac{1+z}{4}\right)\left(\frac{R_v}{10\ \mathrm{km\ s}^{-1}}\right)[1 + \xi(\Delta v)] \quad (1)$$

and is seen to depend on the primordial $(\mathrm{D/H})_p$ ratio, the column density $N_{\mathrm{H\,I}}$ and redshift z of the LLS, and the observational velocity resolution R_v. The quantity $1 + \xi(\Delta v)$ accounts for the possibility that Lyman forest clouds may be "clustered" in velocity space around LLSs. A similar quantity, the clustering of forest clouds around each other, has been observationally estimated to be approximately $\xi(\Delta v) \sim 1$ for absorber velocity separations $\Delta v \lesssim 100$ km s^{-1} (Chernomordik 1995; Meiksin & Bouchet 1995). In practice, there is a strong observational bias to claim deuterium detections in only those clouds that show the smallest Doppler broadening of absorption lines. The expected narrow width of the deuterium line, as well as the

---

[1] Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550.

[2] Department of Physics, University of California, 9500 Gilman Drive, San Diego, La Jolla, CA 92093-0319; gfuller@ucsd.edu.

relative widths of the deuterium and hydrogen lines, may then be used to further reduce the interloper possibility (Rugers & Hogan 1996a; Burles & Tytler 1996b).

Even should this issue be resolved, there is a plethora of usually hidden and implicit assumptions and decisions that must be made in any assessment of the observational data to extract a *primordial* D/H. These assumptions revolve around issues of chemical evolution and formation histories of LLSs that show deuterium. Any such assumptions may be worrisome, given that even such basic aspects of LLSs as morphology, environment, and their masses are poorly understood. LLSs are clouds or sheets of highly ionized gas with temperatures around a few times 10^4 K and with approximate neutral column densities $N_{\rm H\,I} \approx 3 \times 10^{17}$ cm^{-2}. It is commonly assumed that the bulk of the gas in LLSs is ionized by the diffuse UV background at high redshift. Nevertheless, local sources for the ionizing radiation, such as young blue stars (York et al. 1990; Gruenwald & Viegas 1993) or hot galactic halo gas (Viegas & Friaça 1995), have also been proposed. There may be some evidence that the absorption features of LLSs may be the result of lines of sight passing through a multiphase medium that consists of a "cool" photoionized component and a hot, collisionally ionized component (Giroux, Sutherland, & Shull 1994). It is even difficult to eliminate entirely the possibility that a particular LLS is the result of looking through the gas of one, or a few, planetary nebulae.

It is instructive to estimate typical parameters of an LLS, such as total baryon mass, spatial dimension, and total hydrogen density. One generally assumes heating/cooling equilibrium and ionization equilibrium of the cloud with the background ionizing radiation. The approximate timescale to reach heating/cooling equilibrium is $\tau \simeq 5 \times 10^4[J_0/(10^{-21}\ {\rm ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}})]^{-1}$ yr, with J_0 the specific intensity of ionizing photons at $E_\gamma = 13.6$ eV, whereas the timescale for D/H ionization equilibrium is $\tau \simeq 10^4[n_{\rm H}/(10^{-3}\ {\rm cm^{-3}})]^{-1}$ yr, with $n_{\rm H}$ the total hydrogen density. Assuming heating/cooling and/or ionization equilibrium for metals, as well as spherical geometry for the cloud with a line of sight passing close to the center of the cloud, one finds the total baryon mass,

$$M_b \approx 4 \times 10^6 \left(\frac{U}{10^{-3}}\right)^{5.2} \left(\frac{J_0}{10^{-21}\ {\rm ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}}}\right)^{-2} \times \left(\frac{N_{\rm H\,I}}{3 \times 10^{17}\ {\rm cm^{-2}}}\right)^3 M_\odot\ , \quad (2)$$

the radius,

$$R \approx 2 \left(\frac{U}{10^{-3}}\right)^{2.07} \left(\frac{J_0}{10^{-21}\ {\rm ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}}}\right)^{-1} \times \left(\frac{N_{\rm H\,I}}{3 \times 10^{17} {\rm cm^{-2}}}\right) {\rm kpc}\ , \quad (3)$$

and the total hydrogen density for the cloud,

$$n_{\rm H} \approx 5 \times 10^{-3} \left(\frac{U}{10^{-3}}\right)^{-1} \times \left(\frac{J_0}{10^{-21}\ {\rm ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}}}\right) {\rm cm^{-3}}\ . \quad (4)$$

In these expressions, U is the ionization parameter, i.e., the ratio of the density of ionizing photons (with energies $E_\gamma >$ 13.6 eV) to the total hydrogen number density. The ionization parameter is inferred from either the observed relative abundances of ionization states of "metals" or the inferred temperature of the cloud (Donahue & Shull 1991). Typical uncertainties in U are about 1 order of magnitude, implying a 5 order of magnitude uncertainty in the mass scale of a spherical, one-component, photoionized LLS. Similarly, even under the assumption that the diffuse UV background is the source of the ionization of the cloud, there is considerable uncertainty in J_0, translating into uncertainty in the basic cloud parameters. We conclude that not only is it difficult to determine the masses of the objects in which D/H ratios are observationally inferred, but it is also uncertain how to translate these D/H ratios into a cosmic average. Though quite low mass clouds may be rare or unlikely, it is difficult to *rule out* a very small mass for some LLSs. Such small clouds could have been subject to significant local deuterium destruction or production.

Numerical simulations (Cen et al. 1994; Katz et al. 1996) suggest that there are two broad classes of hydrogen absorption systems with hydrogen column densities sufficiently high ($\gtrsim 3 \times 10^{17}$ cm^{-2}) to be considered Lyman limit absorbers: (1) "field" clouds that are distinct and isolated from (proto) galactic systems and (2) the tenuous outer regions of an otherwise massive (proto) galactic disk or halo. In the first case, of isolated field clouds, the geometries are not well determined, and they could be compact spherical systems or extended sheets. One may imagine that the chemical evolution histories of these two classes of Lyman limit absorbers are different as a result of different formation histories, mixing scales, star formation rates, and/or likelihood of outflows. The question whether different chemical evolution histories in clouds could give rise to inhomogeneity in the observed D/H ratios requires resolution.

Chemical evolution calculations are characterized by specifications of an initial mass function (IMF) and a star formation rate. We follow the notation of Malaney & Chaboyer (1996) and take the star formation rate Ψ (in Gyr^{-1}) and the IMF $\phi(m)$ (in $M_\odot^{-2}$), so that Ψ/Ω_g represents a typical inverse timescale for consumption of baryons into stars and $m\phi(m)dm$ is the fraction of mass going into stars within the stellar mass range m to $m + dm$. Here Ω_g is the fractional contribution of cold gas in damped Lyα systems to the critical density and takes values $\Omega_g \sim 0.003$ at redshift $z \approx 3$–4 (Lanzetta, Wolfe, & Turnshek 1995; Storrie-Lombardi et al. 1995). In this notation, the evolution of cold gas with time can be written as

$$\frac{d\Omega_g(t)}{dt} = -\Psi(t) + \int_{m_l(t)}^{m_{\rm up}} (m - m_r)\Psi[t(z) - \tau(m)]\phi(m)dm\ , \quad (5)$$

whereas the evolution of the deuterium mass fraction, $X_{\rm D}$, with time is given by

$$\frac{dX_{\rm D}(t)}{dt} = -\frac{X_{\rm D}(t)}{\Omega_g(t)} \int_{m_l(t)}^{m_{\rm up}} (m - m_r)\Psi[t(z) - \tau(m)]\phi(m)dm\ . \quad (6)$$

Here $m_{\rm up}$ represents the mass of the largest stars formed, m_r is the remnant mass of a star of mass m, and $m_l(t)$ is the lowest stellar mass that could have returned its gas to the interstellar medium within the age of the universe, $t(z)$ [i.e., the lifetime τ of a star with mass $m_l(t)$ has to satisfy $\tau(m_l) = t(z)$].

We may approximate the evolution of the deuterium mass fraction if we assume a constant star formation rate (and IMF), neglect remnant masses, and approximate Ω_g and $m_l(t)$ as constant. This yields $X_{\rm D}(t) = X_{\rm D}(0) \exp(-t/\tau_{\rm D})$, with $\tau_{\rm D}$ the typical timescale for deuterium destruction,

$$\frac{1}{\tau_{\rm D}} = \frac{\Psi}{\Omega_g} \int_{m_l[t(z)]}^{m_{\rm up}} m\phi(m)dm \, , \tag{7}$$

such that Ψ/Ω_g is the characteristic timescale for incorporation of baryons into stars and the integral is the fraction of stellar material that has been returned to the interstellar medium (ISM) by redshift z. Note that the formalism for estimating maximum deuterium depletion factors in the solar neighborhood as developed by Edmunds (1994) is not applicable in the high-redshift regime that we consider here. This is because the gas mass fractions in LLSs and damped Lyα systems are undetermined.

It has become possible recently to derive constraints on the average star formation rate and IMF from observations of damped Lyα systems (Timmes, Lauroesch, & Truran 1995; Malaney & Chaboyer 1996). In order to be consistent with the observed decline in $\Omega_g(z)$ with decreasing redshift, Malaney & Chaboyer (1996) argue that typical average star formation rates are $\Psi \approx 10^{-2.5}$ Gyr^{-1} for $3 \lesssim z \lesssim 4$. Star formation rates in this range would imply a characteristic timescale for incorporation of baryons into stars of only ~ 1 Gyr. Discounting the possibility of outflow, and assuming IMFs close to standard (Salpeter), the predicted metal enrichment by Malaney & Chaboyer (1996) is also in rough agreement with the observed metallicities in damped systems (Lu et al. 1996). However, average deuterium destruction factors, $\exp(-t/\tau_{\rm D})$, are predicted to be small ($\sim$1%–5%) in the redshift range $3 \lesssim z \lesssim 4$, mainly because it is thought that only a small fraction of stellar material (0.1–0.2) has been returned to the ISM.

The question arises as to how one would have to change the chemical evolution history of a given LLS in order to "achieve" significant deuterium destruction. This may be done in two ways: either locally, in stochastic chemical evolution scenarios, or globally, by using nonstandard chemical evolution scenarios. In stochastic chemical evolution, the cosmic average star formation rate and IMF are unchanged; nevertheless, significant deuterium depletion in an individual LLS may result from local variations in the IMF and star formation rate, or simply from poor sampling of the IMF due to a finite number of stars. Note that the spread in deuterium destruction factors in LLSs increases with decreasing mass scale, and we consider here the possibility that *some* LLSs may be fairly small in mass (because of the uncertainties in J_0 and U in eq. [2]), even though this may not be true on average or for the majority of LLSs. In nonstandard chemical evolution scenarios, cosmic average IMF and star formation rates are altered, yet the implied abundance yields still may agree with observations if one invokes, for example, a peaked IMF or mass/metal outflows. In an example taken from *galactic* chemical evolution, it has been shown recently that destruction of deuterium by a factor of 10 between epochs at high redshift and the time of solar system formation may be possible in models that employ an early metal-rich galactic wind (Scully et al. 1997).

Nevertheless, stringent limits can be placed on the maximum possible deuterium destruction in individual LLSs at high redshift by stars with masses below $M \lesssim 40$ $M_\odot$, provided the abundances of certain key isotopes are determined confidently. Stars must be massive enough that their main-sequence lifetimes [$\log \tau(m) = 10.0 - 3.6 \log m + 1.0 \log^2 m$, with τ in years and m in solar masses; Scalo 1986] are shorter than the age of the universe at redshift $z \sim 3$–4 [assuming a closed universe, the age at a given redshift is $t \approx 6.51(1+z)^{-3/2}$ h^{-1} Gyr, with h the Hubble parameter in units of 100 km s^{-1} Mpc^{-1}]. This implies that only stars with masses $M \gtrsim 2$ $M_\odot$ could have contributed to a possible deuterium depletion in the interstellar medium, a conclusion that is quite insensitive to the adopted cosmology, the value of the Hubble parameter, and the precise redshift of the LLS. Stars in the mass range 2 $M_\odot \lesssim M \lesssim 4$ $M_\odot$ are believed to be significant ^{12}C producers. The ^{12}C is transported to the surfaces of these stars during dredge-ups, when the base of the convective zone reaches shells that are highly carbon enriched. The ^{12}C-enriched material is subsequently returned to the ISM in planetary nebula ejecta (Iben & Truran 1978; Renzini & Violi 1981). Observations of stars in the Magellanic Clouds and the Galaxy lend strong support to net production of ^{12}C in stars in this mass range, where typically solar proportions of ^{12}C are produced (with a characteristic spread, or uncertainty, of a factor of 3). From theoretical arguments, it is believed that carbon and oxygen production yields in these stars must increase slightly with decreasing metallicity. More massive AGB stars (4 $M_\odot \lesssim M \lesssim 8$ $M_\odot$) with approximately solar metallicity should in fact be net destroyers of ^{12}C, as a consequence of the effects of hot bottom burning (van den Hoek & Groenewegen 1997; Forestini & Charbonnel 1997). Theoretical arguments imply that the effects of hot bottom burning may be less drastic for low-metallicity stars, where the ^{12}C abundance yield may then be only 1/10 solar. It should be noted that hot bottom burning does not affect the total abundance in CNO isotopes. The net sum of CNO isotopes produced should increase with increasing stellar mass. Even though ^{12}C production in AGB stars is a complicated issue because of the uncertain details of convective dredge-up, hot bottom burning, and planetary nebula ejection, it is commonly believed that intermediate-mass stars must be the main production sites for ^{12}C (J. W. Truran 1996, private communication). The ejecta of massive stars, $M \gtrsim 8$ $M_\odot$, that undergo Type II supernova explosions are expected to be enriched not only in ^{12}C but also in heavier isotopes such as ^{28}Si and ^{56}Fe, with typical production mass fractions of 1 to a few times the corresponding solar mass fraction (Woosley & Weaver 1995). Production factors are less certain for more massive stars, $M \gtrsim 30$–40 $M_\odot$, in particular for the heavier isotopes.

The observational determination of carbon and silicon abundances in LLSs (e.g., [C/H] $= -2.2$ and -3.0 for the two clouds in the system at $z = 3.572$ determined by Tytler et al. [1996] from the observations of the carbon ionization states C II, C III, and C IV) can be used to constrain stellar deuterium depletion. Adopting carbon production of 1 times solar over the stellar mass ranges 2 $M_\odot \lesssim M \lesssim 4$ $M_\odot$ and 8 $M_\odot \lesssim M \lesssim 40$ $M_\odot$, and using [C/H] $= -2$ for the LLS, one can infer that not more than $\sim$1% of the gas in the LLS could have been cycled through stars in the given mass range. This implies that deuterium depletion by most stars with $M \lesssim 40\ M_\odot$ cannot exceed $\sim 1\%$. Note that this constraint *cannot* be circumvented by invoking metal-rich winds (outflow), because the *same* stars that deplete deuterium also produce ^{12}C abundantly. Moreover, it seems unlikely that a particular LLS could result from a line of sight passing through one or a few deuterium-depleted planetary nebulae, especially given the low observationally inferred carbon abundances for the LLSs in question. For less massive planetary nebulae it would be hard to understand how the carbon abundance could be low, while for more massive planetaries a low nitrogen abundance would be a puzzle.

If one imposes the constraint that significant deuterium depletion by stars must have occurred, then there are only a few, seemingly highly unlikely, possibilities. Chemical evolution could have proceeded via a sharply peaked IMF at $M \approx 6\ M_\odot$. Observational consequences of such a scenario may include the significant enrichment of the LLS in other isotopes, such as ^{14}N. As a second possibility, a large fraction of material may have been cycled through an early generation of supermassive stars, $M \gtrsim 1000\ M_\odot$, which may eject material that could be deuterium depleted or deuterium enhanced (Fuller, Woosley, & Weaver 1986) but that otherwise shows only minimal enrichment in other species (it is possible that only ^{4}He would be produced). Direct inference of black hole remnants might establish the viability of such a scenario, but so might the detection of an intermediate-mass element abundance pattern characteristic of hot *rp*-process nucleosynthesis. Is there a loophole in our arguments centered on carbon overproduction? Maybe the carbon abundance in an LLS is underestimated, since either the dominant carbon ionization state is C I or else carbon is depleted on grains. Whereas one can place observational constraints on the C I column density (S. Burles 1996, private communication), the existence of dust in LLSs is not easily observationally constrained. In fact, AGB stars at the present epoch are thought to produce grains in circumstellar outflows. However, it seems unlikely that significant amounts of dust in LLSs could survive evaporation by the ambient ionizing radiation field at high redshift. Since the typical evaporation time of a dust grain is expected to be much shorter than the cosmic time, it would be improbable to catch an LLS in a time interval during which significant amounts of ^{12}C are still locked up in grains. Last, it may be that carbon production, and particularly the dredge-up processes and/or hot bottom burning in low-metallicity AGB stars, is not well understood.

Deuterium may also be produced or destroyed by nuclear photodisintegration in the presence of a γ-ray source: ^{4}He(γ, pn)^{2}H, ^{4}He(γ, ^{2}H)^{2}H, or ^{2}H(γ, n)p. For most γ-ray sources, production of ^{2}H dominates over destruction because the number density of ^{4}He targets is much greater than that of ^{2}H targets. In fact, ^{4}He photodisintegration has been proposed as an efficient non-BBN source for deuterium (Gnedin & Ostriker 1992), even though it has been subsequently shown that this would yield anomalously large ratios $^3\mathrm{He}/^2\mathrm{H} \sim 10$, in conflict with the presolar abundance ratio $^3\mathrm{He}/^2\mathrm{H} \sim 1$ (Sigl et al. 1995). In any case, in the absence of direct ^{3}He abundance determinations, one may posit that an LLS is enhanced (or depleted) in deuterium since it had once been close to a powerful γ-ray source. Assume, for example, the existence of a population of γ-ray bursters at redshift $z_b \lesssim 1000$, each of which radiates a flux with spectrum hard enough to produce γ-ray energies slightly above the ^{4}He(γ, ^{2}H)^{2}H threshold, $E_{\rm th} \approx 23$ MeV. In order for these γ-ray bursters not to overproduce the diffuse X-ray/γ-ray background at the present epoch, the comoving γ-ray burster density has to be smaller than

$$N_\gamma^c \lesssim 10\, \frac{1}{1+z_b} \left\{ \frac{j_\gamma[z=0,\ E_{\rm th}/(1+z_b)]}{10^{-5}\ \mathrm{MeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}} \right\} \times \left(\frac{E}{10^{60}\ \mathrm{ergs}} \right)^{-1}\ \mathrm{Mpc^{-3}}\ , \quad (8)$$

where j_γ is the specific X-ray/γ-ray intensity at the present epoch determined at the energy $E_{\rm th}/(1+z_b)$ and 10^{-5} MeV^{-1} cm^{-2} s^{-1} sr^{-1} is the approximate present specific intensity at $E_\gamma \approx 20$ MeV (Fichtel et al. 1977). Here E is the total energy in γ-rays above threshold in a single burst. An adopted approximate comoving distance between γ-ray bursters of $r_c \sim 10$ Mpc should be compared with the maximum distance by which an individual LLS could have been separated from a γ-ray burst in order to still have had significant deuterium production by ^{4}He photodisintegration. This comoving distance is

$$r_p^c \lesssim 10^{-2}(1+z_b) \left(\frac{E}{10^{60}\ \mathrm{ergs}} \right)^{1/2} \left[\frac{(^4\mathrm{He}/^2\mathrm{H})_p}{2.8 \times 10^3} \right]^{1/2}\ \mathrm{kpc}\ , \quad (9)$$

where $(^4\mathrm{He}/^2\mathrm{H})_p$ is a primordial number ratio. These distances indicate that significant deuterium production, as well as destruction, by $^4\mathrm{He}/^2\mathrm{H}$ photodisintegration should be regarded as an improbable process. Spatially varying D/H ratios at high redshift, if they exist, may have their origin in the intermediate-mass–scale primordial inhomogeneity of the baryon-to-photon ratio. Jedamzik & Fuller (1995) pointed out that such primordial isocurvature fluctuations may yield order unity D/H fluctuations on galactic mass scales ($M \simeq 10^{10}$–$10^{12}\ M_\odot$) and fluctuations in D/H by a factor of ~ 10 on the postrecombination Jeans mass scale ($M_{\rm J} \simeq 10^5$–$10^6\ M_\odot$). Nevertheless, such scenarios of BBN can only agree with observationally inferred primordial abundance constraints if a variety of criteria are met, such as the efficient collapse of high-density regions, the presence of a cutoff for isocurvature fluctuations on mass scales $M \lesssim M_{\rm J}$ (cf. Jedamzik & Fuller 1995; Gnedin, Ostriker, & Rees 1995; Kurki-Suonio, Jedamzik, & Mathews 1997), and the moderate-to-significant ^{7}Li depletion in low-metallicity Population II stars. Note that, contrary to recent claims (Copi, Olive, & Schramm 1996), models that predict intrinsic fluctuations in D/H on the LLS scale are *not* generally ruled out by the isotropy of the cosmic microwave background radiation. Future observations of D/H ratios in different LLSs may constitute the first test for the presence or absence of baryon-to-photon fluctuations on intermediate mass scales.

In conclusion, it is difficult to envision a *compelling* model for differential D/H destruction or production in LLSs that could explain the apparent observationally inferred discordance. The logical leading candidates for such a model are either stochastic chemical evolution *or* anomalous chemical evolution involving a finely tuned star formation rate or IMF. However, we have argued that most such models may be ruled out by ^{12}C overproduction. In any case, future observations of additional LLSs showing deuterium may provide insight into the resolution of this problem: either (1) misidentification or misanalysis of deuterium lines in LLSs, (2) super–horizon-scale primordial inhomogeneity at the BBN epoch, or (3) very finely tuned IMF and star formation rates (i.e., quite different from those inferred from galactic chemical evolution considerations) in some LLSs. With the advent of the Sloan Digital Sky Survey, one may expect a substantial increase in the number of known bright quasars in the near future. It has been estimated that this may yield on the order of ~ 100 LLSs suitable for the determination of D/H ratios (C. J. Hogan 1996, private communication). With the help of these data, one may gain important new insights into chemical/stellar evolution and the galaxy formation problem.

We wish to thank B. Balick, S. Burles, C. Cardall, C. Charbonnel, C. Hogan, J. Prochaska, M. Shull, J. Truran, S. Viegas, and A. Wolfe for useful discussions. We also acknowledge the hospitality of the Institute for Nuclear Theory at the University of Washington, where a substantial part of this research was performed. This work was supported by NSF grant PHY-9503384 and NASA theory grant NAG 5-3062 at the University of California, San Diego and under the auspices of the US Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-ENG-48 and Department of Energy nuclear theory grant SF-ENG-48.

REFERENCES

Burles, S., & Tytler, D. 1996a, Science, submitted
———. 1996b, preprint
Cardall, C., & Fuller, G. M. 1996, ApJ, 472, 435
Carswell, R. F., Rauch, M., Weyman, R. J., Cooke, A. J., & Webb, J. K. 1994, MNRAS, 268, L1
Carswell, R. F., et al. 1996, MNRAS, 278, 506
Cen, R., Miralda-Escudé, J., Ostriker, J. P., & Rauch, M. 1994, ApJ, 437, L9
Chernomordik, V. V. 1995, ApJ, 440, 431
Copi, C. J., Olive, K. A., & Schramm, D. N. 1996, ApJL, submitted (astro-ph/9606156)
Donahue, M., & Shull, J. M. 1991, ApJ, 383, 511
Edmunds, M. G. 1994, MNRAS, 270, L37
Epstein, R. I., Lattimer, J. M., & Schramm, D. N. 1976, Nature, 263, 198
Fichtel, C. E., Hartman, R. C., Kniffen, D. A., Thompson, D. J., Ögelman, H. B., Özel, M. E., & Tümer, T. 1977, ApJ, 217, L9
Forestini, M., & Charbonnel, C. 1997, A&AS, in press (astro-ph/9608153)
Fuller, G. M., Woosley, S. E., & Weaver, T. A. 1986, ApJ, 307, 675
Giroux, M. L., Sutherland, R. S., & Shull, J. M. 1994, ApJ, 435, L97
Gnedin, N. Yu., & Ostriker, J. P. 1992, ApJ, 400, 1
Gnedin, N. Yu., Ostriker, J. P., & Rees, M. J. 1995, ApJ, 438, 40
Gruenwald, R., & Viegas, S. M. 1993, ApJ, 415, 534
Hata, N., Steigman, S., Bludman, S., & Langacker, P. 1997, Phys. Rev. D, 55, 540
Hu, E. M., Kim, T.-S., Cowie, L. L., Songaila, A., & Rauch, M. 1995, AJ, 110, 1526
Iben, I., Jr., & Truran, J. W. 1978, ApJ, 220, 980
Jedamzik, K., & Fuller, G. M. 1995, ApJ, 452, 33
Katz, N., Weinberg, D. H., Hernquist, L., & Miralda-Escudé, J. 1996, ApJ, 457, L57
Kurki-Suonio, H., Jedamzik, K., & Mathews, G. J. 1997, ApJ, 479, 31
Lanzetta, M. K., Wolfe, A. M., & Turnshek, D. A. 1995, ApJ, 440, 435
Lu, L., Sargent, W. L. W., Barlow, T. A., Churchill, C. W., & Vogt, S. S. 1996, ApJS, 107, 475
Malaney, R. A., & Chaboyer, B. 1996, ApJ, 462, 57
Meiksin, A., & Bouchet, F. R. 1995, ApJ, 448, L85
Renzini, A., & Violi, M. 1981, A&A, 94, 175
Rugers, M., & Hogan, C. J. 1996a, ApJ, 459, L1
———. 1996b, AJ, 111, 2135
Scalo, J. M. 1986, Fundam. Cosmic Phys., 11, 1
Scully, S., Cassé, M., Olive, K. A., & Vangioni-Flam, E. 1997, ApJ, 476, 521
Sigl, G., Jedamzik, K., Schramm, D. N., & Berezinsky, V. S. 1995, Phys. Rev. D, 52, 6682
Songalia, A., Cowie, L. L., Hogan, C. J., & Rugers, M. 1994, Nature, 368, 599
Steigman, G. 1994, MNRAS, 269, L53
Storrie-Lombardi, L. J., McMahon, R. G., Irwin, M. J., & Hazard, C. 1995, in QSO Absorption Lines, ed. G. Meylan (Berlin: Springer), 47
Timmes, F. X., Lauroesch, J. T., & Truran, J. W. 1995, ApJ, 451, 468
Tytler, D., Fan, X.-M., & Burles, S. 1996, Nature, 381, 207
van den Hoek, L. B., & Groenewegen, M. A. T. 1997, A&AS, in press (astro-ph/9610030)
Viegas, S. M., & Friaça, A. C. S. 1995, MNRAS, 272, L35
Wampler, E. J., Williger, G. M., Baldwin, J. A., Carswell, R. F., Hazard, C., & McMahon, R. G. 1996, A&A, 316, 33
Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181
York, D. G., Caulet, A., Rybski, P., Gallagher, J., Blades, J. C., Morton, D. C., & Wamsteker, W. 1990, ApJ, 351, 412