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IS HIGH PRIMORDIAL DEUTERIUM CONSISTENT WITH GALACTIC EVOLUTION?

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ABSTRACT

Galactic destruction of primordial deuterium is inevitably linked through star formation to the chemical evolution of the Galaxy. The relatively high present gas content and low metallicity suggest only modest D destruction. In concert with deuterium abundances derived from solar system and/or interstellar observations, this suggests a primordial deuterium abundance in possible conflict with data from some high-redshift, low-metallicity QSO absorbers. We have explored a variety of chemical evolution models including infall of processed material and early, supernovae-driven winds with the aim of identifying models with large D destruction that are consistent with the observations of stellar-produced heavy elements. When such models are confronted with data, we reconfirm that only modest destruction of deuterium (less than a factor of 3) is permitted. When combined with solar system and interstellar data, these results favor the low deuterium abundances derived for the QSO absorbers by Tytler et al.

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

1. INTRODUCTION

Observations of high-redshift absorbers along the lines of sight to distant QSOs reveal nearly unprocessed primordial gas. In a handful of such systems there is evidence for deuterium; the inferred abundance may be very nearly the primordial value. For two high-z, low-Z systems, Tytler and collaborators (Tytler, Fan, & Burles 1996; Burles & Tytler 1996) derive low deuterium abundances, $\mathrm{D/H} = (2.4 \pm 0.5) \times 10^{-5}$, similar to those inferred from observations of the local interstellar medium (Linsky et al. 1993; Linsky 1998). Such low values have been challenged by Songaila, Wampler, & Cowie (1997), who suggest a larger deuterium abundance, $\mathrm{D/H} > 4 \times 10^{-5}$, for one of the Burles & Tytler (1996) absorbers. In contrast, deuterium abundances nearly an order of magnitude higher, $\mathrm{D/H} = (19 \pm 4) \times 10^{-5}$, have been claimed by Carswell et al. (1994), Songaila et al. (1994), and Rugers & Hogan (1996) for other high-redshift systems with metal abundances equally close to primordial. However, using better data obtained for one of these systems, Tytler, Burles, & Kirkman (1997) find no evidence for deuterium and exclude the published (high) abundance at the "10 σ" level. Nonetheless, Hogan (1997 and C. H. Hogan 1997, private communication), Wampler (1996 and E. J. Wampler 1997, private communication), and Songaila (1997) argue that the spectra of other absorbing systems require high D/H (e.g., Webb et al. 1997). The high-D, low-D dispute awaits more data for its resolution.

Even though these QSO absorbers have very low metal abundances, suggesting very little stellar activity, their D content must still be considered only a lower limit to the primordial deuterium abundance, $(\mathrm{D/H})_p$, since D is only destroyed by stellar processes subsequent to big bang nucleosynthesis (BBN). To reconcile the current low abundance of D inferred from observations of the local interstellar medium (ISM), $(\mathrm{D/H})_{\mathrm{ISM}} = (1.6 \pm 0.1) \times 10^{-5}$ (Linsky et al. 1993), with a primordial value as large as that suggested by Hogan and collaborators requires that deuterium has been destroyed by an order of magnitude, or more, in the course of the evolution of the Galaxy. Although such high abundances are now strongly challenged observationally, it is still important to investigate whether any chemical evolution scenarios exist that permit large D-destruction factors and, if so, how their predictions compare with the available observational constraints on the distribution—in space and in time—of the abundances of the other elements.

2. GALACTIC EVOLUTION OF DEUTERIUM

As summarized by Tosi (1996, and references therein), those models for the evolution of the disk of our Galaxy that are in agreement with the largest set of available observational constraints predict that deuterium has been depleted by less than a factor of 3. Thus, to reproduce the abundances, by mass, observed in the solar system, $X_{2\odot} = (3.6 \pm 1.3) \times 10^{-5}$, and in the local interstellar medium, $X_{2\mathrm{ISM}} = (2.2 \pm 0.3) \times 10^{-5}$ (Geiss 1993; Linsky et al. 1993, respectively), none of these *good, standard* models would allow initial deuterium abundances higher than $X_{2i} \simeq 8 \times 10^{-5}$. Such a low upper bound to primordial D is much lower than the value, $X_{2\mathrm{RH}} = (29 \pm 6) \times 10^{-5}$, suggested by Rugers & Hogan (1996; hereafter, RH). In all of the models considered by Tosi (1996) (Carigi 1996; Chiappini & Matteucci 1996; Dearborn, Steigman, & Tosi 1996, hereafter

DST; Galli et al. 1995; Prantzos 1996), those with large initial deuterium either cannot fit the D abundances observed in the solar system and/or in the local ISM or cannot account for the presently observed amount of disk gas and/or the abundances of the heavier elements. Although other models designed to permit higher D destruction have been proposed (e.g., Vangioni-Flam & Audouze 1988; Vangioni-Flam, Olive, & Prantzos 1994; Olive et al. 1995; Scully et al. 1996, 1997), in general they have not always been tested against all of the available observational constraints, and their self-consistency has been questioned (e.g., Edmunds 1994; Prantzos 1996).

To investigate if it is possible to avoid this apparent inconsistency (high primordial D, low Galactic D), we have pursued two distinct approaches. On the one hand, we have developed a series of general (i.e., model-independent) arguments along the line of reasoning described by Steigman & Tosi (1995), and, on the other hand, we have actually computed the evolution predicted for several specific, albeit ad hoc, models for the halo and the disk of the Galaxy that were designed to maximize D destruction.

3. A MODEL-INDEPENDENT APPROACH

The evolution of deuterium after BBN is straightforward because, when incorporated in a star, it is completely destroyed, burned to ^{3}He during the pre–main-sequence evolution. If the "virgin" fraction of the ISM (either now or at the time of the formation of the solar system) were known, the primordial (pre-Galactic) D abundance could be inferred directly from ISM or solar system observations. The more material that is cycled through stars, the more D destruction and vice-versa. But, the more material that is cycled through stars, the more heavy elements that are synthesized and the more mass that is tied up in unevolved low-mass stars and in stellar remnants. Efficient D destruction and efficient star formation go hand in hand. Thus, there is the possibility that the observed metallicity and/or the disk gas-fraction may be exploited to constrain the deuterium depletion factor in a manner insensitive to the details of specific models of Galactic evolution. We explore one such approach below; see Steigman & Tosi (1995) for an alternate approach.

Consider a "representative" sample of the ISM. Some fraction (by mass) of that material, f_0, will have never been through stars. In this "virgin" fraction the deuterium is primordial ($X_2 = X_{2p}$), and there are no metals ($Z = 0$). The remainder of the material will have been through one or more generations of stars that destroyed all of the deuterium ($X_2 = 0$) but that did produce some heavy elements. For example, in a fraction f_1, which has been through one (and only one) generation of stars, there will be no deuterium, but there are some heavy elements. Estimating the metallicity of this "one-generation" fraction is complicated. Some of the matter may be from long-lived, low-mass stars formed long ago, and some may be from short-lived, high-mass stars formed very recently. Thus, the gas returned to the ISM will have come from a mixture of stars of all masses, including the very low-mass ones, which destroy deuterium but do not contribute much to the enhancement of the heavy-element abundances, and the higher mass stars, which destroy deuterium and do enhance the Galactic metallicity. In this manner, the average metallicity ($\langle Z_1 \rangle$) of this one-generation subsample is a mean, weighted by the initial mass function (IMF).

Generalizing the above description to material that has been through two, three, ... generations of stars ($f_2, f_3, \ldots$), we may relate the deuterium and heavy-element mass fractions as follows:

$$X_2 = f_0 X_{2p} , \tag{1}$$

$$Z = f_1\langle Z_1 \rangle + f_2\langle Z_2 \rangle + f_3\langle Z_3 \rangle + \cdots , \tag{2}$$

$$1 = f_0 + f_1 + f_2 + f_3 + \cdots . \tag{3}$$

As they stand, these relations are not very useful. However, if there exists a lower bound ($Z_{\rm min}$) to all the $\langle Z_i \rangle$ ($Z_{\rm min} \leq \langle Z_i \rangle$), equation (2) can be rewritten as

$$Z \geq (1 - f_0) Z_{\rm min} \tag{4}$$

or

$$f_0 \geq 1 - Z/Z_{\rm min} , \tag{5}$$

so that

$$X_{2P} \leq \frac{X_2}{1 - Z/Z_{\rm min}} . \tag{6}$$

Equations (4)–(6) summarize, in a compact form, the anticipated connections: the more material that is cycled through stars, the higher the metallicity and the more deuterium that will have been destroyed. Thus, the present (ISM or presolar) value of Z, supplemented with an estimate of $Z_{\rm min}$, may be used to provide a bound on f_0 and, therefore, on X_{2p}. To implement this approach, we have chosen oxygen as a good tracer of the total metallicity, and to estimate $Z_{\rm min}$, we have computed the contribution to the metallicity from a single stellar population: $Z_{\rm min} \equiv \min(\langle Z_1 \rangle)$, where

$$\langle Z_1 \rangle = \frac{\int_{m_l}^{m_u} M_{16,\rm net}\, \phi(m) dm}{\int_{m_l}^{m_u} M_{\rm ej}\, \phi(m) dm} . \tag{7}$$

$M_{\rm ej}$ is the total mass ejected by stars of mass m, $M_{16,\rm net}$ is the mass ejected in the form of newly synthesized oxygen, and $\phi(m)$ is the IMF. The oxygen enrichment provided by one generation of stars thus depends on the stellar nucleosynthesis yields we have adopted and on the IMF through its slope (α) and upper (m_u) and lower (m_l) mass limits.

To explore the uncertainties traceable to stellar yields, we have computed $\langle Z_1 \rangle$ adopting both the minimum (Chiosi & Caimmi 1979; hereafter, CC79) and the maximum (Woosley & Weaver 1995; hereafter, WW95) oxygen yields from the literature. Similarly, for the IMF we have chosen the two most extreme popular slopes appropriate for the range of massive stars that produce oxygen: $\alpha = 3.3$ as in Tinsley (1980) and $\alpha = 2.35$ as in the extrapolation of the Salpeter (1955) IMF; we allow both m_u and m_l to vary. Figure 1 (*top*) shows the behavior of the "virgin" fraction, $f_0 = 1 - Z_{16}/\langle Z_{16} \rangle$, as a function of the lower mass limit (m_l) to the IMF (with $m_u = 100\ M_\odot$), for oxygen yields taken from WW95 (*dotted line*) and from CC79 (*solid line*), respectively. The IMF is Tinsley's (1980), and we adopt for the local oxygen abundance at the time the solar system formed $Z_{16\odot} = 9.5 \times 10^{-3}$ (Anders & Grevesse 1989). We have explored all combinations of the parameters and find for the minimum of the one-generation yield $\langle Z_1 \rangle_{\rm min} = 0.012$. Using this value for $Z_{\rm min}$, we conclude that the fraction of gas that has never been through stars is $f_0 > 0.21$. This suggests (see eq. [1]) that under "normal" conditions

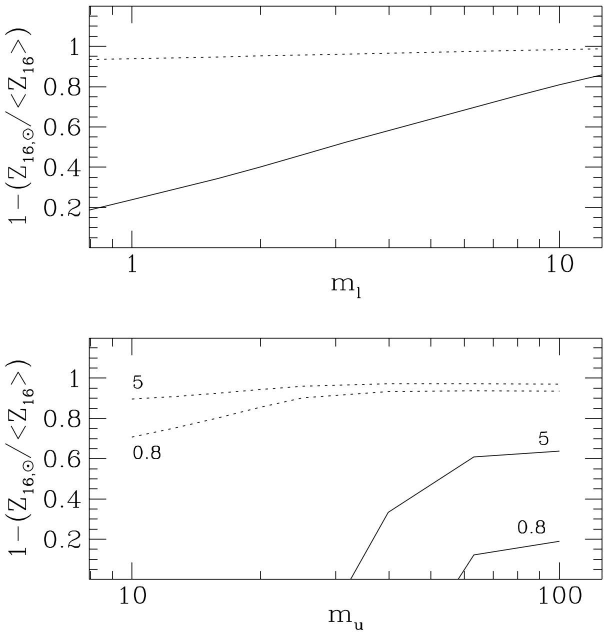

FIG. 1.—Upper limits to the virgin fraction of the ISM (see eq. [5]), resulting from the oxygen yields weighted over Tinsley's (1980) IMF. Solid lines correspond to CC79 yields, and dotted lines correspond to WW95 yields. *Top*, the dependence on the IMF lower mass limit (with $m_u = 100$ $M_\odot$); *bottom*, the dependence on the upper mass limit (with $m_l = 0.8$ or $5\ M_\odot$).

(standard yields, reasonable IMFs), deuterium cannot be destroyed by more than a factor of 5.

This upper bound to D destruction is clearly sensitive to our choice of $\langle Z_1 \rangle_{\rm min}$ and of $Z_\odot$. To obtain an extreme upper bound, we have been careful to adopt those values for both quantities that permit the maximum D depletion. The Anders & Grevesse (1989) estimate of the solar metallicity is quite robust. Although the Sun may not provide a fair sample of the local ISM 4.5 Gyr ago, its abundance may, instead, provide an upper bound to the metallicity of the local ISM at that epoch, since the Sun appears to be more metal rich than the average of the local stars of its age. Indeed, if the average local metallicity when the solar nebula collapsed were similar to, or even lower than, that derived from Orion and the local H II regions, i.e., 0.2 dex lower than $Z_\odot$, our upper bound on D destruction will be reduced. As for $\langle Z_1 \rangle_{\rm min}$, our bound is derived from those theoretical yields in the literature with the lowest O production and using the IMF for the local region with smallest fraction of massive stars (i.e., of oxygen producers). For these reasons, we regard a factor of 5 as a robust upper bound to possible D destruction.

Our bound on D destruction is general in the sense that it is independent of the details of specific chemical evolution models; the only inputs are from the IMF and the stellar yields. However, it is key that the amount of deuterium destruction and the metallicity are linked through our assumption that all the stellar ejecta do contribute to the enrichment of the ISM. This will be the case in the absence of winds capable of removing from the Galaxy part or all of the stellar ejecta. In contrast, this D-destruction/metallicity connection may be avoided if winds, perhaps triggered by the explosions of multiple supernovae as originally suggested by Larson (1974) for elliptical galaxies, were present earlier in the evolution of the Galaxy. In the extreme case of the total removal (permanently!) from the Galaxy of all the ejecta of stars more massive than a given mass, the effect of such a wind on the oxygen enrichment in the ISM is equivalent to cutting off the IMF at a value of m_u equal to that mass. Such an effect is illustrated in Figure 1 (*bottom*) for two choices of m_l (0.8 and 5 $M_\odot$). For the WW95 yields there remains a very tight constraint from the connection between metallicity and D destruction, while the CC79 yields permit much more destruction.

As noted by B. E. J. Pagel (1997, private communication), there is another way in which the D-destruction/metallicity connection may be weakened: black hole formation. If all stars with $m \geq m_{\rm bh}$ collapse without returning any newly synthesized material to the ISM, the average yield per stellar generation will be reduced. The effect of this, too, may be inferred from Figure 1 (*bottom*); from the point of view of chemical enrichment, it is equivalent to the material from such stars being expelled from the Galaxy via winds. There are two potential problems associated with too small a value of $m_{\rm bh}$ or, equivalently, with winds that effectively cut off the IMF above m_u. In both cases, the oxygen yield is more strongly reduced than the helium yield so that the effect is to increase their ratio, $\Delta Y/\Delta Z$ (Maeder 1992). Høg et al. (1998) and Thuan & Izotov (1998) argue that $\Delta Y/\Delta Z \leq 3$. From Figure 15 in Maeder (1992), for the Scalo (1986) IMF, we infer that to satisfy this limit requires $m_{\rm bh} \geq 55\ M_\odot$. Since for our robust case we use Tinsley's (1980) IMF, which has fewer massive stars than Scalo's (1986), according to Maeder's (1992) arguments the lower limit to $m_{\rm bh}$ must be even larger. As a result (assuming $m_u = m_{\rm bh}$), even with the CC79 yields there is a limit on f_0 (see Fig. 1). Thus, depending on the actual yields (CC79 or WW95) and on the appropriate lower mass limit m_l, limits to $\Delta Y/\Delta Z$ provide bounds on deuterium destruction in the presence of winds and/or black hole formation. Another constraint on mass loss or black hole formation comes from the observed gas fraction, which will decrease if significant mass is removed from the ISM, leaving more mass locked into long-lived stars and/or stellar remnants (Edmunds 1994). Thus, although winds and/or black hole formation are promising avenues to pursue if the D-destruction/metallicity connection is to be weakened, there are still some observational constraints that must be satisfied.

These general results serve as a guide, permitting us to identify potentially fruitful approaches to designing chemical evolution models that, while destroying significant amounts of deuterium, may avoid exhausting the interstellar gas and/or overproducing the heavy elements. With standard IMFs and no significant winds, large D destruction requires that so much mass has been cycled through stars that the observed metallicity would be exceeded. This D-destruction/metallicity connection may be broken, for example, by adopting a nonstandard IMF biased against high-mass stars that are the main oxygen producers. Although this will allow more gas to be cycled through stars, destroying deuterium while avoiding overproducing oxygen, at present there is currently no significant evidence for an anomalous IMF (Wyse 1997). Alternatively, as suggested by Vangioni-Flam & Cassé (1995) and by Scully et al. (1997), the offending metals might have been removed by strong winds. Since there is no good evidence for variations of the IMF (e.g., Richer & Fahlman 1996; Wyse 1997), we will pursue the latter approach in our search for specific Galactic evolution models that may be capable of destroying deuterium efficiently while preserving consistency with the observational data.

4. CHEMICAL EVOLUTION MODELS

To explore in detail whether Galactic winds and/or infall of D-depleted gas may lead to observationally consistent models that permit high D destruction, we have computed a series of numerical chemical evolution models including such winds. We describe these models below and compare their predictions with the observational data available for our Galaxy. In following the evolution of the elements produced mainly by long-lived stars, such as ^{3}He, ^{14}N, and ^{56}Fe, it is of fundamental importance that the instantaneous recycling approximation be avoided.

Bearing in mind that the initial disk abundance, X_{2i}, may not necessarily be the primordial one, X_{2p}, we consider two possible scenarios:

1. For the *good*, *standard* models summarized by Tosi (1996), fitting the observed ISM D abundance constrains the initial disk deuterium abundance to be $X_{2i} \leq 6 \times 10^{-5}$, in contrast to the RH primordial value of $X_{2p} = X_{2\mathrm{RH}} = 29 \times 10^{-5}$. In this case, most of the D destruction must have occurred prior to disk formation. Therefore, in this case the disk must form out of already processed gas. This requires either that an unknown (and improbable) mechanism burned most of the primordial D prior to galaxy formation (without producing a significant metallicity) or that most of the destruction must have taken place during the halo phase. This latter hypothesis assumes that the disk formed out of gas shed from the halo, which is in disagreement with recent observational results (Ibata & Gilmore 1995; see the discussions in Chiappini, Matteucci, & Gratton 1997 and in Pagel & Tautvaišienė 1995).

2. If the initial disk abundance is, instead, $X_{2i} = X_{2p} = 29 \times 10^{-5}$, it is necessary to invoke a much larger D consumption during disk evolution to deplete the deuterium abundance down to the observed solar system and local ISM values. This, however, requires a much larger early star formation rate (SFR) which, in turn, as we have seen in our general considerations above, would lead to excessive metal enrichment (see, e.g., Vangioni-Flam & Audouze 1988). These conclusions may possibly be evaded if the evolution includes the effect of strong Galactic winds (see, e.g., Scully et al. 1997) and/or the infall of D-depleted gas. In any case, a very high initial SFR in the disk violates the constraint that the peak SFR can only be a factor of a few larger than the present SFR (e.g., Twarog 1980; Prantzos 1998).

During the early halo phase, if the SFR were much higher, so too would have been the rate of supernova explosions, perhaps triggering strong winds. In contrast, strong winds are highly improbable at present in the disk of our Galaxy (except perhaps in its outer layers), where both the gravitational potential and the gas density are likely too high to allow the gas to reach escape velocity (Spitzer 1990; Tenorio-Tagle 1996). Fountains (i.e., gas leaving the disk temporarily but returning later somewhere in the disk) may occur, but they will not remove the metals permanently. Before considering models with strong, early winds, we first explore the effects of infall.

4.1. *Models with Infall*

Infall generally has the effect of raising the disk D abundance toward the primordial value. It is difficult to avoid this conclusion because it has been shown, both theoretically (Tosi 1988b; Matteucci & François 1989, hereafter MF) and observationally (e.g., Savage & de Boer 1981) that the infalling gas has a metallicity of, at most, 0.2–0.3 $Z_\odot$. Therefore, it is quite unlikely that all the deuterium in the infalling gas has been destroyed. For the sake of completeness, however, we have revisited the broad range of models described in DST and in Tosi (1988a), allowing for arbitrarily low D/H in the infalling gas. The predictions for the local evolution of deuterium in one representative set of these models (see DST and Tosi 1988a for the model assumptions and parameters), which displays the key trends common to all such models, are shown in Figure 2, together with the 2 σ ranges of the abundances (by mass) derived from solar system and local ISM observations. Also shown in the figure are two models from DST: the solid line corresponds to model 1-T-Vb [SFR = exp $(-t/15$ Gyr); infall $F = 4 \times 10^{-3}$ $M_\odot$ kpc^{-2} yr^{-1}; metallicity $Z_{\mathrm{infall}} = 0.2$ $Z_\odot$], and the dotted line corresponds to the no-infall model (NI-Z-III).

None of these models is capable of satisfactorily reconciling a large primordial abundance, $X_{2p} = X_{2\mathrm{RH}}$, with the observed pre-solar and local ISM values. Indeed, to reach the present ISM value starting from such a high initial abundance requires nearly D-free infall, $X_{2,\mathrm{infall}} = 0.1X_{2p}$ (*long-dashed line*), but then the D abundance predicted for the solar system is larger than that observed. For the extreme choice, $X_{2,\mathrm{infall}} = 0$ (*short-dashed line*), the solar abundance can be fitted, but then the predictions for the D abundance at the present epoch are too low compared to those observed in the local ISM. The best compromise is achieved by assuming $X_{2,\mathrm{infall}} = 0.2X_{2p}$ (*dash-dotted line*) that, however, corresponds to a maximum allowed primordial abundance, $X_{2p} = 20 \times 10^{-5}$ [(D/H)$_p = 13 \times 10^{-5}$], which, while large, is still lower than the RH value by a factor of 1.5. Even this case is not entirely realistic, since *standard* models (as summarized by Tosi 1996) suggest that the metallicity will exceed solar in gas in which deuterium has been depleted by a factor of 5. Therefore D-depleted infalling gas will have high metallicity, while deuterium should be virtually undepleted in low-metallicity infalling gas.

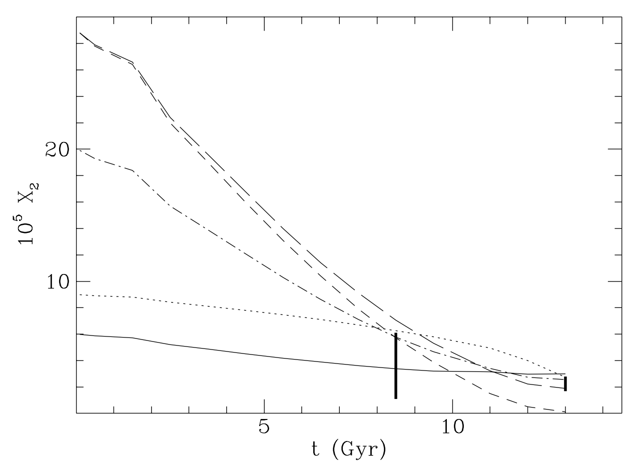

FIG. 2.—Evolution in the solar ring of the D abundance by mass. Vertical bars give the 2 σ ranges for the abundances derived from solar system and local ISM observations. The dotted and solid curves correspond to DST's models NI-Z-III and 1-T-Vb; all the others correspond to models assuming depleted D in the infalling gas ($X_{2,\mathrm{infall}} = 0$ for the short-dashed line, $X_{2,\mathrm{infall}} = 0.1X_{2p}$ for the long-dashed line, and $X_{2,\mathrm{infall}} = 0.2X_{2p}$ for the dash-dotted line).

TABLE 1

MODEL PARAMETERS

Model	Type	Wind[a]	w	ν_h (Gyr^{-1})	ν_d (Gyr^{-1})	τ_h (Gyr)	τ_d (Gyr)	Infall[b]	IMF
A	Two-infall	D; halo	1.5	10	1.0	0.03	8.0	P	Scalo 1986
B	Two-infall	D; halo	1.5	10	1.0	0.03	8.0	E	Scalo 1986
C	Two-infall	N; halo	20.	10	1.0	0.03	8.0	P	Scalo 1986
D	Two-infall	D; halo + disk	1.5	10	1.0	0.03	8.0	P	Scalo 1986
E	Two-infall	N; halo + disk	20.	10	10	0.03	8.0	P	Scalo 1986
F	Two-infall	D; halo	1.5	10	1.0	0.03	8.0	P	Padoan et al. 1997
G	Sequential	D; halo	1.5	10	10	0.03	0.03	P	Scalo 1986
H	Sequential	D; halo	1.5	10	0.5	0.03	0.03	P	Scalo 1986
I	Sequential	D; halo	1.5	10	0.5	0.03	0.03	P	Padoan et al. 1997
M......	Sequential	D; halo	1.5	10	0.5	0.03	0.03	P	Scully et al. 1996
N	Sequential	D; halo	1.5	10	0.5	8.0	8.0	P	Scalo 1986
O	Sequential	D; halo	1.5	10	0.5	3.0	3.0	P	Scalo 1986
P	Sequential	D; halo	1.5	10	0.5	0.5	0.5	P	Scalo 1986
Q	Sequential	D; halo	1.5	5	0.5	0.03	0.03	P	Scalo 1986
R	Sequential	D; halo	1.5	0.5	0.5	0.03	0.03	P	Scully et al. 1997
S	Sequential	N; halo + disk	1.5	0.5	0.5	0.03	0.03	P	Scully et al. 1997
T	Sequential	N; halo + disk	10	0.5	0.5	0.03	0.03	P	Scully et al. 1997
U	Sequential	D; halo + disk	1.5	0.5	0.5	0.03	0.03	P	Scully et al. 1997

[a] D = differential wind (removes supernova ejecta); N = normal wind (removes supernova ejecta and local gas).

[b] P = primordial; E = enriched with $Z_{\rm inf} = 0.2\, Z_{\odot}$.

The no-infall (NI) model (*dotted line*) actually predicts *less* D destruction than even those models with infall of D-depleted gas. This is because to reproduce the current gas and total mass in the disk, the NI models must have a lower SFR, leading to less D consumption.

Unfortunately, the NI model and those with $Z_{\rm infall} \geq Z_{\odot}$ do not satisfy several important observational constraints such as the abundance gradients and the metallicity distribution of the G dwarfs (e.g., Tosi 1988b; MF). Besides, it would be quite improbable that the metallicity of the infalling material is higher than solar, since both the halo and the closest external galaxies (LMC and SMC) are metal poor compared to the Sun. Thus, *standard* models with D-depleted infall fail to reconcile a high primordial abundance of deuterium with the observed solar system and ISM values.

Next we study the effect of winds on the evolution of the Galaxy halo and disk using models based on the "sequential" models described by MF and the "two-infall" models of Chiappini et al. (1997) that permit different choices of the star formation rate, of the IMF, and of the relative importance of winds.

4.2. *Models with Winds*

We have modified the "sequential" models (MF) and the "two-infall" models (Chiappini et al. 1997) by allowing the Galaxy to lose mass through winds, and we have explored the consequences for the destruction of deuterium, for the overall age-metallicity relation, for the variations of the ratios of abundances with the overall metallicity, and for the metallicity distribution in old stars. Before presenting our results, we briefly describe the basic assumptions and parameters adopted for these models.

4.2.1. *Sequential Models*

In these models (see MF for details and specific parameter choices), there is a continuity between the halo and disk evolution in the sense that the halo and the disk form as distinct phases of a unique process. The Galactic disk is approximated by several independent rings, each 2 kpc wide, without exchange of matter among them. Continuous infall of gas ensures that the surface mass density in each ring increases with time. The star formation rate depends on the total surface mass density and on the surface gas density. The infall rate varies with Galactocentric distance in such a way that the disk forms from the inside out.

4.2.2. *Two-Infall Models*

These models assume that the Galaxy formed as a result of two main infall episodes. During the first one, the halo and part of the thick disk formed (some thick disk stars seem to have been accreted, as shown by Gratton et al. 1998), whereas the second episode is responsible for the thin disk. The timescale for the formation of the halo and thick disk is quite short ($\sim$0.5–1 Gyr), whereas the timescale for the formation of the thin disk is quite long ($\sim$8 Gyr), suggesting that the thin disk formed mainly out of extragalactic primordial gas. This timescale ensures a very good fit to the new data on the G-dwarf metallicity distribution (Rocha-Pinto & Maciel 1996, 1997). The SFR is of the same form as in MF described above, except that a threshold in the surface gas density ($\sim 7\, M_{\odot}\, {\rm pc}^{-2}$) is assumed. When the gas density drops below this threshold, star formation stops. Such a threshold has been suggested by some star formation studies (Kennicutt 1989).

Since the presence of a threshold leads naturally to a period between the first and the second infall episode where there is no active star formation, these models reproduce well the data in the most recent compilation by Gratton et al. (1998), which reveals the presence of a gap in star formation at the end of the thick-disk phase. The main advantage of the two-infall models is the decoupling between the rate of gas loss from the halo and that of gas infalling onto the disk. This allows a much longer timescale for disk evolution compared to that of the halo and thick disk phases. An important aspect of these models is that the threshold adopted in the star formation process limits star formation in the halo phase, allowing for the formation of stars with low-metallicity, as required by the observed metallicity distribution of halo stars.

4.2.3. *Ranges of Parameters*

For both the sequential models and the two-infall models, there are many model parameters that may be varied. In probing the influence of winds, we assume that the mass loss is proportional to the SFR, and we can choose to utilize such winds either in the disk, the halo, or both. The relative importance of the winds is controlled by the ratio, *w*, of the mass-loss rate to the SFR (see Matteucci & Tosi 1985), which we vary from 1.5 to 20. Furthermore, the winds can expel all the elements or only those produced by massive stars. Considering the production sites of the most important elements, preferential loss of gas ejected by massive stars implies removal of most of the new oxygen (which is only synthesized in massive stars), part of the carbon (which is produced in both high- and intermediate-mass stars), a small part of the iron (which is mostly produced by Type I supernovae, with a small contribution from Type II supernovae), and a negligible fraction of the nitrogen (which is produced almost exclusively by intermediate-mass stars). Since such a wind will modify the element ratios predicted for halo stars, it is crucial to compare the model predictions with the available observational data on the *relative* abundances of the elements.

For the timescale of the SFR in the halo, we have considered models with 0.1–0.2 Gyr, while for that in the disk we have allowed 1–2 Gyr. For the formation timescale of the halo and for the disk, we have explored 0.03–8 Gyr. We have allowed any infall to either be primordial ($Z = 0$) or enriched ($Z = 0.2\ Z_\odot$). Finally, we have experimented with several different IMFs (Scalo 1986; Scully et al. 1996, 1997), including time-dependent cases (Padoan, Nordlund, & Jones 1997; Chiappini, Matteucci, & Padoan 1998; Scully et al. 1997).

We have run a very large number of models, both sequential and two-infall, varying all the above parameters in various combinations, and we have identified the common characteristics as well as any significant differences. Table 1 lists the adopted parameters for a significant subsample of the examined cases. In the next sections we choose three representative models to illustrate the behavior found for the sequential models and three for the two-infall models.

5. RESULTS

Our results for D destruction and chemical evolution are shown in Figures 3–7. The results for three representative sequential models (I, M, Q) are shown in Figures 3, 5, and 7. Model I uses the Padoan et al. (1997) IMF, while model Q employs that of Scalo (1986). For model M, we adopt the metallicity-dependent IMF from Scully et al. (1996). With these models it is easy to achieve significant, even excessive, D destruction, as seen in Figure 3. Indeed, many models of this type that we have investigated permit even more D destruction than that shown for model I in Figure 3. However, these models encounter severe problems that are evident in Figure 5 and in the lower panel of Figure 7. Tuned to cycle gas through stars efficiently, so as to destroy primordial deuterium, these models predict excessive overabundances of oxygen and magnesium (relative to iron) at low metallicities. The G-dwarf metallicity distributions predicted by these models are orthogonal to those observed: high at low metallicity where the data are low, low at high metallicity where the data are high.

This inconsistency in the predicted G-dwarf distribution compared to that observed may be overcome if it is assumed, ad hoc, that the IMF during the earliest epochs (e.g., the first 1 Gyr, as in Scully et al. 1997) has no stars with mass below 2 $M_\odot$. However, we have always found in such cases that if the SFR is consistent with the observational constraints, the predicted metallicity of the oldest stars is excessive (e.g., despite the ameliorating effect of the wind, oxygen reaches solar abundance in the first 1–2 Gyr). If, instead, we constrain the metallicity to remain within the observational range, we are forced to adopt a very low SFR, at least a factor of 10 lower than the minimum presently observed local rate.

For the two-infall case, we display the results of three representative models (A, C, F) in Figures 4, 6, and 7. These models all assume infall of unprocessed (primordial) material. Models A and C use the Scalo (1986) IMF, while model F uses the Padoan et al. (1997) IMF. For model C, winds are very important; the ratio of the mass-loss rate to the SFR is $w = 20$. This is required in order to compensate for the overabundance of oxygen predicted by these models, which all have a very high initial SFR. As seen in Figure 4, in these models, the deuterium is destroyed rapidly during the first phase but restored during the second infall episode. Thereafter, these two-infall models have only modest D destruction. Starting with a high initial abundance of deuterium, there is no way these models can account for the

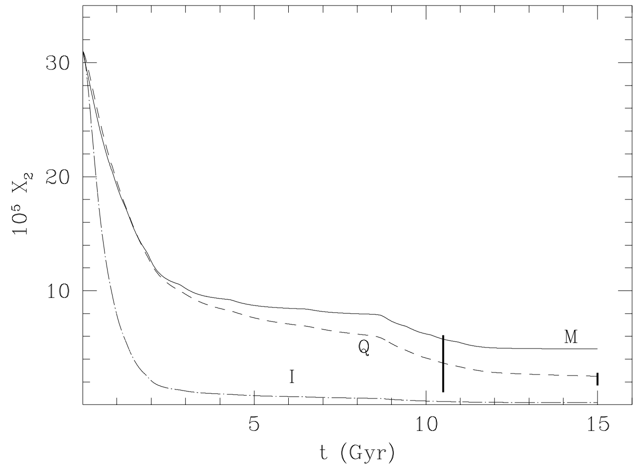

FIG. 3.—Same as Fig. 2 for the sequential models I (*dot-dashed line*), M (*solid line*), and Q (*dashed line*).

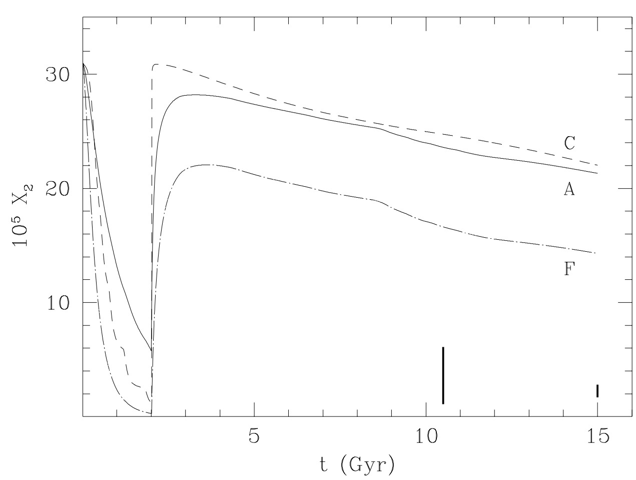

FIG. 4.—Same as Fig. 3 for the two-infall models A (*solid line*), C (*dashed line*), and F (*dot-dashed line*).

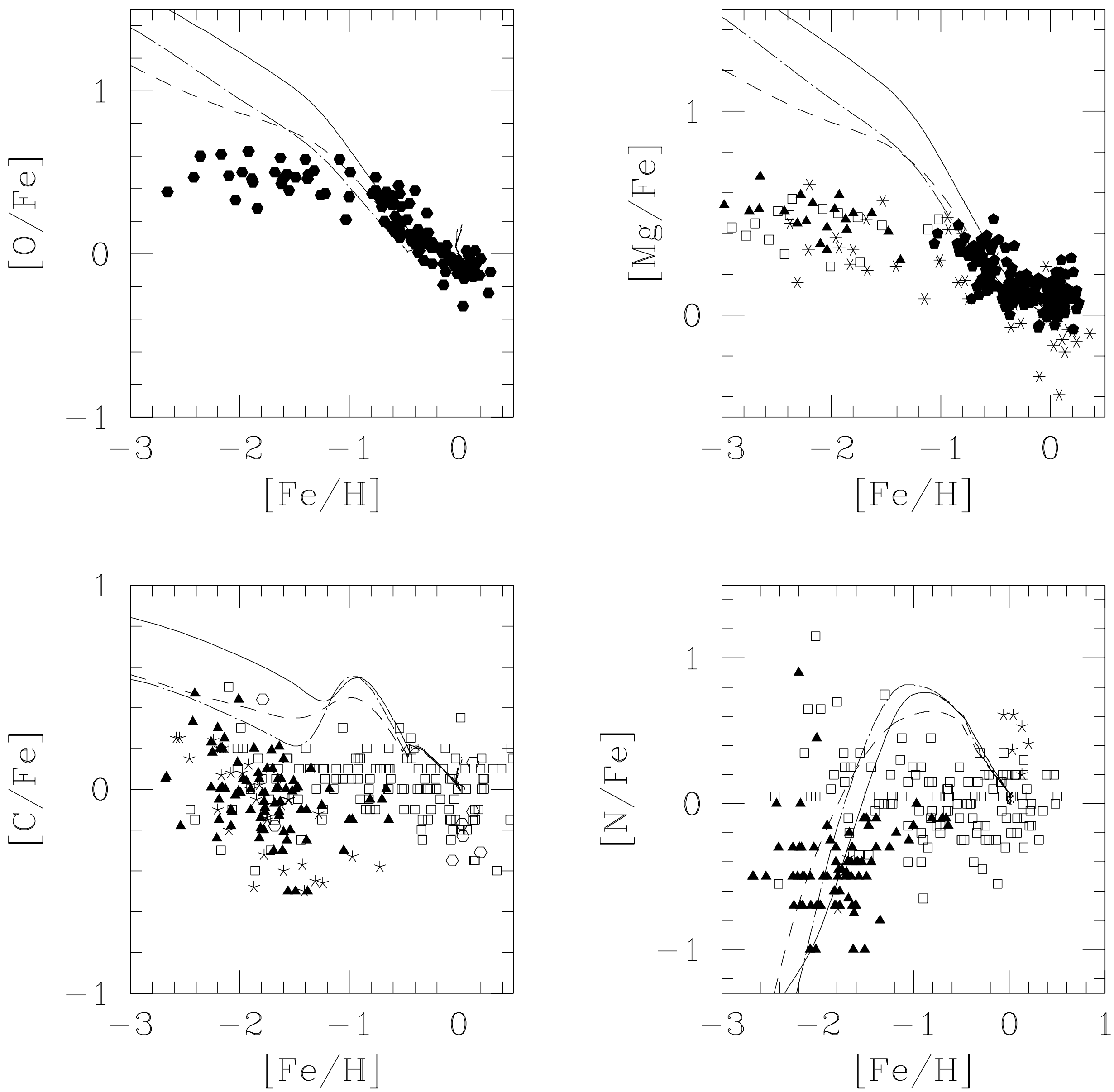

FIG. 5.—Relative abundances [O/Fe], [Mg/Fe], [C/Fe], and [N/Fe] vs. [Fe/H] predicted for the sequential models. The models are labeled as in Fig. 3. As in Chiappini et al. (1997), the data were taken from Laird (1985), Gratton & Ortolani (1986), Tomkin, Sneden, & Lambert (1986), Carbon et al. (1987), Gratton & Sneden (1987), Magain (1987, 1989), Edvardsson et al. (1993), and Gratton et al. (1998).

relatively low abundances observed in the solar system or the present local ISM. In Figure 6, the predicted relative metallicities (O/Fe, Mg/Fe, C/Fe, and N/Fe), as a function of [Fe/H], are compared with the data. Despite the large spread in the data, models A, C, and F provide a rather poor fit to the abundance ratios and are not in complete agreement with the observed G-dwarf metallicity distribution shown in Figure 7 (*top*). Although many two-infall models can be found that are consistent with the observed metallicities, all such models permit only modest D destruction, by a factor that ranges from nearly unity (infall compensating for stellar destruction) up to ~ 1.9 at the time of the formation of the solar system and up to ~ 2.2 at the present epoch.

The obstacle to obtaining large D depletion is that it is generally necessary to assume much larger star formation efficiencies in the halo than in the disk, coupled with short timescales for the formation of both components. It is apparent from the figures that only the sequential models, such as I, M, and Q, are capable of sufficient (or even excessive) D destruction. This is because the second infall episode, which gives rise to the disk in the two-infall models, replenishes the ISM with large amounts of deuterium, thus compensating for most of its previous consumption. The sequential models fail, however, in comparison with the other observational constraints. In particular, their predicted G-dwarf metallicity distributions, shown in Figure 7, are dramatically different from those observed. The reason is that in these models infall occurs only during halo and disk formation, and the very short timescales for these phases permit only very little gas accretion. Consequently, the rapid consumption of the available—nearly pristine—gas yields high numbers of metal-poor stars. Hence, these models lead to a predicted metallicity distribution that is

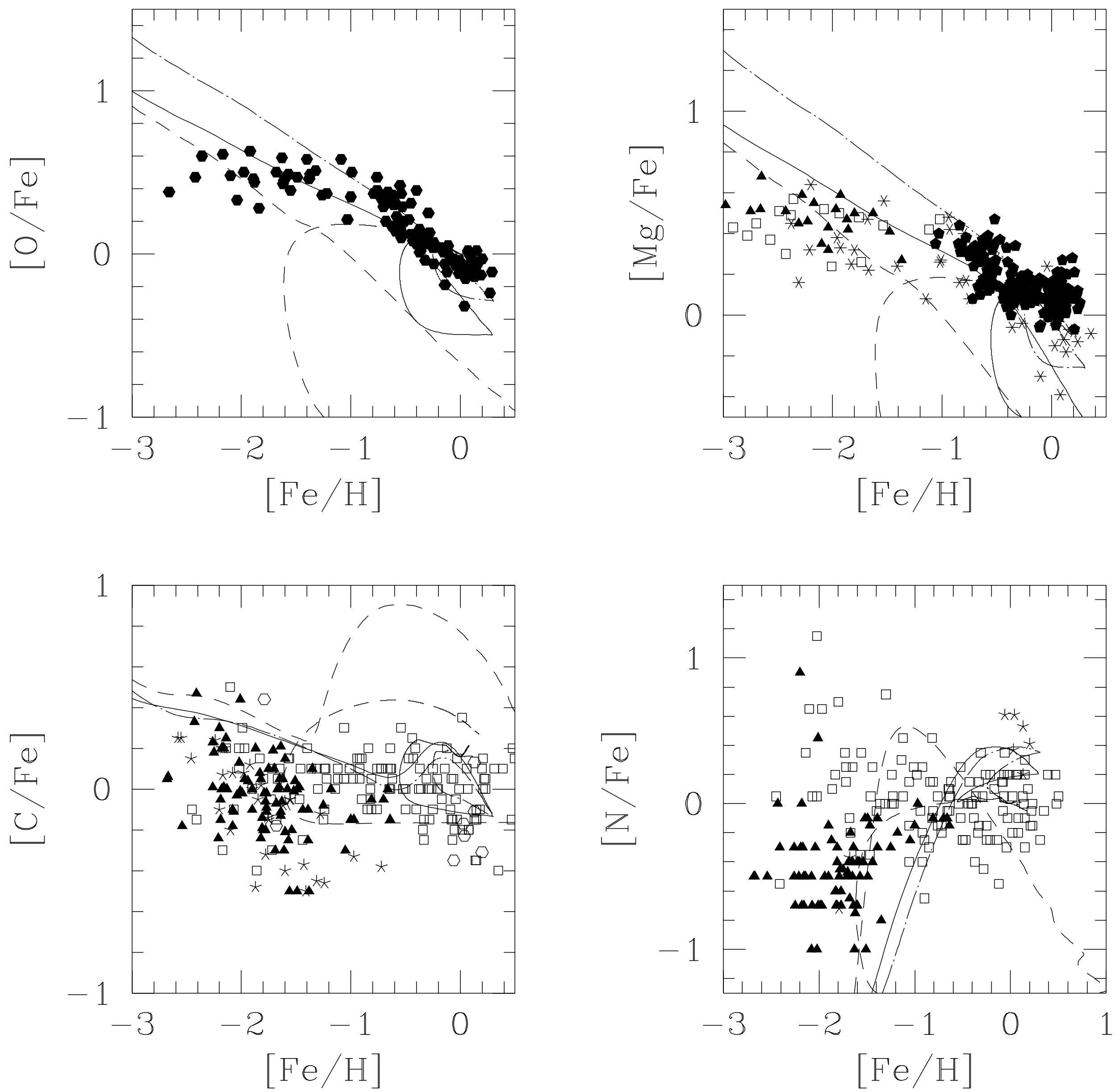

FIG. 6.—Same as Fig. 5 for the two-infall models. The models are labeled as in Fig. 4.

shifted toward low metallicities compared to what is observed.

From our extensive study of all these models, it is clear that those that destroy large amounts of deuterium do not fit the other constraints, whereas those that are in good agreement with the variety of observational data have much less deuterium consumption (depletion by factors smaller than 2–3). Basically, the relatively high gas content and low metallicity of the local ISM is incompatible with efficient cycling of the gas through stars. In contrast, Scully et al. (1997) claim their model II does fit the observational constraints while destroying deuterium by an order of magnitude. However, for the following reason, their model II cannot be describing the chemical evolution of the solar vicinity of the Galaxy. Scully et al. (1997) fix the overall normalization of their SFR by requiring that model II reproduce the observed present, local gas fraction. They do not normalize their SFR to the present, local SFR. As a result, they failed to notice that the predicted present SFR for model II is an order of magnitude smaller than that observed locally (Tinsley 1980; Timmes Woosley, & Weaver 1995). If the model II SFR were renormalized to bring it into agreement with the observed local value, several observational obstacles would be encountered. An increased SFR leads to more rapid production of the heavy elements, along with even more deuterium destruction. To compensate for the former, perhaps the outflow rate could be increased as well. But this will result in a much smaller present gas fraction, no longer consistent with the data. Furthermore, since the model II initial SFR is nearly 200 times higher than that at present, if the present SFR were normalized to that observed locally, the initial SFR would have been far too large to be consistent with the observed luminosity distribution of galaxies (Pozzetti, Bruzual, & Zamorani 1996; i.e., young galaxies would be too bright) and also inconsistent with the observed age-metallicity relation (Twarog 1980; Scalo 1986; Prantzos 1998). To test these expectations, we have constructed models R, S, T, and

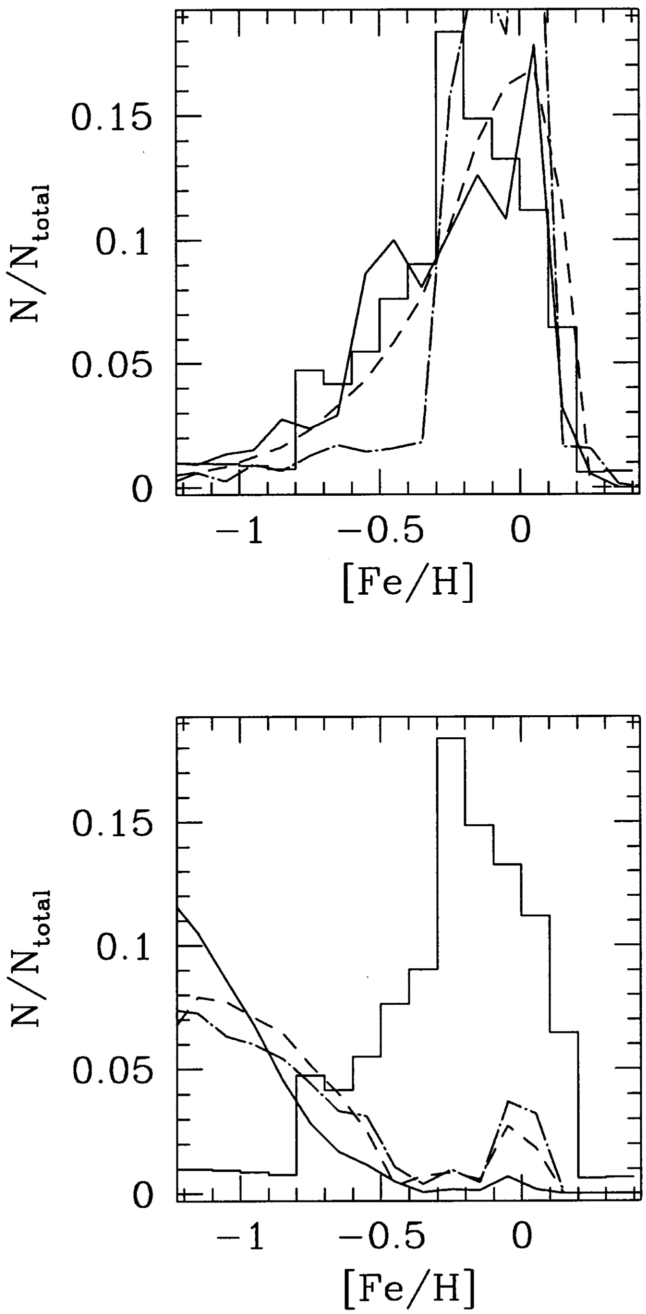

FIG. 7.—G-dwarf metallicity distribution in the solar vicinity predicted by the different models. The upper panel is for the two-infall models, and the lower panel is for the sequential models. The data are from Rocha-Pinto & Maciel (1996). The models are labeled as in Figs. 3 and 4.

U (see Table 1) using the IMF of Scully et al. (1997) and employing a SFR and a variety of winds analogous to those in their model II. In all of these cases, we confirm that the metallicity is too high (reaching the solar value at $\sim$1–2 Gyr) and the present gas fraction too small for consistency with the observational data.

6. DISCUSSION

Observations in the local ISM and in the solar system provide valuable lower bounds to the primordial abundance of deuterium. If these data are to be utilized to predict, or bound from above, the primordial abundance, it is necessary to calculate, or bound, the destruction of deuterium in the Galaxy during its evolution. Although most models of chemical evolution suggest only modest destruction (e.g., Audouze & Tinsley 1974; Steigman & Tosi 1992, 1995; Edmunds 1994; Galli et al. 1995; Palla, Galli, & Silk 1995; Pilyugin & Edmunds 1996; Prantzos 1996), it is claimed that models may be designed to destroy a significant fraction of primordial deuterium (e.g., Vangioni-Flam & Audouze 1988; Vangioni-Flam, Olive, & Prantzos 1994; Scully & Olive 1995; Vangioni-Flam & Cassé 1995; Scully et al. 1996, 1997). To address this impasse, we have first pursued an approach that is nearly independent of any chemical evolution models, relying only on the simple fact that to destroy deuterium, gas must be cycled through stars, and stars produce heavy elements. We have found that destruction of D by more than a factor of 5 seems unlikely (see Fig. 1, *top*). However, we have noted that since elements such as oxygen are synthesized in massive stars while the bulk of the gas is cycled through lower mass stars, this constraint on D destruction may be circumvented if the debris of the massive stars is removed from the disk of the Galaxy permanently (see Fig. 1, *bottom*). Alternatively, a radically different early IMF might permit significant D destruction while avoiding overproduction of the heavy elements, but there is no evidence for any variations in the IMF (Wyse 1997). Furthermore, such a radically different IMF would inevitably alter the abundance ratios of elements produced in different stellar sites (e.g., oxygen/iron, nitrogen/iron, etc.). Recently Chiappini et al. (1998) studied the effects of a variable IMF and concluded that although the IMF may be a function of time, such a time-variation must be small during the disk lifetime if the available observational constraints in the solar vicinity are to be satisfied. We have also considered the effect of infall of partially processed material in which some fraction of the primordial deuterium has been destroyed. Even in these models, D destruction is limited to a factor of $\sim$1.4–2.0 when the Sun formed and $\sim$1.6–2.3 at present.

To explore the observational constraints on D destruction further, we have attempted to couple the evolution of the halo with that of the disk while allowing for high initial SFR and outflow (winds) along with infall. Although the two-infall models appear consistent with the heavy-element data, they permit only modest destruction: less than a factor of $\sim$1.9 when the Sun formed and $\sim$2.2 at present. In contrast, the sequential halo/disk models allow almost any D-destruction factor, but none of the models we explored are consistent with the bulk of the observational data.

Although there are no "theorems" forbidding large D destruction, it is quite difficult to break the connection between large gas fraction, low metallicity, and modest D destruction. Star formation, infall, and outflow are linked inextricably in the ecology and evolution of the Galaxy. Rapid star formation is required if a large fraction of the initial deuterium ($\gtrsim$90%) is to be destroyed. But rapid star formation results in rapid production of the heavy elements and in a rapidly decreasing gas fraction. Infall of primordial or nearly unprocessed gas may ameliorate the effect of a high SFR by diluting the metallicity and replenishing the gas trapped in long-lived stars and stellar remnants. However, the deuterium in the infalling gas drives the interstellar abundance back toward the higher primordial value resulting in less net D destruction. Outflow of processed material may help keep the metallicity low, but when coupled with a large SFR, it will result in a small gas fraction at present. For these reasons it is difficult to design chemical evolution models that destroy deuterium efficiently while maintaining consistency with the other observational data.

In all the models that we and others have explored that are consistent with the observational data, the D destruction at present is limited to a factor of 3 or less. If we adopt this as an upper bound, then we may bound from above the primordial abundance of deuterium: $X_{2p} \leq 3X_{2\mathrm{ISM}}$. Adopting the Linsky et al. (1993) value for $(\mathrm{D/H})_{\mathrm{ISM}} = 1.6 \pm 0.1 \times 10^{-5}$ and assuming for the hydrogen mass fraction at present 0.70 ± 0.01 and primordially 0.76 ± 0.01, we derive a 2 σ upper bound of $(\mathrm{D/H})_p \leq 5.0 \times 10^{-5}$. Clearly, this inferred upper bound to primordial deuterium is in conflict with the high D/H values claimed for some QSO absorbers (Carswell et al. 1994; Songaila et al. 1994; Rugers & Hogan 1996) but is entirely consistent with the low values derived by Tytler et al. (1996) and by Burles & Tytler (1996). For standard BBN, this upper bound to primordial D/H corresponds to a lower bound to the universal ratio of nucleons to photons of $\eta_{10} \geq 4.0$ or, in terms of the baryon density parameter (Ω_B) and the Hubble parameter ($\mathrm{H}_0 = 100\ h$ km s^{-1} Mpc^{-1}), $\Omega_B h^2 \geq 0.015$. Such a lower bound to η_{10}, in the context of standard BBN, leads to a predicted lower bound on the primordial mass fraction of ^{4}He ($Y_p \geq 0.244$), which is in modest disagreement with that inferred from observations of low-metallicity extragalactic H II regions (Olive & Steigman 1995; Olive, Skillman, & Steigman 1997) unless systematic errors are responsible for the low value of Y_p derived from the data. This latter possibility receives support from the new data of Thuan & Izotov (1998), who derive $Y_p = 0.244 \pm 0.002$. Primordial deuterium is an invaluable barometer. Until the observational situation of nearly primordial gas in QSO absorbers is resolved by more data, local ISM and/or solar system data in concert with estimates or bounds to Galactic D destruction will continue to provide useful cosmological constraints.

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