LOW-MASS STARS AND THE $^3$He PROBLEM

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Received 1996 October 7; accepted 1996 November 13

ABSTRACT

Standard chemical evolution models predict an overabundance of $^3$He from low-mass stars (in the range of 1–3 $M_\odot$) with respect to the measured solar and present-day abundances and hence indicate a possible problem with the yields of $^3$He in these stars. Because $^3$He is one of the nuclei produced in big bang nucleosynthesis (BBN), it is noted that Galactic and stellar evolution uncertainties necessarily relax constraints based on $^3$He. We incorporate into chemical evolution models that include outflow the new yields for $^3$He of Boothroyd & Malaney (1995), which predict that low-mass stars are net destroyers of $^3$He. Since these yields do not account for the high $^3$He/H ratio observed in some planetary nebulae, we also consider the possibility that some fraction of stars in the 1–3 $M_\odot$ range do not destroy their $^3$He in their post-main-sequence phase. We also consider the possibility that the gas expelled by stars in these mass ranges does not mix with the ISM instantaneously thus delaying the $^3$He produced in these stars, according to standard yields, from reaching the ISM. In general, we find that the Galactic D and $^3$He abundances can be fitted regardless of whether the primordial D/H value is high ($2 \times 10^{-4}$) or low ($2.5 \times 10^{-5}$).

Subject headings: Galaxy: abundances — ISM: abundances — nuclear reactions, nucleosynthesis, abundances — stars: interiors

1. INTRODUCTION

The abundances of the light elements, D, $^3$He, $^4$He, and $^7$Li, serve as a critical test to the standard hot big bang model (Walker et al. 1991). In the case of two of these elements, $^4$He and $^7$Li, primordial values can be reasonably well determined directly from observations. $^4$He may be inferred from low-metallicity H II regions (see, e.g., Pagel et al. 1992; Olive & Steigman 1995; Olive, Skillman, & Steigman 1997; Skillman et al. 1997; Olive & Scully 1996), while the uniform abundance of $^7$Li in halo dwarfs is interpreted to be the primordial value for $^7$Li/H (Spite & Spite 1982). Although possible stellar depletion of as much as a factor of 2 cannot be categorically excluded, higher depletion is in conflict with $^7$Li observed in these stars and with maintaining the tightness of the plateau (Steigman et al. 1993; Vaucrait & Charbonnel 1995; Lemoine et al. 1996). Fields & Olive (1996) and Fields et al. (1996) have argued that on the basis of these two isotopes alone, one can constrain the single parameter (the baryon-to-photon ratio, $\eta$) of standard big bang nucleosynthesis (BBN) with the degree of constraint depending on the allowed $^7$Li depletion and the maximum systematic errors allowed in the $^4$He determination.

The consistency of the two remaining elements, D and $^3$He, with such a best fit $\eta \approx 1.8 \times 10^{-10}$ based on $^4$He and $^7$Li, may pose a challenge for many chemical evolution models. Let us first discuss deuterium, which may eventually give the cleanest constraints but at present has some ambiguities. Deuterium evolution by itself is straightforward, since D is only produced in BBN and destroyed by stellar processing (Reeves et al. 1973; Epstein, Lattimer, & Schramm 1976). Thus, the present $HST$ determined ISM D/H values give a robust upper bound on $\eta$, but alone do not specify the degree of depletion between BBN and the present day. While progress has been made recently in determining this primordial value by observing D/H in quasar absorption systems, a consistent (D/H), has not yet been found. Both a high primordial value of D/H around $2 \times 10^{-4}$ (Carswell et al. 1994; Songaila et al. 1994; Rugers & Hogan 1996a, 1996b) and low (D/H) $\sim 2.5 \times 10^{-5}$ (Tytler, Fan, & Burles 1996; Burles & Tytler 1996) have been measured. Both of these measurements have strengths and weaknesses. The high D measurement agrees well with best-fit $\eta$ for $^4$He and $^7$Li (Fields et al. 1996), but requires destruction factors of $\sim 10$ for D to reach its present-day observed values. While models exist which can accomplish this (see, e.g., Vangioni-Flam & Audouze 1988; Scully & Olive 1995; Scully et al. 1996a, 1996b), these models prove problematical for $^3$He, since in traditional low-mass star models D is converted into $^3$He. The low D measurement on the other hand proves less of a problem for traditional $^3$He evolution but would require large systematic errors on the primordial $^4$He measurement (Copi, Schramm, & Turner 1995a) and a significantly higher primordial $^7$Li abundance (by a factor of about 3). The possibility that both the high and low D/H measurements are correct and indicate a possible baryon inhomogeneity has been explored in Copi, Olive, & Schramm (1996).

Since D is converted to $^3$He in the pre-main-sequence phase of stellar evolution, the chemical evolution of these two isotopes is closely linked. In what we refer to as traditional models, $^3$He may be produced or destroyed, though not totally (no more than what is expected in massive stars) in the main-sequence phase. As the primordial D/H ratio is increased, these models will produce more $^3$He, whose evolution must be fitted to match the solar and present-day abundances. We discuss these abundances in § 3 below.

Vangioni-Flam, Olive, & Prantzos (1994) have explored the evolution of D and $^3$He using simple closed-box chemical evolution models adopting a (D/H)$_0$ of D/H $= 7.5 \times 10^{-5}$ which is consistent with the primordial $^7$Li inferred by observations and within 2 $\sigma$ plus estimated sys-

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tematics of $^4\text{He}$ (see e.g., Olive & Scully 1996 for a recent discussion on these observed abundances). They found that $^3\text{He}$ is overproduced compared with the observed solar and present–day values of $^3\text{He}$ unless it is assumed that $^3\text{He}$ is destroyed significantly in low-mass stars (i.e., at levels comparable to the destruction in more massive stars). There exists, however, some observational evidence that at least some low-mass stars are net producers of $^3\text{He}$. Rood, Bania, & Wilson (1992) and Rood et al. (1995) find as many as three planetary nebulae with abundances of $^3\text{He}/\text{H}$ as high as $\sim 10^{-3}$. When $^3\text{He}$ production in low-mass stars as calculated by Iben & Truran (1978), Vassiladis & Wood (1993), or Weiss, Wagenhuber, & Denissenkov (1995), is included, there is always a problem with the overproduction of $^3\text{He}$, particularly with respect to the observed solar value (Olive et al. 1995; Galli et al. 1995; Dearborn, Steigman, & Tosi 1996).

As an attempt to overcome the conflict between these observations and the results of Vangioni-Flam et al. (1994), Scully et al. (1996a) proposed that the solution to the problem may be one of chemical evolution. Scully et al. (1996a) considered models that included a higher production of massive stars early in the Galactic history by choosing an initial mass function (IMF) that was skewed more toward massive star production at early times in the Galactic evolution but resembled a more normal IMF at later times. Since larger mass stars are net destroyers of $^3\text{He}$ this could reduce the predicted abundance at the solar epoch. While significantly lower solar $^3\text{He}$ abundances resulted from these models, they still exceeded the observed solar value by a factor of $\sim 2$. Scully et al. (1996a) also considered the possibility that the solar system $^3\text{He}$ may have been depleted from the Galactic abundance at that time and computed the degree to which explosions of supernovae in the solar neighborhood may have affected the observed elemental abundances. They found that at best only 10% of the initial $^3\text{He}$ could be destroyed by this process and concluded that chemical evolution could not fully account for the $^3\text{He}$ problem.

In an attempt to find models that can reproduce the observed solar and present-day D abundances assuming primordial deuterium values as high as those inferred from the quasar absorption systems, Scully et al. (1996b) considered a class of models that included an early epoch of star formation skewed toward massive star production coupled with a supernova wind–driven outflow mechanism. Outflow aids in the D destruction and helps in avoiding overproducing metals associated with the massive star production (Vangioni-Flam & Cassé 1995). These models successfully reproduce a number of observational constraints including the age-metallicity relationship (from Edvardsson et al. 1993) and the distribution of low-metallicity G dwarfs (from Pagel 1988). These models, however, were found to overproduce $^3\text{He}$ by a factor of $\sim 10$ at the solar epoch assuming standard stellar yields such as those of Iben & Truran (1978). The recent observations of Gloeckler & Geiss (1996) indicate that the sum $(\text{D} + ^3\text{He})/\text{H}$ has remained relatively constant since the solar epoch. This would indicate that overall low-mass stars are neither destroyers nor producers of $^3\text{He}$ (Turner et al. 1996). Scully et al. (1996b) found that if stars in the narrow mass range from 0.9 $M_\odot$ to $\sim 1 M_\odot$ produce $^3\text{He}$ according to standard stellar evolutionary theory, while those more massive destroy it, the predicted $^3\text{He}$ abundance matches the solar and present-day observations. Furthermore, this would explain the high $^3\text{He}$ abundances measured in planetary nebulae if their progenitors lie in this mass range.

Recent work in stellar nucleosynthesis has indicated that low-mass stars may indeed be net destroyers of $^3\text{He}$ if one includes the effects of rotational mixing in low-mass stars on the red giant branch (Charbonnel 1994, 1995a, 1995b; Hogan 1995; Wasserburg, Boothroyd, & Sackman 1995; Weiss et al. 1995; Boothroyd & Sackman 1995; Boothroyd & Malaney 1995). In contrast to the result of Scully et al. (1996b), the extra mixing does not take place for stars that do not undergo a helium core flash (i.e., stars $> 1.7$–$2 M_\odot$). Thus, stars less than $1.7 M_\odot$ are responsible for the $^3\text{He}$ destruction (Charbonnel 1995b). This would imply that the progenitor stars of the high $^3\text{He}$ observed by Rood et al. must exceed this mass to avoid a conflict. Unfortunately, the very high $^3\text{He}/\text{H}$ abundances seen in planetary nebulae are more representative of 1 $M_\odot$ stars, as these are the only stars able to produce abundances as high as $^3\text{He}/\text{H}$ $\sim 10^{-3}$. (The predicted yields of $^3\text{He}/\text{H}$ in low-mass stars falls as $M^{-2}$ in standard stellar models (Iben & Truran 1978); see also Galli et al. 1996.)

In this paper, we consider in more detail ways in which low-mass stars affect the problem of the overproduction of $^3\text{He}$. We will incorporate yields from stellar models that include the effects of rotational mixing (Boothroyd & Malaney 1995) into a wide range of chemical evolution models to test their ability to solve the $^3\text{He}$ problem. Note that in these models, the destruction of $^3\text{He}$ is not complete. To fit the C and O ratios, only about 80% destruction is required after the initial production phase. Thus, these “destruction” models actually just keep the $^3\text{He}$ approximately constant, which fits the observations of Gloeckler & Geiss (1996). As an attempt to sidestep the apparent conflict between these new yields and the planetary nebulae abundances of $^3\text{He}$, we shall consider the possibility in which some percentage of stars (on the order of 10%) follow a post–main-sequence evolutionary path that does not include rotational mixing. The planetary nebulae observed by Rood et al. would then be included in this class of stars. We shall test the ability of this scenario to reproduce the solar and present-day $^3\text{He}$ observations.

Another possibility we will examine is that the gas expelled from low-mass stars does not instantaneously mix in with the ISM. The low velocity of the planetary nebulae may translate into mixing times of several billions of years. Thus, only a fraction of the $^3\text{He}$ predicted by standard stellar evolution models for low-mass stars would be present in the gas from which the solar system formed. As we will see, such an assumption is not compatible with significant amounts of D destruction. We begin by describing our basic chemical evolution models. We briefly outline the observational data of D and $^3\text{He}$ in § 3. In § 4, we discuss in detail the results of models that include a time delay in allowing material from planetary nebulae to mix in with the ISM. In § 5 we discuss the results of models that include the yields of Boothroyd & Malaney (1995).

2. CHEMICAL EVOLUTION

In this section, we provide a basic outline for the chemical evolution models we will be using in this work. We want to consider models capable of destroying deuterium by a large factor but do not overproduce metals, which generally result from the increased stellar processing necessary. Scully
et al. (1996b) have developed a class of models that include supernova wind-driven outflow that satisfy these criteria. In addition, these models satisfy a number of observational constraints such as solving the well-known G dwarf problem and reproducing the age-metallicity relationship. We shall adapt these models for this work. A summary of the main features of these models is given below.

To follow the evolution of the mass contained in gas, we use the classical chemical evolution equations (see, e.g., Tinsley 1980). The evolution of the gas mass density in the disk including outflow is given by

\[
\frac{dM_\text{g}}{dt} = -\psi(t) + e(t) - o(t) .
\]  
(1)

In this equation, \(\psi(t)\) is the rate at which gas is being used up by star formation, \(o(t)\) is the rate of outflow described below, and \(e(t)\) is the rate at which gas is returned to the ISM by stellar deaths either in supernova events or in planetary nebulae given by

\[
e(t) = \int_{m_{\text{up}}}^{m_{\text{up}} + m_\text{r}} \rho(m, t)\psi(t - \tau(m) - T_p)dm .
\]  
(2)

Here \(m_{\text{up}}\) is the upper mass limit of stars that form and \(m_\text{r}\) is the remnant mass. We adopt the remnant mass from Iben & Tutukov (1984). \(\tau(m)\) is the main-sequence lifetime of stars adopted from Scalo (1986). We have also incorporated an additional time delay, \(T_p\), to account for the delay of material from planetary nebulae in mixing in with ISM. \(T_p\) is a free parameter in our models for stars with mass less than \(8 M_\odot\) and set equal to zero for stars more massive than this, which we assume will supernova and mix in with the ISM on a very short timescale.

The quantity \(o(t)\) in equation (1) is the rate at which gas leaves the disk. In this work, we shall adopt the outflow mechanism detailed in Scully et al. (1996b). In these models, some fraction of the energy of a supernova event is assumed to go into heating ISM gas to the escape velocity of the disk, leaving the system. The rate at which mass is lost from the system can be determined from

\[
\frac{1}{2}M_\text{w}v_\text{esc}^2 = eE_{SN}N_\text{SN} ,
\]  
(3)

where \(v_\text{esc}\) is the escape velocity, which is taken to be roughly twice the rotational velocity, i.e., \(\sim 500 \text{ km s}^{-1}\). We assume that the dark matter dominates the gravitational potential of the Galaxy and therefore the escape velocity will be taken to be a constant. This will not be the case in merger models (see, e.g., Mathews & Schrämmer 1993), where the escape velocity would be lower initially, allowing for possibly higher outflow rates. \(E_{SN}\) is the energy per supernova event, which is assumed to be \(10^{51} \text{ ergs}\), and \(N_\text{SN}\) is the supernova rate.

All of the supernova energy would be available for heating the ISM gas to escape velocity if radiative cooling of the expanding shell was not important before remnants collide. A critical supernova rate can be determined that the actual supernova rate must exceed if cooling is unimportant before supernova remnants collide and merge. David, Forman, & Jones (1990) have determined this critical supernova rate to be

\[
N_\text{crit} = 0.83 \text{ kpc}^{-3} \text{ yr}^{-1} \left( \frac{n}{\text{ cm}^{-3}} \right)^{1.82} ,
\]  
(4)

where \(n\) is the number density of the ISM gas. Scully et al. (1996b) found that in their models \(N_\text{SN}\) never exceeds this critical value, so cooling is always important. Thus, in order to determine the fraction of energy per event that goes into heating the gas (i.e., \(e\)) the residual thermal energy of a supernova remnant after it has collided and merged with other remnants must be determined. Larson (1974) has estimated the ratio of the residual energy to initial supernova energy in terms of the supernova and critical supernova rates to be

\[
e = 0.22 \left( \frac{N_\text{SN}}{N_\text{crit}} \right)^{0.32} ,
\]  
(5)

which is then used to determine the rate of mass loss in equation (3).

In addition to the gas that leaves the disk due to supernova heating, it is assumed that some fraction of the supernova ejecta does not cool radiatively and is flushed directly out of the Galaxy. Vader (1986) demonstrated that simple supernova-driven wind models with a homogeneous ISM cannot reproduce the observed chemical properties of dwarf elliptical galaxies and proposed this additional metal enhancement to Galactic wind models. The fraction of the metals produced in the supernova progenitors that does not cool radiatively and is blown out of the Galaxy is denoted by \(\nu\) and will be adjusted to match the observed metallicity in the solar neighborhood.

We now turn to the evolution of heavy elements in models including outflow of the type described above. We assume that all stars of a mass greater than \(8 M_\odot\) will supernova. It will be convenient to rewrite the rate of mass ejected by stars, \(e(t)\), to be the sum of the rate ejected by those that supernova, \(e_\text{s}\), and all other stars, \(e(t) - e_\text{s}\). Equation (1) may then be rewritten as

\[
\frac{dM_\text{g}}{dt} = -\psi(t) + e(t) - ve_\text{s}(t) - M_\text{w} ,
\]  
(6)

where \(o(t)\) has now been replaced by \(ve_\text{s}(t) + M_\text{w}\) to reflect the contribution from the wind-driven outflow and metal enrichment. Equation (6) may then be extended:

\[
\frac{d(XM_\odot)}{dt} = -\psi(t)X + e_\text{s}(t)X - ve_\text{s}(t)X - M_\text{w}X ,
\]  
(7)

where \(e_\text{s}(t)\) and \(e_\text{s}(t)\) represent the amount of metals ejected by stars and by Type II supernovae, respectively. This equation can be rewritten to read

\[
\frac{dX}{dt} = \left[ \frac{ve_\text{s}(t) - e(t)}{M_\text{g}} \right] X - \frac{ve_\text{s}(t) + e(t)}{M_\text{g}} ,
\]  
(8)

As in Scully et al. (1996b) we will consider three different initial values for primordial D/H. In cases where a high primordial D value is assumed, D/H = \(2 \times 10^{-4}\) we will consider models similar to model II in Scully et al. (1996b). The evolution of these models is divided into two phases. The first phase consists of a steeply declining exponential SFR of only massive stars (\(>2 M_\odot\)), which lasts for only the first 0.5–1.0 Gyr. This is followed by a phase with an exponential SFR with a more normal IMF that continues to the present day. For the first phase, a SFR of the form \(\psi(t) \sim e^{-t/\tau}\) is chosen that lasts for \(\tau\) Gyr. A power-law IMF is chosen of the form \(\phi(m) \sim m^{-2.7}\) for the range 2–100 \(M_\odot\). The second phase with a SFR of \(\psi(t) \sim e^{-t/5}\) using the same power-law IMF but is in the range 0.4–100 \(M_\odot\). For cases in which an intermediate (D/H) of D/H = \(7.5 \times 10^{-5}\) is
chosen, we shall adopt a model similar to model Ib of Scully et al. (1996b). A SFR proportional to the gas mass is chosen, specifically, \( \psi = 0.28 M_\odot \), with a power-law IMF, \( \varphi \propto m^{-2.7} \) in the mass range of 0.4–100 \( M_\odot \). Finally, we will also consider the possibility that the primordial D/H value is low, \( D/H = 2.5 \times 10^{-5} \). Here we will use the model Ic from Scully et al. (1996b). In this case, a constant SFR is assumed \( \psi = 0.07 \) with the same IMF as in the intermediate (D/H)\(_p\) case. The IMF has been normalized in each case such that
\[
\int_{m_{\text{low}}}^{m_{\text{up}}} \varphi(m) dm = 1 ,
\]
where \( m_{\text{low}} \) and \( m_{\text{up}} \) correspond to the limits of the mass range for each phase.

We determine the abundance of \( ^{16}\text{O} / ^{14}\text{O} \) in our models adopting the yields of Woosley & Weaver (1995). As previously mentioned, we have allowed the fraction of supernova that participate in the Galactic wind, denoted by \( \nu \), to be a free parameter in all of our models, and it is adjusted to reproduce the solar abundance of \( ^{16}\text{O} \). In Figure 1, we show the evolution of the oxygen abundance corresponding to the models chosen for the three values of \( (D/H)\_p \). Also shown is the evolution of oxygen for the case of high primordial D/H in the absence of the winds (\( \nu = \epsilon = 0 \)) for comparison. Since the metal-enhanced wind we are employing leads to an enrichment of the intergalactic medium, there is a limit to the value of \( \nu \) that can be translated into a limit on the maximum value for \( (D/H)\_p \) in these types of models. We will return to this question in § 5. All of the models we present unless otherwise noted result in a D evolution consistent with the observations that we present in the next section.

3. OBSERVATIONAL CONSTRAINTS ON D AND \( ^{3}\text{He} \) EVOLUTION

Since our primary constraint on models of Galactic chemical evolution is the abundance of D/H (and to some extent \( ^{3}\text{He} / ^{4}\text{He} \)), we briefly describe the adopted abundances at the present, solar, and in the case of D/H, primordial times. These abundances were described recently in more detail in Scully et al. (1996a), and we refer the reader there for more information. The uncertainties given below are statistical (shown first) and systematic. The present-day ISM D abundance has been determined by Linsky et al. (1993, 1995) using the HST to be
\[
(D/H)_0 = 1.60 \pm 0.09 \times 10^{-5} .
\]
We shall adopt this value for D/H today. The present-day \( ^{3}\text{He} \) abundance has been determined in a number of Galactic H II regions (Balser et al. 1994). A large range of values exist from \( 1.1 \times 10^{-5} \). This range may be indicative of a bias and/or pollution (Olive et al. 1995) or stochastic evolution (Copi et al. 1995b). A recent measurement of ISM \( ^{3}\text{He} \) gives (Gloeckler & Geiss 1996)
\[
(^{3}\text{He}/^4\text{He})_0 = 2.1^{+0.9}_{-0.8} \times 10^{-5} .
\]
We will use this latter value when comparing to the results of chemical evolution models. The presolar D and \( ^{3}\text{He} \) abundances were recently discussed in Geiss (1993) and in Scully et al. (1996b). Our adopted presolar values of D, \( ^{3}\text{He} \), and D + \( ^{3}\text{He} \) are:
\[
\begin{align*}
[(D + ^{3}\text{He})/^{2}\text{He}]_0 &= (4.1 \pm 0.6 \pm 1.4) \times 10^{-5} , \\
(^{3}\text{He}/^{4}\text{He})_0 &= (1.5 \pm 0.2 \pm 0.3) \times 10^{-5} , \\
(D/H)_0 &= (2.6 \pm 0.6 \pm 1.4) \times 10^{-5} .
\end{align*}
\]
We note that recent measurements of surface abundances on Jupiter show a somewhat higher value for D/H, \( D/H = 5 \pm 2 \times 10^{-5} \) (Niemann et al. 1996). This value is marginally consistent with the abundances listed above.

Finally, there have been several recent reported measurements of D/H in high-redshift quasar absorption systems. Such measurements are in principle capable of determining the primordial value for D/H and hence \( \eta \) because of the strong yet monotonic dependence of D/H on \( \eta \) (see, e.g., Walker et al. 1991). However, at present, detections of D/H using quasar absorption systems indicate both a high and low value of D/H. As such, we caution that these values may not turn out to represent the true primordial value. Nevertheless, we will explore in this work, the consequences of choosing either a high or low \( (D/H)\_p \). Thus, we will consider in turn \( (D/H)\_p = 2.0 \times 10^{-4} \) (Carswell et al. 1994; Songaila et al. 1994; Rugers & Hogan 1996a, 1996b) and \( (D/H)\_p = 2.5 \times 10^{-5} \) (Tytler et al. 1996; Burles & Tytler 1996). We also note that the Jovian measurements of D/H are only marginally consistent with the low \( (D/H)\_p \) values.

The evolution of D in the ISM can be determined by extending equation (7). Since D is only destroyed in stars, equation (7) becomes
\[
\frac{d(M_G D)}{dt} = -\psi(t) D - \dot{M}_W D .
\]
By substitution and some further simplification, we find
\[
\frac{dD}{dt} = \frac{[\nu e(t) - \psi(t)]D}{M_G} .
\]
in fact some evidence for a dispersion in $^{3}\text{He}$ in Galactic H II regions (Balser et al. 1994). In addition, the long timescales and relatively low nebular expansion velocities that typically average 20–30 km s$^{-1}$ (Weedman 1968) associated with planetary nebulae could contribute to a delay in the mixing of $^{3}\text{He}$ into the ISM.

To model this effect, we first choose a primordial value for D/H. We then run a chemical evolution model such that we delay the gas from stars under 8 $M_{\odot}$ from returning to the ISM. Figure 2 illustrates the results for high D/H with time delays of 1, 5, and $\infty$ Gyr. While the $^{3}\text{He}$ evolution is now improved in each case, none is able to reproduce a viable D and $^{3}\text{He}$ evolution, using traditional assumptions about $^{3}\text{He}$ evolution in low-mass stars. Delay times of less than 7 Gyr can destroy enough D but still overproduce $^{3}\text{He}$. Longer delay times more closely reproduce the $^{3}\text{He}$ observations but do not destroy D by more than a factor of $\sim 1.5$.

Figure 3 shows similar results for model I with the lower (D/H)$_{p} = 7.5 \times 10^{-5}$. While a delay time of $\infty$ can reproduce the $^{3}\text{He}$ observations, again D cannot be destroyed by more than a factor of $\sim 1.5$. We estimate that the longest time delay that can still reproduce both the solar and present-day D observations can only reduce the $^{3}\text{He}/H$ by a factor of 20% from the same model run with no time delay and traditional $^{3}\text{He}$ evolution in low-mass stars. We can conclude that the delayed mixing of material into the ISM can clearly not be entirely responsible for the observed solar value of $^{3}\text{He}$. This combined with our previous results (Scully et al. 1996a, 1996b) all point to the stellar yields as being primarily responsible for the observed $^{3}\text{He}/H$ abundances.

The exception to this conclusion is the case of low primordial D/H. Of course in this case, D need not be destroyed by much more than a factor of 1.5. In Scully et al. (1996b), this case did not greatly overproduce $^{3}\text{He}$, and a time delay of even 1 Gyr would further improve the comparison with the data. It remains a difficulty in these models however, to produce a sufficient amount of heavy elements such as oxygen.

5. EFFECTS OF NEW $^{3}\text{He}$ YIELDS

A number of recent papers suggest that stars less massive than 2 $M_{\odot}$ may be net destroyers of $^{3}\text{He}$ when the effects of rotational mixing in the red giant phase of stellar evolution is included (see, e.g., Charbonnel 1994, 1995a, 1995b; Hogan 1995; Wasserburg, Boothroyd, & Sackman 1995; Weiss et al. 1995; Boothroyd & Sackman 1995; Boothroyd & Malaney 1995). Boothroyd & Malaney (1995) give detailed results for $^{3}\text{He}$ destruction factors in stars between 1 and 9 $M_{\odot}$, which we have implemented into our chemical evolution models. Main-sequence mass loss is not expected to affect these yields due to the small mass-loss rates for low-mass stars. We remind the reader that these $^{3}\text{He}$ destruction mechanisms take place in the post–main-sequence phase of stellar evolution. Traditional main-sequence evolution is unchanged.

Boothroyd & Malaney have already tested their results using the models of Vangioni-Flam et al. (1994) and have adopted a model in which $\psi = 0.25 \sigma$. They have suggested that values of $(D/He) < 1.2 \times 10^{-4}$ are unable to reproduce a viable D + $^{3}\text{He}$ evolution using their $^{3}\text{He}$ yields. This corresponds to an upper limit to $(D/He) < 1.0 \times 10^{-5}$. The model they have chosen, however, is designed to give the correct gas fraction and D destruction for a $(D/He) = 7.5 \times 10^{-5}$. In the following, we will examine the evolution of D and $^{3}\text{He}$ in models that are more suited to destroy D for the chosen $(D/He)$, as well as satisfy other observational constraints including the present-day gas fraction using the Boothroyd & Malaney yields for $^{3}\text{He}$.

In Figure 4, we show the results of including the Boothroyd & Malaney yields into model II of Scully et al. (1996b) with high primordial D/H. As one can see the model has been chosen to match the solar and ISM D/H abundances starting at $(D/He) = 2 \times 10^{-4}$. As we indicated earlier, this model incorporates supernovae driven winds to regulate the oxygen abundance. The evolution of $^{3}\text{He}/H$ using the Boothroyd & Malaney yields is shown by the solid curve in Figure 4. This model is able to reproduce the present-day $^{3}\text{He}/H$ observation and is within the errors including systematics for the solar observation. The effects of rotational mixing on the red giant branch on the $^{3}\text{He}/H$ abundance is dramatic as is seen by comparing the solid curve to the dashed one, which utilizes the standard stellar yields of Iben & Truran (1978).
We have also tested the new yields for the case of intermediate \((\text{D/H})_p = 7.5 \times 10^{-5}\). Figure 5 shows the resulting D/H and \(^3\text{He}/\text{H}\) evolution. In this case, the solar \(^3\text{He}/\text{H}\) observation is reproduced but the model gives a somewhat low abundance of \(^3\text{He}/\text{H}\) with respect to the present-day observation. For completeness, we show the results for the case of low \((\text{D/H})_p = 2.5 \times 10^{-5}\) in Figure 6. In this case, because low primordial D/H corresponds to both high \(\eta\) and low primordial \(^3\text{He}/\text{H}\), the Boothroyd and Malaney yields predict too little \(^3\text{He}/\text{H}\). Indeed, the standard yields as shown by the dashed curve show an evolution closer to the data. Curiously, it seems that the reduced yields in fact work better for the higher \((\text{D/H})_p\). We can conclude that the new yields based on \(^3\text{He}\) destruction on the red giant branch of low-mass stars can solve the \(^3\text{He}/\text{H}\) problem even (and especially) for the higher \((\text{D/H})_p\), when combined with the Galactic evolution models of the type discussed.

Although the reduced yields of Boothroyd & Malaney (1995) are capable of explaining the rather flat evolution over time of \(^3\text{He}/\text{H}\), they cannot account for the high \(^3\text{He}/\text{H}\) observed in planetary nebulae (Rood et al. 1992, 1995). As Boothroyd & Malaney suggest, it may be that not all stars undergo the extra mixing subsequent to first dredge-up and that the main-sequence produced \(^3\text{He}\) remains intact. In Scully et al. (1996b), it was shown that the \(^3\text{He}\) evolution and planetary nebulae data could be fitted if only stars between 0.9 and \(~1 \, M_\odot\) produced \(^3\text{He}\) in significant quantities. For the initial mass functions considered, this represented some 10\%–15\% of all stars becoming planetary nebulae. In Figure 7, we show the result for the high D/H case when 90\% of all stars in the 1–9 \(M_\odot\) mass range undergo the post–main-sequence destruction. The remaining 10\% follow standard evolutionary theory and therefore can account for the observation of high \(^3\text{He}\) in planetary nebulae. Recall that all stars in this mass range produce \(^3\text{He}\) while on the main sequence. In most cases, (chosen here to be 90\%) post–main-sequence processing leads to the destruction of \(^3\text{He}\). In the remaining cases, \(^3\text{He}\) destruction might be stopped in some binary systems or in systems in which the red giant envelope configuration is disturbed. The dashed line in Figure 7 shows the case when 100\% of the stars destroy \(^3\text{He}\) as given by the reduced yields. As one can see, the reduced yields seem to fit better, slightly over-producing \(^3\text{He}\) at the solar epoch and slightly under-
producing $^3$He today. With the 10% mix of stars that do not destroy $^3$He, $^3$He is overproduced at the solar epoch by a factor of about 2, though the present-day abundance is acceptable.

In Figure 8, we show the cases for $(D/H)_p = 7.5 \times 10^{-5}$ with a 90%/10% mix as discussed above and in Figure 9, for the case of low D/H, the mix is 40%/60%, which we found works best in matching the $^3$He observations. Again, the dashed curves show the results using only the reduced yields. As one can see from these figures, the addition of some stars that do not undergo the $^3$He destruction processes on the red giant branch are quite consistent with the solar and ISM observations of $^3$He.

Finally, as we noted earlier, a considerable amount of enriched material is expelled from the Galaxy in these types of models, particularly those with high primordial D/H. Such a metal-enhanced wind would contribute to the enrichment of the intergalactic gas with heavy elements and indeed there is evidence that such an enrichment has occurred. For example, in the clusters observed by Mushotzky et al. (1996) and Loewenstein & Mushotzky (1996) the mean oxygen abundance was found to be roughly half solar. For our model with high $(D/H)_p$, the enrichment was found to produce a metallicity of about $Z_{\text{IGM}} \sim 0.2 Z_\odot$ (Scully et al. 1996b) assuming a total intergalactic gas mass equal to 10 times the Galactic mass. We have explored increasing $(D/H)_p$ in our models to determine the maximum allowed value without overproducing metals in the intergalactic medium due to our outflow mechanism. For $(D/H)_p = 3 \times 10^{-4}$, $Z_{\text{IGM}} \sim 0.3 Z_\odot$. In our models, we cannot increase the deuterium abundance beyond $(D/H)_p = 5.4 \times 10^{-4}$ as higher primordial abundances would require such an increased SFR that no gas would remain in the disk today. This value of $(D/H)_p$ corresponds to a $Z_{\text{IGM}} \sim 0.6 Z_\odot$.

In completing this paper, we became aware of the very recent work of Galli et al. (1996). In that work, Galli et al. (1996) determine the masses of the planetary nebulae observed by Rood et al. (1992, 1995). Indeed, they confirm that the progenitor masses of the nebulae are $\lesssim 2 M_\odot$, as was suspected. They also consider a chemical evolution model with $(D/H)_p \approx 3.5 \times 10^{-5}$ with standard stellar yields as well as those provided by Boothroyd, which account for $^3$He destruction on the red giant branch. To match the solar and present-day abundances of $^3$He, they too require a mixture of these yields and their results are in qualitative agreement with those presented here.

6. CONCLUSION

It appears that the abundance of $^3$He is in fact little changed over the history of the Galaxy. This is particularly difficult to understand if the primordial abundance of deuterium is as high as observed in some recent measurements of D/H in quasar absorption systems because chemical evolution models using standard stellar yields for $^3$He in low-mass stars are known to lead to a gross overproduction of $^3$He at both the solar and present-day epochs. Unless the total deuterium astation factor is less than about 1.5, we have found that imposing a delay for the mixing of $^3$He-rich material does not substantially improve the evolution of $^3$He. This further reinforces our conclusion that chemical evolution alone cannot solve the $^3$He problem.

In this paper, we have implemented new $^3$He yields for low-mass stars, which account for possible extra-mixing mechanisms on the red giant branch and lead to a strong depletion of $^3$He (Boothroyd & Malaney 1996). These yields do in fact provide for a flat evolution for $^3$He over the history of the Galaxy. However, they cannot account for the high $^3$He abundances observed in planetary nebulae. As such, we argue that although these extra-mixing mechanisms may be operative for most low-mass stars in their post–main-sequence evolution, in some fraction of stars the main-sequence–produced $^3$He must remain intact. In some cases, such a mix, fits the data (solar and ISM) quite well. We also determine an upper bound to $(D/H)_p \lesssim 5 \times 10^{-4}$ based on the maximum allowed amount of intergalactic heavy element enrichment. This limit assumes that the intergalactic medium has less than one-half solar metallicity. This limit is significantly higher than the highest values of D/H observed in quasar absorption systems. In conclusion, the present-day and solar abundances of D and $^3$He can be made consistent with either high or low primordial D/H (low or high $\eta$). Thus, the solution to the "$^3$He problem" is clearly not cosmological but rather of Galactic or stellar origin.

We would like to thank M. Cassé, M. Lemoine, and E. Vangioni-Flam for helpful discussions. The work of K. A. O. and S. T. S. was supported in part by DOE grant.
DE-FG02-94ER-40823 at the University of Minnesota, and the work of D. N. S. was supported in part by the DOE (at Chicago and Fermilab) and by NASA through NAGW-2381 (at Fermilab). The work of J. W. T. was supported in part by NSF grant AST 92-17969 and by NASA under grant NAG 5-2081.

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