

THE LOCAL ABUNDANCE OF ^3He : A CONFRONTATION BETWEEN THEORY AND OBSERVATION

SEAN T. SCULLY,¹ MICHEL CASSÉ,² KEITH A. OLIVE,¹ DAVID N. SCHRAMM,^{3,4}
JAMES TRURAN,³ AND ELISABETH VANGIONI-FLAM⁵

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ABSTRACT

Determinations of the ^3He concentrations in Galactic matter serve to impose interesting and important constraints both on cosmological models and on models of Galactic chemical evolution. At present, observations of ^3He in the solar system and in the interstellar medium today suggest that the ^3He abundance has not increased significantly over the history of the Galaxy, while theoretical models of Galactic chemical evolution (utilizing current nucleosynthesis yields from stellar evolution and supernova models) predict a rather substantial increase in ^3He . We consider the possibility that the solar ^3He abundance may have been affected by stellar processing in the solar neighborhood prior to the formation of the solar system. Such a discrepancy between solar abundances and average Galactic abundances by as much as a factor of 2 may be evidenced by several isotopic anomalies. Local destruction of ^3He by a similar amount could serve to help reconcile the expected increase in the ^3He abundance predicted by models of Galactic chemical evolution. We find, however, that the production of heavier elements, such as oxygen, places a strong constraint on the degree of ^3He destruction. We also explore the implications of both alternative models of Galactic chemical evolution and the stellar yields for ^3He in low-mass stars, which can explain the history of the ^3He concentration in the Galaxy.

Subject headings: Galaxy: abundances — Galaxy: evolution —
nuclear reactions, nucleosynthesis, abundances — Sun: abundances

1. INTRODUCTION

There is an inherent difficulty associated with the utilization of the observed abundances of D and ^3He to predict their primordial values. Namely, the connection between the primordial abundances of D and ^3He and their solar or present-day values depends sensitively on models of Galactic chemical evolution. In principle, measurements of D in quasar absorption systems could dramatically help us bridge this gap by providing directly the primordial abundances of D hence the value of the baryon-to-photon ratio, η , from big bang nucleosynthesis (BBN) (Walker et al. 1991). However, recent measurements of this kind (Carswell et al. 1994; Songaila et al. 1994; Tytler & Fan 1995) must be viewed as preliminary, as the determined D abundance in the two absorption systems observed are not concordant with each other. Until such measurements yield a single consistent value for primordial D, we must continue to be guided by models of Galactic chemical evolution.

It has been well established that models of Galactic chemical evolution, consistent with the constraints imposed by element abundance determinations, are capable of destroying significant amounts of deuterium (Truran & Cameron 1971; Gry et al. 1984; Delbourgo-Salvador et al. 1985; Vangioni-Flam & Andouze 1988; Vangioni-Flam, Olive, & Prantzos 1994; Vangioni-Flam & Cassé 1995). However, as was recently discussed in Olive et al. (1995), the problem rests not with the destruction of D, but rather with

the production of ^3He . Though ^3He is partially destroyed in massive stars, ^3He production in low-mass stars generally leads to a net increase in the ^3He abundance over the evolutionary history of the Galaxy. Observations of large ^3He enhancements in planetary nebulae (Rood, Bania, & Wilson 1992; Rood et al. 1995) support the conclusion that ^3He is indeed produced in low-mass stars. An excess of ^3He is difficult to avoid if low-mass stars are strong producers of this isotope, as indicated by the calculations of Iben & Truran (1978) and more recently by Vassiliadis & Wood (1993) and Weiss, Wagenhuber, & Denissenkov (1995). However, recent models with increased mixing have been calculated, which both bring the carbon and oxygen isotopic ratios to their observed levels in red giants and lead to a net destruction of ^3He (Charbonnel 1994; Wasserburg, Boothroyd, & Sackmann 1995; Hogan 1995). At present, these models are quite preliminary, and it is premature to draw a firm conclusion. However, if their results are confirmed, ^3He will be significantly less problematic, unless the primordial D abundance is as high as observed by Songaila et al. (1994) and Carswell et al. (1994); in this case we would still require ^3He destruction factors in excess of what current calculations bear out (Olive et al. 1995).

Abundance determinations of ^3He at the time of the formation of the solar system seem to indicate that the solar ^3He abundance is very close to that of the primordial abundance. Here we will examine in some detail the possibility that the ^3He abundance in the solar system may be depleted with respect to Galactic averages at the time of its formation. We find, however, that the abundances of the heavier elements—most notably oxygen and neon—impose a strong constraint on the degree of depletion of ^3He . We are therefore left with the following possibilities: either the initial deuterium abundance is low, with $D/H \sim 3 \times 10^{-5}$ (we will discuss rough lower limits imposed by models of chemical evolution); or more dramatic changes are required

¹ School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455.

² Service d'Astrophysique, DSM, DAPNIA, CEA, France.

³ Department of Astronomy and Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, IL 60637-1433.

⁴ NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510-0500.

⁵ Institut d'Astrophysique de Paris, 98bis Boulevard Arago, 75014 Paris, France.

in models of chemical evolution, which have the effect of maintaining a rather flat evolution of ^3He with time (we will show an example of this type of model below); or the stellar yields of ^3He in low-mass stars are lower than previously thought.

Because deuterium is converted to ^3He in the pre-main-sequence phase of stellar evolution, models without a significantly depressed initial D abundance are subject to problems with ^3He production. If the initial abundance of D is rather low ($D \lesssim 3 \times 10^{-5}$), the present-day ^3He abundance found in standard models of Galactic chemical evolution are not excessive and are consistent with the observed range $1\text{--}5 \times 10^{-5}$ (Balsler et al. 1994). However, even in these cases, there appears to be a problem with the abundance of ^3He as measured in meteorites, giving the presolar value of ^3He . That is, on the basis of chemical evolution models, we expect more ^3He than is observed in the solar system (Olive et al. 1995; Galli et al. 1995; Tosi, Steigman, & Dearborn 1995). In this paper we will thus consider in turn the possibility that ^3He in the solar system has been depleted with respect to the Galactic average, the accuracy of the measurement of solar ^3He , and what we can learn from Galactic chemical evolution.

2. SOLAR DEPLETION OF ^3He ?

In principle, it is possible that the abundance of ^3He at the time of the formation of the solar system does not reflect the Galactic average at that time. It is necessary to consider the degree to which element abundances in the solar system were affected by the explosions of supernovae in the solar neighborhood immediately prior to the formation of the solar system (Reeves 1978; Olive & Schramm 1982). This may be evidenced by several “anomalous” isotopes (of carbon, oxygen, and neon) seen in cosmic rays. However, late contributions to the abundances of ^{16}O and ^{20}Ne , which are produced solely in Type II supernovae, may render the solar system isotopic ratios of these elements anomalous. That is, the solar abundances may not represent the true average Galactic abundance. For the oxygen and neon isotopes, these differences may be as large as a factor of 2. We now examine the possibility that the solar ^3He abundance may also not be representative of the true Galactic abundance.

From the observed anomalies in ^{26}Al and ^{107}Pd (Lee 1979; and references therein) and more recently ^{41}Ca , and the short timescales associated with their half-lives ($\sim 10^6$ yr), the element abundances in our solar system were probably affected by at least one supernova within that time period prior to formation. Even a single supernova explosion in a star forming region can have dramatic consequences on the element abundances of that region. As was argued by Olive & Schramm (1982), a handful of the first few supernovae in an early OB association is capable of producing nearly the entire observed solar abundance of ^{16}O and ^{20}Ne . Thus we would expect that the solar isotopic ratios such as $^{17,18}\text{O}/^{16}\text{O}$ and $^{22}\text{Ne}/^{20}\text{Ne}$ may be diluted with respect to the Galactic average. It is therefore of interest to question whether or not the abundance of ^3He (which would be depleted in the ejecta of the first few supernovae in an association) is comparably depleted.

To deplete ^3He , we must require that a significant amount of material in the solar neighborhood underwent stellar processing prior to the formation of the solar system. Let us suppose that a fraction f of the total initial gas of the

association went into stars prior to the solar epoch. It is then reasonable to assume that a fraction $\sim 0.1f$ of the gas went into stars with masses greater than $10 M_\odot$. [For example, with a Salpeter 1955 initial mass function (IMF) $\phi(m) \propto m^{-2.35}$ between 0.1 and $100 M_\odot$, the fraction is 12%; for a Scalo 1986 mass function, it may range from 5% to 15% depending on the star formation rate (SFR)]. If we denote by X_* the mass fraction of some heavy element (such as O) ejected by massive stars, the total mass fraction of the element after the explosions of stars more massive than $10 M_\odot$, which thus determines (and must be less than) the solar abundance, is then given by

$$X_f = \frac{0.1fX_* + (1-f)X_i}{(1-f) + 0.1f} < X_\odot, \quad (1)$$

where X_i is the initial mass fraction of the element and we have assumed that $0.9f$ of the initial gas mass is still locked in stars. To maximize our estimate of ^3He destruction (as this will maximize our estimate for f), we can assume that $X_i = 0$. Solving for f , we have

$$f < \frac{X_\odot}{0.1X_* + 0.9X_\odot}. \quad (2)$$

For oxygen, $X_* \sim 0.1$ and $X_\odot \sim 0.01$, so that $f \lesssim \frac{1}{2}$. Thus, we can cycle no more than half the mass of the associations through stars prior to the formation of the solar system.

Although a significant amount of gas may be cycled through stars, only a small fraction of ^3He depleted gas can be released back into the association. If we take X to represent ^3He in equation (1), and now take $X_* = 0$ (which assumes that ^3He is totally destroyed in massive stars) and X_i to be the primordial ^3He mass fraction, we find

$$X_f = \frac{(1-f)X_i}{1-0.9f} \lesssim 0.9X_i. \quad (3)$$

This indicates that only about 10% of the initial ^3He can be destroyed, even though changes in the heavy-element abundances occur at a level of a factor of 2.

It is possible, of course, to further deplete ^3He in the gas which forms the solar system at the expense of excessive metal production. Such overproduction of metals can perhaps be reconciled with ^3He depletion, if the heavy elements could somehow be expelled from the solar neighborhood. As Lattimer, Schramm, & Grossman (1977) pointed out, the bulk of the heavy-element ejecta from supernovae can rapidly form into dust grains. These dust grains can behave like explosive “shrapnel” and penetrate regions exterior to the association. This might allow the association itself, and hence the solar system, to fail to show a large heavy-element excess, even though the total heavy-element enrichment would be part of the integrated Galactic enrichment. This assumes, of course, that the entire association region is not totally disrupted by the supernovae explosion prior to the formation of the solar system. However, as was shown in Olive & Schramm (1982), a significant amount of oxygen and neon is produced which should not be trapped in grains. Because of the behaviors of these elements, we believe that it is unlikely that more than about 10% of the ^3He present in the association could be destroyed before the formation of the solar system.

An obvious recourse to resolving the problem of the overproduction of ^3He at the solar epoch is to question the measurement of the solar ^3He abundance. In the next

section we examine the observational data on the solar abundances of D and ^3He .

3. D AND ^3He IN PRESOLAR NEBULAE

Because the crucial data in attempts to estimate the primordial D/H and $^3\text{He}/\text{H}$ values come from solar system measurements, it is useful to examine critically the origin of these abundances and to attempt to provide an accurate estimate of their uncertainties.

The determination of the solar abundances of D and ^3He involves $^3\text{He}/^4\text{He}$ measurements both in meteorites and also directly in the solar wind. Direct D/H measurements are irrelevant for the Sun, since D is completely burned to ^3He in the solar convective zone. Moreover, D/H measurements are difficult to interpret in planetary bodies (Earth, Jupiter, etc.); because D preferentially enters molecules relative to H, abundance determinations require a knowledge of complex chemical fractionation histories. However, because essentially all primordial D has been burned to ^3He in the solar convective zone and because the convective zone is not hot enough to burn ^3He , the solar wind measurement of $^3\text{He}/^4\text{He}$ provides a measurement of the presolar abundance of $(\text{D} + ^3\text{He})/^4\text{He}|_{\odot}$ by number. Solar wind measurements, made using foil collectors during Apollo lunar missions, yielded values for $^3\text{He}/^4\text{He}$ ranging from 4 to 5.5×10^{-4} . Geiss & Reeves (1972) and Bochsler & Geiss (1989) (see also Geiss 1993 for a recent review) argue that the variation can be corrected for, and that the best solar wind ratio is $^3\text{He}/^4\text{He}|_{\text{sw}} = (4.1 \pm 1) \times 10^{-4}$ (where the error is statistical). This is in good agreement with the low-temperature component emitted by carbonaceous chondrites in stepwise heating experiments (Black 1972; Weiler et al. 1991), for which $^3\text{He}/^4\text{He}|_{\text{sw}} \simeq (4.5 \pm 1) \times 10^{-4}$, and also with the *ISEE 3* solar wind data (Coplan et al. 1984), which yields 4.4×10^{-4} . However, some fractionation in all the solar wind $^3\text{He}/^4\text{He}$ measurements cannot be excluded, which would add an additional systematic error to the above value. The extreme value for $^3\text{He}/^4\text{He}$ observed for the Apollo solar wind measurement of 5.5×10^{-4} cannot be excluded as a central value; hence, a systematic uncertainty of 1.4×10^{-4} for $^3\text{He}/^4\text{He}$ cannot be excluded at present. The most recent measurement of $^3\text{He}/^4\text{He}$ in the solar wind from the over-the-solar-pole measurements made with the Solar Wind Ion Composition Spectrometer (SWICS) on the *Ulysses* spacecraft gives $^3\text{He}/^4\text{He} = (4.4 \pm 0.4) \times 10^{-4}$ (Bodmer et al. 1995).

The presolar $^3\text{He}/^4\text{He}|_{\odot}$ ratio is thought to be best measured in meteorites. Initially, Black (1971) proposed that the high-temperature (high T) component emitted by stepwise heating experiments using carbonaceous chondrites (see also Eberhardt 1974) was the primordial component ($^3\text{He}/^4\text{He} \sim 1.5 \times 10^{-4}$). However, Weiler et al. (1991) have argued that this high-temperature component is dominated by gas trapped in presolar grains (diamonds) which formed in locations far removed from the solar system. Weiler et al. (1991) propose that another gas component known as "Q" is a better candidate for the primordial component. Fortunately, the difference in $^3\text{He}/^4\text{He}$ between the high-*T* carbonaceous chondrite component and Q is relatively small:

$$^3\text{He}/^4\text{He}|_Q = (1.6 \pm 0.04) \times 10^{-4}. \quad (4)$$

However, a potential interpretational (systematic) error persists, since neither Q nor diamonds nor the high-*T* carbonaceous chondrite component has been unequivocally

proved to represent $^3\text{He}/^4\text{He}|_{\odot}$. Taking $^3\text{He}/^4\text{He}|_Q$ as $^3\text{He}/^4\text{He}|_{\odot}$, but allowing for systematics to include the range of relevant meteoritic $^3\text{He}/^4\text{He}$ values, yields $^3\text{He}/^4\text{He}|_{\odot} = (1.6 \pm 0.04 \pm 0.3) \times 10^{-4}$. The presolar D is estimated by subtracting $^3\text{He}/^4\text{He}|_{\odot}$ from the SWICS solar wind value. To convert to ratios relative to hydrogen requires multiplying by the number ratio of $^4\text{He}/\text{H}|_{\odot}$, which is estimated to be 0.09 ± 0.01 (note that this is 10% lower than that used by Geiss 1993) from the best-fit solar model $Y = 0.27$ (Truck-Chièze et al. 1988; Bahcall & Pinsonneault 1992) with metallicity $Z = 0.02$. This yields

$$\left. \frac{\text{D} + ^3\text{He}}{\text{H}} \right|_{\odot} = (4.1 \pm 0.6 \pm 1.4) \times 10^{-5} \quad (5)$$

and

$$\left. \frac{^3\text{He}}{\text{H}} \right|_{\odot} = (1.5 \pm 0.2 \pm 0.3) \times 10^{-5} \quad (6)$$

and thus

$$\left. \frac{\text{D}}{\text{H}} \right|_{\odot} = (2.6 \pm 0.6 \pm 1.4) \times 10^{-5}. \quad (7)$$

The latter number is in reasonable agreement with the $\text{HD}/\text{H}_2 = (1-3) \times 10^{-5}$ ratio measured in Jupiter (Smith, Schempp, & Baines 1989). Although planetary D ratios are subject to chemical fractionation, this is minimized for HD on Jupiter, since the bulk of the deuterium and hydrogen is in HD and H_2 there. However, molecular line blanketing does still allow for significant systematic errors. For this reason, Jupiter is still not the best source for a solar system D determination, but it does provide a consistency check.

4. CHEMICAL EVOLUTION

The solar system abundance of ^3He is thus seen to be approximately a factor of 2 lower than that predicted by even the more optimistic models of Galactic chemical evolution, which tend to yield abundance ratios at least as high as 3×10^{-5} for $^3\text{He}/\text{H}$, when ^3He production in lower mass stars is included (Olive et al. 1995). In what follows we will look at three different approaches to resolving the problem of excess solar ^3He . We first consider possibilities for which the primordial value of D/H is low. A low initial D/H lowers $^3\text{He}/\text{H}$, as there is less D to be converted to ^3He in the pre-main-sequence evolution of stars. However, as we will show, one cannot take arbitrarily low values of D/H [of course D/H is always bounded from below by the interstellar medium (ISM) measurements of D/H yielding $\text{D}/\text{H} = (1.6 \pm 0.09^{+0.05}_{-0.1}) \times 10^{-5}$ (Linsky et al. 1993, 1995)], since some amount of deuterium destruction necessarily accompanies the production of heavy elements in the Galaxy. We then consider "higher" values of D/H, which requires some dramatic changes to simple models of chemical evolution, such as an increased production of massive stars in the early Galaxy as well as metal enriched outflow. We will also examine some remaining alternatives regarding the stellar production of ^3He . Note, however, that there may be a quite disturbing dispersion of D/H in the local ISM which would complicate the analysis (Vidal-Madjar 1991; Ferlet 1992; J. L. Linsky 1995, private communication).

As was noted earlier, the questions concerning high versus low D/H may become moot if the determinations of

primordial D/H in quasar absorption systems yield a single consistent value. To date there are three measurements of D/H in quasar absorption systems. Two (in the same system) yield a high value for $\text{D}/\text{H} \approx (1.9\text{--}2.5) \times 10^{-4}$ (Carswell et al. 1994; Songaila et al. 1994), while the third (in a different system) yields a significantly lower value, $\text{D}/\text{H} \approx (1\text{--}2) \times 10^{-5}$. It is clear that, on the basis of these measurements, we cannot with confidence claim any knowledge of the primordial abundance of deuterium. Indeed, it has been argued (Levshakov & Takahara 1995) that measurements of this type may not be able to determine D/H to better than an order of magnitude. In other words, they would expect a large dispersion in the observational data. Is this what we are seeing?

Interestingly enough, the two values for D/H identified above are in some respects both beneficial and detrimental to big bang nucleosynthesis. The high value of D/H corresponds to a value for the baryon-to-photon ratio $\eta \approx 1.5 \times 10^{-10}$ (Walker et al. 1991). Consequences of this high D/H were recently discussed in Vangioni-Flam & Cassé (1995). With regard to the other light elements produced in big bang nucleosynthesis, the low value for η corresponds to a ^4He mass fraction $Y_p \approx 0.23$, which is in remarkable agreement with what one expects from the data on ^4He from extragalactic H II regions (Olive & Steigman 1995; Olive & Scully 1995). $^7\text{Li}/\text{H}$ is predicted to be around 2×10^{-10} , which is also compatible within errors with recent data (Molaro, Primas, & Bonifacio 1995). The problem occurs with the evolution of ^3He when ^3He production is included (note that models of chemical evolution can be constructed which can account for the necessary D/H destruction in this case). In Olive et al. (1995) it was found that the abundance of ^3He at the time of solar system formation could be high by as much as a factor 10. Even in the absence of ^3He production, it was found that massive stars were required to destroy at least 90% of their initial $\text{D} + ^3\text{He}$ in order to reproduce the solar and ISM values of ^3He . This amount of destruction is excessive, even for the most massive stars (Dearborn, Schramm, & Steigman 1986).

On the other hand, the low value of D/H between 1 and 2×10^{-5} corresponds to a value of $\eta \approx (7\text{--}9) \times 10^{-10}$. In contrast to the high-D/H case, we would expect a much milder problem with ^3He (to be discussed below). However, now the ^4He mass fraction is predicted to be $Y_p > 0.249$, a value larger than most of the ^4He measurements (Pagel et al. 1992; Skillman et al. 1995) in extragalactic H II regions, which already contain some nonprimordial ^4He . (However, again, possible systematic errors cannot be excluded [Copi, Schramm, & Turner 1995a; Sasselov & Goldwirth 1995]). In addition, $^7\text{Li}/\text{H}$ is expected to be greater than 5×10^{-10} , requiring a significant amount of ^7Li depletion, contrary to what one expects (Steigman et al. 1993) from the positive measurements of ^6Li in halo stars (Smith, Lambert, & Nissen 1992; Hobbs & Thorburn 1994). Furthermore, as we will next show, a minimal amount of D destruction is demanded for consistency with the observed level of heavy-element production in the Galaxy. A completely flat evolution for D is probably excluded on these grounds.

The classical constraints on Galactic evolution are characterized by varying degrees of stringency. Among these, the trends in $[\text{Fe}/\text{H}]$ with time are easily satisfied, since the age-metallicity relation suffers from a larger dispersion over the observed age range (Edvardsson et al. 1993; Nissen 1995). The $[\text{O}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ relationship is mainly sen-

sitive to the stellar yields and not to the different histories of star formation (assuming a constant IMF). The metallicity distribution of disk stars is far from being definitely established. Indeed, much work is needed before a clear picture of the metallicity distribution can be reached (e.g., Olsen 1994; R. Cayrel 1995, private communication). Information on metallicities, ages, and kinematics, with the same high accuracy as obtained by Edvardsson et al. (1993), is needed for a much larger stellar sample. Moreover, Grenon (1989, 1990) remarks that the radial migration of stars in the Galaxy can blur the local metallicity distribution.

Other global characteristics which should be considered are the gas fraction, σ , the overall metallicity, Z , and individual abundance ratios (Fe/H , O/H etc.) at solar birth and in the present ISM. To the list of constraints, we must also add the D/H and $^3\text{He}/\text{H}$ ratios at solar birth and at the present time, in relation to the primordial value. Indeed, since primordial nucleosynthesis is much more constrained than Galactic evolution, it is reasonable to harmonize the second to the first, and not the contrary (as has sometimes been done recently).

Many models have been proposed to follow the chemical evolution of the Milky Way, invoking, for example, a prompt initial enrichment (Truran & Cameron 1971), infall of primordial material (Timmes, Woosley, & Weaver 1995; Fields 1995), metal-enriched infall originating from the halo (Ostriker & Thuan 1975), and early massive star formation (Larson 1986; Wyse & Silk 1987). Studies of Galactic chemical evolution remain in their infancy, however, since we do not yet have good theories of Galaxy formation and star formation. It would be unwise, for the sake of simplicity, to limit the investigation to “classical” models under the pretext that they have been widely used. In effect, if the high primordial D/H ratio is confirmed, special models leading to a strong D destruction avoiding overproduction of ^3He and Z will be required.

An alternative way of looking at variations from the Galactic mean has been carried out by Copi et al. (1995b), who consider the stochastic variations from Galactic evolution models. Their conclusions concerning the allowed range of primordial D and ^3He are similar to, and compatible with, those we discuss here.

4.1. Low D/H

We will first explore the possible consequences of a very low primordial value of D/H and examine the extent to which a low D/H could explain the apparent flatness of the $^3\text{He}/\text{H}$ evolution in the Galaxy. We begin by estimating the minimum possible amount of D/H destruction. In simplified models of Galactic chemical evolution, it is possible to derive some analytic relations between abundances, yields, the gas fraction, and the IMF, if one assumes the instantaneous recycling approximation (that is, that the enriched mass that is ultimately to be ejected from a star is incorporated into the ISM at the time of formation of the star, in contrast to its appropriate delayed entry at the end of the star’s lifetime). Indeed, the degree to which deuterium is destroyed can be expressed simply by

$$\frac{\text{D}}{\text{D}_p} = \sigma^{R/(1-R)} \quad (8)$$

(Ostriker & Tinsley 1975), where σ is the gas mass fraction, D_p is the primordial D abundance, and the return fraction,

R, is given by

$$R = \int_{M_1}^{M_{\text{sup}}} (M - M_{\text{rem}}) \phi(M) dM. \quad (9)$$

In equation (9) M_1 is the main-sequence turnoff mass (normally a function of time), M_{sup} is the upper mass limit for star formation, and M_{rem} is the remnant mass.

It is also possible to express the metallicity in terms of the gas mass fraction and the yields of metals in stars (Searle & Sargent 1972):

$$Z = \frac{P_Z}{1 - R} \ln \sigma^{-1}, \quad (10)$$

where

$$P_Z = \int_{M_1}^{M_{\text{sup}}} \left(\frac{M_Z}{M} \right) M \phi(M) dM \quad (11)$$

and M_Z/M is the mass fraction ejected in metals. Equations (8) and (10) can be combined, yielding

$$\frac{D}{D_p} = e^{-ZR/P_Z}. \quad (12)$$

As one can see from equation (8), a low primordial value for D/H will require a small return fraction, R . In principle, one can easily adjust the IMF to yield a small value for R . However, because of the similarity in the definitions of R and P_Z , their ratio is almost independent of the details of the IMF. Thus D/D_p near unity implies a metallicity much less than solar.

The interdependence between deuterium and metallicity can be seen in Figure 1. In order to reach solar metallicity at the time the solar system formed, we require a deuterium destruction factor of at least 1.6, implying that $(D/H)_p \gtrsim 2.5 \times 10^{-5}$. We note that this factor is somewhat dependent upon the assumed yields for the heavier elements. For example, this limit was obtained using the stellar yields of Woosley & Weaver (1993); whereas had we used the yields

of Maeder (1992), which allow for more heavy-element production in the mass range from 9 to 11 M_\odot , the minimum destruction factor could be lowered to about 1.3. It is worth noting that, beyond the uncertainties of the yields which are essentially related to those associated with the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction rate, the lower mass limit of the stellar progenitor of the Type II supernovae which synthesize the heavy elements is influential because of the preference in the IMF toward lower mass stars. Indeed, the limit is greatly increased as the slope of the IMF is decreased. All of these effects can be seen in Figure 1, where we have plotted (for various choices of the parameters which govern the SFR) the metallicity at the solar epoch in units of solar metallicity, Z/Z_\odot , as a function of the ratio of the *present* deuterium abundance to the primordial one, thus indicating the total deuterium destruction factor for a variety of Galactic evolution models. We have chosen an SFR proportional to the mass in gas, and an IMF $\phi(m) \propto m^{-2.7}$, shown here by the upper set of points denoted by circles (yields from Maeder 1992) and crosses (yields from Woosley & Weaver 1993). For the lower set of points, a steeper IMF, $\phi(m) \propto m^{-3}$, was chosen. In each case, the lower mass limit of the IMF was 0.4 M_\odot (lowering this choice to 0.1 M_\odot would further lower the curves). It is important to note that, when ^3He production is taken into account, even the modest deuterium destruction factor (of 1.6) yields an overproduction by about a factor of 2 in solar ^3He .

4.2. Higher D/H

In this section, we will consider an alternative to low primordial D/H and rely on more distinctive models of Galactic chemical evolution to resolve the problem concerning the solar ^3He abundance. As we have stated earlier, the choice of a higher value for primordial D/H alleviates some of the pressure in matching the BBN calculations to the observational determinations of ^4He and ^7Li . Clearly, the higher the value we choose for primordial D/H, the more difficult it will be to keep ^3He under control. We choose specifically the value $(D/H)_p = 7.5 \times 10^{-5}$, which corresponds roughly to the ^7Li trough and is in modest agreement with ^4He (at the 2σ plus systematics level).

The models we consider below specifically involve mass outflow. Open Galactic models have been considered in the past (Tinsley 1980; Tosi 1988), but infall has been invoked more often than outflow. Formally, the two reverse processes are included in the general formalism of Galactic chemical evolution (Tinsley 1980) and cosmochronology (Cowan, Thielemann, & Truran 1989). There is clear evidence for galactic winds in external galaxies, even for spirals (Wang et al. 1995), and particularly those experiencing bursts of star formation, whereas evidence for significant infall of extragalactic matter are meager (Murphy, Lockman, & Savage 1995). Of course, this reflects only constraints arising from the present state of the solar vicinity and proves nothing about the early Galaxy.

Outflow has its own merit: as we will see below, it will help to explain very high destruction factors of D (Vangioni-Flam & Cassé 1995) while, if necessary, avoiding an overproduction of metals. At the same time, it could reduce the rise of the $^3\text{He}/\text{H}$ ratio. De Young & Heckman (1994) proposed that energy from supernova explosions and stellar-driven winds resulting in blowing portions of the ISM containing enriched material out of the Galaxy. Different kinds of outflows can be imagined, which vary consider-

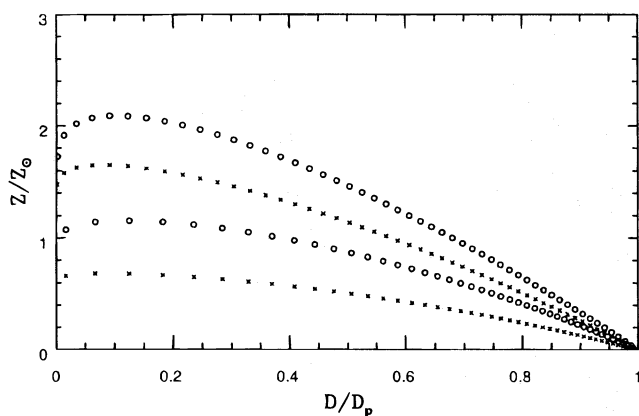


FIG. 1.—Dependence of the metallicity produced as a function of the deuterium destruction factor D/D_p for a large sample of models. The metallicity is plotted in solar units. The SFR used was $\psi \propto M_{\text{gas}}$, where the constant of proportionality ranges from 0.01 to 1.0. The circles correspond to the choice of stellar yields from Maeder (1992), while the crosses correspond to the yields of Woosley & Weaver (1993). A power-law IMF was chosen with a slope of -2.7 for the upper two sets of points and -3.0 for the lower two sets.

ably in their durations, intensities, and compositions. For our present purposes, it is sufficient to distinguish whether the outflowing matter consists solely of the ejecta of massive stars or rather is composed of normal ISM material being blown out by supernova-driven winds. In Cassé et al. (1996) we will return to these distinctions in greater detail.

The three specific ingredients that must be added to canonical Galactic evolutionary models in order to obtain significant D destruction without the overproduction of ^3He are (1) an early phase of massive star formation, which presents the advantage of destroying D and ^3He rapidly; (2) a Galactic wind related to the corresponding SN II rate, which limits the rise of Z and ^3He , leading to an even more pronounced decrease of D; and (3) possible modifications of stellar models, leading to an efficient destruction of ^3He , especially in low-mass stars.

One way we have found in which the solar value of ^3He may be lowered is to assume that the IMF prior to the formation of the solar system was skewed more toward massive star formation. The presence of fewer lower mass stars reduces ^3He production, while more massive stars ultimately return to the ISM only a fraction of the ^3He present during the pre-main-sequence phase. We therefore consider models which begin with an IMF favoring more massive stars early in Galactic history but resemble a more normal IMF at later times.

The problem that we immediately encounter is that the emphasis on more massive stars results in an overproduction of heavy elements, such as ^{16}O . We have found that the (closed box) models which are most successful in keeping ^3He flat while destroying enough D also overproduce ^{16}O by a factor of ~ 10 . This problem is alleviated by including outflow. Indeed, McCray & Snow (1979) have shown that supernovae can generate “chimneys,” which can directly transport much of the heavy-element-rich supernova debris out of the Galaxy. We have therefore included “enriched” (relative to the ISM) outflow in our models, both to help solve the heavy-element overproduction problem and to obtain a flatter $^3\text{He}/\text{H}$ evolution. In order to simulate this effect, we have incorporated outflow into our models at a rate proportional to the rate of ejection of material from supernovae.

Since massive stars can lose large amounts of ^3He -depleted outer material via winds before they explode, it is certainly possible for them to deplete ^3He in their surrounding ISM material and eject their metals out of the Galaxy. We allow the outer (hydrogen) envelope of the star which is deficient in ^3He to return to the ISM via winds. Then, in order to maximize the possible effect of an overflow which is tied to the ejecta of exploding stars ($M > 8\text{--}10 M_\odot$), a fraction of the core is expelled from the Galaxy. Such models provide a natural way to understand the heavy-element abundances in the X-ray gas observed in clusters of galaxies (typically, the heavy-element-enriched outflow is produced by elliptical galaxies; see, e.g., Elbaz, Arnaud, & Vangioni-Flam 1995). It might also be noted that early expulsion of metal-rich supernova ejecta is even easier in merger models, where the early Galactic building blocks have a lower mass. Due to the epoch of more massive star formation at earlier times, D is generally very efficiently destroyed in these models.

We should note at this point that our assumptions concerning winds from massive stars prior to the supernova stage may be inappropriate at early Galactic epochs. The

rate of mass loss is generally expected to be dependent upon the initial metallicity of the star (Maeder, Lequeux, & Azzopardi 1980; Maeder & Meynet 1994). Expectations from theoretical studies are generally consistent with, for example, trends in the frequency of Wolf-Rayet stars, as inferred from studies of the Magellanic Clouds (Massey et al. 1995). This suggests that the fraction of the ^3He -depleted outer envelopes of massive stars that is returned to the ISM via winds (prior to supernova-triggered mass ejection) in low-metallicity populations may be significantly reduced. We stress, however, that our aim here is to see how efficiently the evolution of the ^3He abundance can be held relatively flat over the history of the Galaxy. As we will see, we find only modest success despite rather poignant assumptions.

An obvious observational constraint on our choice of an IMF that is skewed toward more massive star production at early times, $\phi(m) \propto m^{-(1.25+0/0\odot)}$, is provided by its consistency with the present-day IMF that results from our model. Figure 2 shows a comparison of the observed and modeled present-day IMF. The observed values are taken from Scalo (1986) and are in good agreement with our model for the more massive stars. This is as expected, since the more numerous massive stars formed early on have long since died out.

It is useful to compare the results we have obtained here with those of our previous study, in which we considered a more standard model. In model 1 of Olive et al. (1995), we chose an SFR $\psi = 0.25\sigma$ with an IMF $\phi(m) \propto m^{-2.7}$ between 0.4 and $100 M_\odot$. The ^3He abundance at the solar formation epoch (taken to be at $t = 9.4$ Gyr) was $^3\text{He}/\text{H} = 5.7 \times 10^{-5}$, rising to 8.8×10^{-5} today. Infall was not included. For a primordial ratio $\text{D}/\text{H} = 7.5 \times 10^{-5}$, the results for D/H and $^3\text{He}/\text{H}$ as a function of time, for a model with an IMF which favors massive stars early and contains enriched outflow in which the rate is proportional to the ejection rate, are compared to model 1 of Olive et al. (1995) in Figure 3. The outflowing gas contains only material below the outer envelope, while the latter ^3He -depleted material is returned to the ISM. In this model the SFR is $\psi = 0.26 M_{\text{gas}}$, and the fraction of outflowing gas is 90% of the supernova ejecta. The IMF is now extended down to $0.1 M_\odot$ to help keep the metallicity and gas mass fraction reasonably low. We view this as a rather extreme model, in which a considerable amount of enriched material

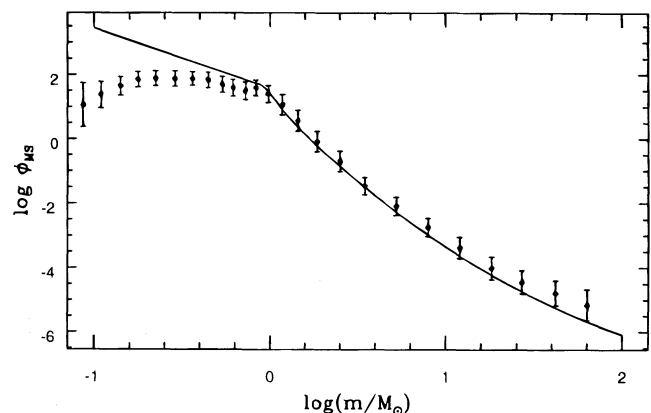


FIG. 2.—Present-day mass function of our adopted model as compared to the data from Scalo (1986).

has been expelled from the Galaxy. Indeed, we impose a limit, arising from the observed metallicity of hot X-ray gas in clusters, on the amount of metals expelled by outflow to be less than 20 times the amount of metals in the Galaxy. This imposes a constraint on the fraction of outflowing gas (90% in this case).

As one can see from Figure 3, our present model, which is based on an IMF skewed toward massive stars early on and contains an enriched outflow, reduces the abundance of ^3He by a factor of about 2 relative to the standard case with a normal IMF and no outflow. Parameters of the model have been chosen such that the degree of deuterium destruction is comparable (and agrees with the data) in the two cases. However, although the present ^3He abundance is acceptable ($^3\text{He}/\text{H}|_0 = 5.1 \times 10^{-5}$), the solar abundance is still high by a factor of slightly over 2 ($^3\text{He}/\text{H}|_\odot = 3.7 \times 10^{-5}$). While this represents a definite improvement, it cannot be regarded as a solution to the problem. Although it appears from Figure 3 that better agreement with the solar data is possible if one assumes a lower time for the formation of the solar system, the model must be adjusted to destroy D on a faster timescale. For example, with $\psi = 0.34 M_{\text{gas}}$ the evolution of deuterium matches the solar (and present-day) observations at $t = 6$ Gyr (corresponding to an age of the Galaxy of 10.6 Gyr), but now $^3\text{He}/\text{H}|_\odot \approx 3.1 \times 10^{-5}$ and the present abundance is 4.9×10^{-5} —a further improvement, but solar ^3He is still too high.

Of course, as is well known, the problem concerning ^3He is also alleviated somewhat by going to higher values of η . In model 3 of Olive et al. (1995), we assumed a primordial deuterium abundance of $\text{D}/\text{H} = 3.5 \times 10^{-5}$. In this case $^3\text{He}/\text{H}|_\odot = 3.4 \times 10^{-5}$, an overproduction by a factor greater than 2. The present ^3He was also slightly high: $^3\text{He}/\text{H} = 6 \times 10^{-5}$. In models with outflow as described above, these numbers are reduced to $^3\text{He}/\text{H}|_\odot = 2.3 \times 10^{-5}$ and $^3\text{He}/\text{H} = 3.2 \times 10^{-5}$ today.

Before we move on, we wish to stress that the problems concerning ^3He that we are discussing here prevail only because we are including the production of ^3He in low-mass

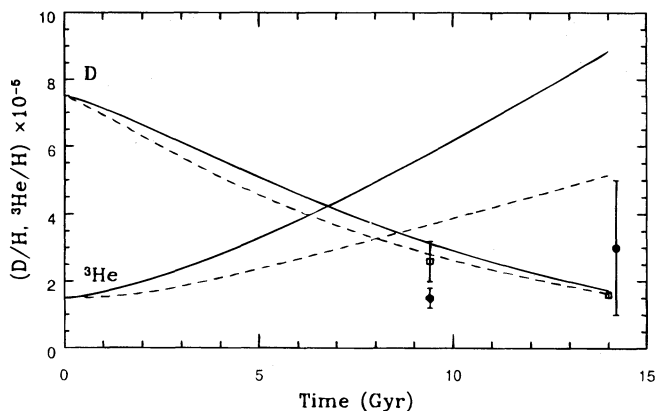


FIG. 3.—Evolution of D/H and $^3\text{He}/\text{H}$ as a function of time for a standard model of Galactic chemical evolution (solid line) and for one which favors massive stars early and includes metal-enriched outflow (dashed line). Also shown are the values of these ratios at the time of formation of the Sun, $t \approx 9.4$ Gyr, and today, for D/H (open squares) and $^3\text{He}/\text{H}$ (filled circles). The present-day ^3He abundance simply shows the range of observed values; the data point does not represent an average. The models were chosen so that D/H is destroyed by a total factor of 5, to the present.

stars. When such production is ignored, there is no problem in matching the solar and ISM data for both D and ^3He in models of these types, as was shown by Vangioni-Flam et al. (1994). The crisis in big bang nucleosynthesis claimed by Hata et al. (1995) is only a crisis because of the limit on the degree of ^3He destruction they allowed. Although the final ^3He abundance in a given star relative to the initial $\text{D} + ^3\text{He}$ abundance, usually called g_3 , is always larger than 0.25 as assumed by Hata et al., even simple models such as the type considered here (without outflow) and in Vangioni-Flam, Olive, & Prantzos (1994) have an effective g_3 which is lower than 0.25, vitiating the purported crisis.

4.3. Alternatives

A critical consideration with regard to the establishment of any realistic constraints on cosmological D and $\text{D} + ^3\text{He}$ is that associated with ^3He production in low-mass stars. Essentially all early estimates of D and ^3He constraints on cosmology (see, e.g., Truran & Cameron 1971; Rood, Steigman, & Tinsley 1976) were based upon the stellar evolution models of Iben (1967a, b), for which analytical fits to the detailed model characteristics were subsequently provided by Iben & Truran (1978). The problem of ^3He then is simply the fact that, with the use of the Iben & Truran (1978) prescriptions, ^3He production in stars in the mass range $\sim 1\text{--}3 M_\odot$ is sufficient to overproduce ^3He in Galactic chemical evolution models (Olive et al. 1995; Galli et al. 1995; Timmes & Truran 1995), relative both to the solar system value of ^3He and to the ^3He concentration in the ISM at the present time (Balsler et al. 1994). Further strong confirmation of this behavior has been provided by recent stellar evolution calculations (Vassiliadis & Wood 1993; Weiss et al. 1995). It would seem to be necessary either to utilize rather extreme assumptions regarding the history of our Galaxy or to identify some significant problem in stellar evolution theory.

An interesting recent paper by Wasserburg et al. (1995) has called attention to the fact that the long-standing problems associated with understanding both low $^{12}\text{C}/^{13}\text{C}$ ratios in low-mass red giant branch stars and low $^{18}\text{O}/^{16}\text{O}$ ratios in asymptotic giant branch stars can be resolved, with the assumption of the occurrence of deep circulation currents extending below the bottom of the standard convective envelope. A concomitant of this process of “cool bottom burning” is the destruction of ^3He . In particular, for the case of a $1 M_\odot$ star, their models predict that after a first dredge-up ^3He enhancement of a factor of ~ 6 , cool bottom processing acts to reduce the ^3He concentration by a factor ~ 10 , yielding a net depletion of ^3He by a factor ~ 2 . If this model is indeed correct, this would aid substantially in the problem of ^3He overproduction, with which we are so concerned in this paper. We note that any mass loss during the first ascent of the red giant branch would inject ^3He -rich material into the ISM and would therefore lessen the impact of the subsequent ^3He destruction, as discussed by Wasserburg et al. However, in the spirit of the preceding sections we will ignore this effect and allow for all of the ^3He destruction suggested by Wasserburg et al., keeping in mind that this may very well be an overestimate.

To test the effect of such a reduction in the ^3He yields, we incorporated the results of Wasserburg et al. (1995) by lowering the Iben & Truran (1978) yields of ^3He at $1 M_\odot$ by a factor of 10. For an initial deuterium abundance of 7.5×10^{-5} , this corresponds to a $g_3 = 0.27$. We reduced the

degree to which the Iben & Truran yields were modified at higher masses such that, at $M > 3 M_{\odot}$, we once again were using the Iben & Truran yields. The results of such a reduction in model 1 of Olive et al. (1995) are shown in Figure 4. Here the evolution of D/H and $^3\text{He}/\text{H}$ are shown in model 1 with both the Iben & Truran yields and the reduced yields. Even in this case, there remains a mild overproduction of ^3He by a factor of about 2. That is, at $t = 9.4$ Gyr, $^3\text{He}/\text{H} = 3 \times 10^{-5}$. In Figure 5 we show the effect of the reduced ^3He yields in the model with outflow discussed in the previous section. Here, finally, we find a value for $^3\text{He}/\text{H}$ at the solar epoch which is perhaps acceptable. At $t = 9.4$ Gyr, $^3\text{He}/\text{H} = 2.4 \times 10^{-5}$. A further improvement is possible by considering models which evolve on shorter timescales as discussed above.

An obvious problem with the reduction in ^3He yields at low stellar masses is the observation of high ^3He concentrations in planetary nebula ejecta (Rood et al. 1992, 1995), which would seem to confirm the predictions of the more standard models for the evolution of low-mass stars along the giant branch. It is clear that this issue must be resolved before a more definitive statement can be made with respect to Galactic evolution constraints on the primordial abundances of D and ^3He .

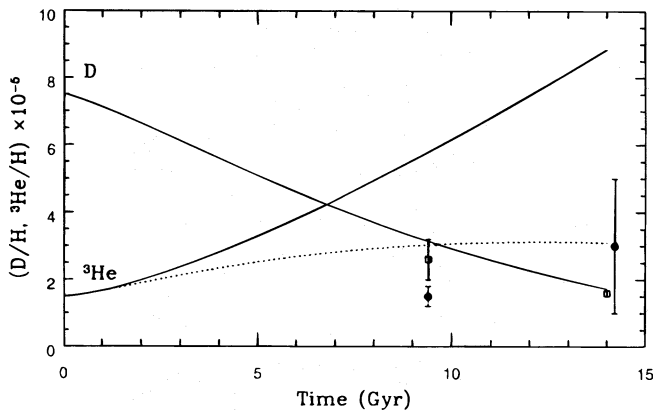


FIG. 4.—As in Fig. 3, for a standard model (solid line) and for one in which the stellar yields of ^3He at low masses have been reduced (dotted line). Deuterium is the same in both cases.

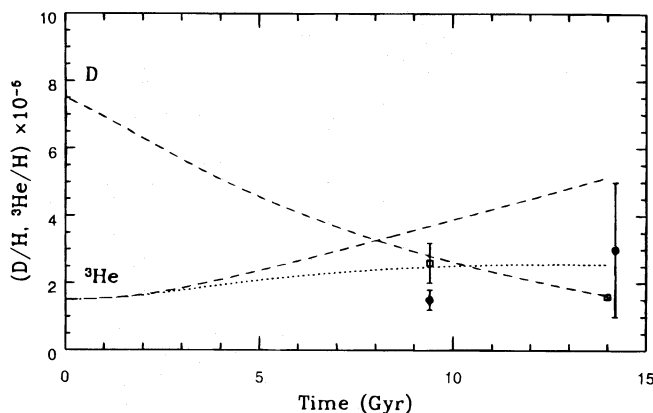


FIG. 5.—As in Fig. 3, for the model with enriched outflow from Fig. 3 (dashed line) and for one with outflow in which the stellar yields of ^3He at low masses have been reduced (dotted line).

A further question of interest is that concerning the composition of the matter involved in “mass infall,” during the later stages of evolution of our Galaxy. In this context we note that while we have not considered such infall models in this paper (see, e.g., Olive et al. 1995), they may provide plausible alternative solutions to the ^3He problem. The implications of infall of matter of primordial composition of the light elements D, ^3He , and ^7Li are certainly quite different from those of processed matter, which may generally be expected to be metal enriched and deuterium depleted. Infall of primordial material is generally beneficial, with the adoption of the lower primordial D abundance, while infall of D- and ^3He -depleted matter improves the situation for the case of a higher primordial D abundance. The fact that the nature and origin of such infalling material is presently uncertain makes it necessary to treat its composition as an additional parameter. This problem is further complicated by the fact that it is even possible for the infalling gas both to be metal enriched and to have an essentially primordial composition of D and ^3He . This could occur if, for example, the ejecta of the first generation of massive stars in the halo of our Galaxy were lost to the surrounding intergalactic medium. The ejecta of stars of $M > 10 M_{\odot}$ collectively represents $\sim 10\%$ of the initial mass formed into stars (e.g., for a Salpeter IMF over the range of $0.1\text{--}100 M_{\odot}$) and is characterized by a metal abundance greater than $10 Z_{\odot}$, assuming $\sim 10^{10} M_{\odot}$ of early star formation would yield $\sim 10^9 M_{\odot}$ of metal-enriched gas ejected, which could contaminate $\sim 10^{10} M_{\odot}$ to solar metallicity and yet have deuterium at a level of only ~ 0.9 of its primordial value.

5. CONCLUSIONS

What can we conclude from this analysis? We have shown that, unlike the abundances of some of the heavier elements such as oxygen and neon, which can differ by as much as a factor of 2 locally relative to their average Galactic abundance by prior supernovae in the solar neighborhood, the local ^3He abundance could only have been affected by at most 10%. It also appears that the ^3He data from a variety of sources is consistent and yields a value $^3\text{He}/\text{H}|_{\odot} = 1.5 \times 10^{-5}$ for the presolar ^3He abundance. Standard models of Galactic chemical evolution yield an excess of ^3He at the solar epoch by a factor which ranges from 2 to 12 depending on the assumed primordial value for D/H. For models with $\text{D}/\text{H} = 7.5 \times 10^{-5}$ initially, the factor of nearly 4 excess in ^3He can be brought down to an excess of about a factor of 2 in models which favor massive stars early on and include the possibility for a substantial amount of metal-enriched outflow. In such models the solar ^3He abundance is brought down to nearly acceptable levels when primordial $\text{D}/\text{H} < 3.5 \times 10^{-5}$. Finally, we considered the possibility that part of the problem may lie in the stellar yields of ^3He . Though it appears that the cut in yields suggested by Wasserburg et al. (1995) may not in itself be sufficient to lower the solar ^3He abundance, that reduction in conjunction with chemical evolution models may. We feel justified in claiming that any apparent “crisis” in big bang nucleosynthesis is rather a (potential) problem for chemical evolution and/or stellar evolution.

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