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# Deuterium at high redshift: Primordial or evolved?

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**Abstract.** On the basis of arguments from galactic chemical evolution we suggest that the recent observations of $D/H$ vs. metallicity in several high redshift absorbers are best understood if the primordial $D$ value is in the range $D_{\rm P}/H \sim 2{-}3 \times 10^{-5}$. This range points to a rather high baryonic density ($\Omega_{\rm B} h^2 = 0.019{-}0.026$) compatible to the one obtained by recent estimates based on the Cosmic Microwave Background (CMB) anisotropy measurements. Slightly higher values ($D/H \sim 4 \times 10^{-5}$) are found in Lyman limit systems. Such values are still compatible with CMB estimates but, if taken at face value, suggest a trend of decreasing $D$ abundance with metallicity. We argue that special assumptions, like differential enrichment, are required to explain the data in that case. A clear test of such a differential enrichment would be an excess of products of low mass stars like C and/or N in those systems, but currently available data of N/Si in DLAs do not favour such a "non-standard" scenario.

**Key words.** cosmology – galaxies: abundances – galaxies: evolution

## 1. Introduction

The well known sensitivity of the primordial $D$ abundance on the baryon-to-photon ratio makes it the best "baryometer" of the Universe, as proposed in Reeves et al. (1973). Adams (1976) suggested that QSO absorption line systems at high redshift offer the best opportunity to determine the primordial $D$ value ($D_{\rm P}/H$), without having to account for its subsequent depletion by successive generations of stars (astration). In the past few years, observations of $D$ in Lyman limit systems (LLS, with $H$ column densities $>3\times10^{17}$ cm$^{-2}$) gave rather conflicting results, pointing either to very high ($>10^{-4}$) or low ($<4\times10^{-5}$) values (e.g. Lemoine et al. 2001 for a review); however, the best determined values favour a low $D_{\rm P}/H \sim 3\times10^{-5}$ (e.g. Burles & Tytler 1998).

Most recently, $D$ has been detected in Damped Lyman alpha systems (DLAs) with higher column densities, $N({\rm HI}) > 2 \times 10^{20}$ cm$^{-2}$ (O'Meara et al. 2000; D'Odorico et al. 2001; Pettini & Bowen 2001). If all the data of high redshift systems (both LLS and DLAs) are taken into account, a trend of decreasing $D$ with metallicity seems to emerge (e.g. O'Meara et al. 2001). However, Pettini & Bowen (2001) suggest that the LLS abundance determinations may suffer from systematic uncertainties and only the DLA values should be considered as reliable, which point to a quite low $D_{\rm P}/H = 2.2 \pm 0.2 \times 10^{-5}$.

In this paper we analyse the recent data of $D$ vs. metallicity in high redshift systems from the point of view of galactic chemical evolution, based on a simple relation existing between $D$ abundance and metallicity. We conclude that the most straightforward interpretation of the data is by assuming a low $D_{\rm P}/H = 2{-}3 \times 10^{-5}$. Slightly higher values can be accounted for by making special assumptions, like "differential" galactic winds or a skewed stellar initial mass function (IMF), which generically produce high abundance ratios of carbon and nitrogen (typical products of intermediate mass stars) with respect to alpha elements (typical products of massive stars), as originally suggested by Jedamzik & Fuller (1997); the fact that such values have not been observed up to now in high redshift absorbers favors again the "conservative" interpretation of low primordial $D/H$, in agreement with the most recent estimates from Standard Big Bang Nucleosynthesis calculations (e.g. Burles et al. 2000).

## 2. Models of deuterium vs. metal evolution

The relationship between $D$ abundance and metallicity $Z$ (expressed by the abundance of a product of massive stars, like O or Si) is investigated in Prantzos (1996, hereafter P96). This relationship can be easily obtained analytically in the framework of IRA (Instantaneous Recycling Approximation) for closed-box models or models with outflow rate proportional to the star formation rate (SFR).

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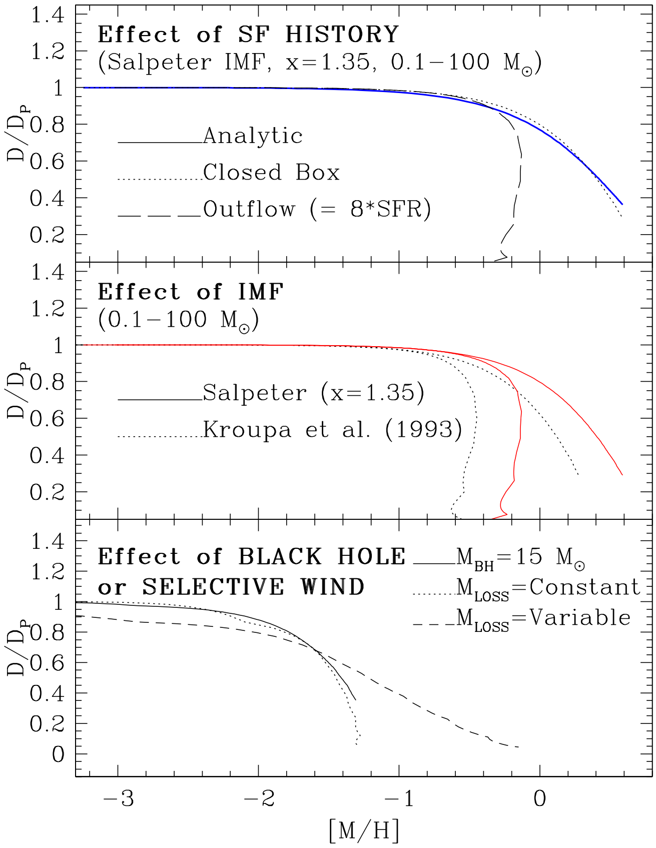

**Fig. 1.** Deuterium vs. metallicity relationship, affected by various model ingredients. *Top:* effect of the Star formation history: an analytical Closed Box model (*solid line*), a numerical Closed Box model (*dotted line*), and an Outflow model (*dashed line*). *Middle:* effect of the IMF: models with the Salpeter IMF with $x = 1.35$ (*solid line*) and with the Kroupa et al. (1993) IMF (*dotted line*). The two curves for each IMF correspond to Closed Box and Outflow models, respectively, as in the top panel. *Bottom:* effect of "differential" enrichment: models are based on the assumptions that stars with $M > 15\ M_\odot$ eject no metals (*solid line*), or that only 1% of the massive star ejecta is retained in the system (*dotted line*), or that the retained fraction of the massive star ejecta varies with time $t$ as $t^3$.

As shown in P96 (his Eq. (6)), the $D$ vs. metallicity relation in these cases is given by:

$$\frac{D}{D_{\rm P}} = {\rm e}^{-\frac{Z}{y}\frac{R}{1-R}} \qquad (1)$$

where $y$ is the metal yield (in the same units as $Z$) and $R$ the return mass fraction (see e.g. Tinsley 1980 for definitions of these quantities).

From Eq. (1) it is obvious that the $D/D_{\rm P}$ vs. $Z$ relation is unique and independent of the history of the system, i.e. it does not depend explicitly either on time, the star formation rate or the gas fraction $\sigma_{\rm GAS}$, which do not appear in the equation. It only depends on $y$ and $R$, both of which depend on the adopted IMF; once the IMF is fixed, there are no more degrees of freedom.

However, it is well known that the IRA solutions fail at very low gas fractions (typically, below 10%) and for the products of low-mass long-lived stars, which return their ejecta in the ISM with a long time delay (see Prantzos & Aubert 1995 for an illustration of the effect). In Fig. 1 (top panel) we plot the relation between $D$ and metallicity for several chemical evolution models: (1) Closed Box with IRA; (2) Closed Box without IRA and (3) Outflow at a rate $f = 8$ SFR. In all cases we adopt a SFR $\psi = 0.25\,\sigma_{\rm GAS}$ Gyr$^{-1}$ and the Salpeter IMF with slope $x = 1.35$ between 0.1 and 100 $M_\odot$; this IMF leads to a return fraction $R \sim 0.31$ and a yield $y \sim 0.6\ Z_\odot$ for oxygen when the yields of Woosley & Weaver (1995) are adopted. It can be seen that the analytical solution matches quite well the numerical one for the closed box model. In the case of outflow the final gas fraction is much lower and the divergence from the analytical solution more important: metallicity reaches lower values and $D$ depletion is more important than in the closed box case. Both effects are due to the impact of deuterium-free and metal-free material returned by low-mass stars at late times in the system, when star formation and metal production have dropped to negligible levels.

The effect of the IMF on the $D$ vs. metallicity relationship is illustrated in the middle panel of Fig. 1. The results of the numerical closed box models are presented for a Salpeter IMF with slope $x = 1.35$ (same as in the top panel) and for a Kroupa et al. (1993) IMF. The latter has a steeper slope in the high mass range ($x = 1.7$ for $M > 1\ M_\odot$) and a swallower one in the low mass range ($x = 1.2$ for $M < 1\ M_\odot$); as a result, it leads to lower metal yield than the Salpeter IMF. For the same gas fraction, lower metallicities are obtained with the Kroupa IMF while $D$ depletion starts at slightly lower metallicity than with the Salpeter IMF.

Despite some differences, the common feature of all the "standard" models presented in the top and middle panels of Fig. 1 (which assume that the ISM is polluted by the ejecta of both low and high mass stars) is that negligible $D$ depletion is obtained below a metallicity $Z = 0.1\ Z_\odot$. This is due to the fact that for all "standard" IMFs one has $y \sim 0.5\ Z_\odot$ and $R \sim 0.3$, i.e. the factor $R/[y(1-R)]$ in Eq. (1) is $R/[y(1-R)] \leq 1$; for metallicities $Z < 0.1\ Z_\odot$ the exponent in Eq. (1) is dominated by the (very small) factor $Z$, leading to $D/D_{\rm P} \sim 1$.

Obviously, "non-standard" assumptions are required in order to obtain $D$ depletion at low metallicities, comparable to those observed in high redshift systems. Some possibilities are explored in the lower panel of Fig. 1, where the duration of the evolution of our model systems is fixed to 2 Gyr (corresponding, roughly, to the ages of the high redshift clouds where $D$ is observed). The common feature of all these models is that they assume "differential" enrichment of the ISM, preferentially by low mass stars, while the metal-rich ejecta of massive stars are lost.

(i) In the first case (*solid curve*), it is assumed that stars with $M > 15\ M_\odot$ form black holes and eject no metals; as a result, the yield $y$ is considerably reduced, metallicity never increases above 0.1 $Z_\odot$ and some $D$ depletion is obtained even below [M/H] $= -1$.

(ii) In the second case (*dotted curve*) it is assumed that a constant fraction $g = 0.01$ of the ejecta of massive stars is retained by the system, while the rest (0.99) is lost from the system through the form of a "selective" galactic wind (which affects only the ejecta of supernovae but not of intermediate mass stars); the evolution of $D$ vs. O is quite similar to the one of case (i) for obvious reasons.

(iii) In the last case (*dashed curve*) it is assumed that the fraction of the ejecta retained by the system varies with time $t$ as $g \propto t^3$, i.e. it is quite small early on and becomes important at late times (for instance, because the system becomes sufficiently massive to retain the ejecta at late times).

The parameters $(M_{\rm BH}, g)$ of the "non-standard" models of cases (i) to (iii) are not based on physical arguments and the only motivation of the underlying assumptions is to show that substantial $D$ depletion can take place even at low metallicities, at least in principle. Note that galactic winds are thought to be a crucial ingredient in models of early-type galaxies (e.g. Larson 1974; Arimoto & Yoshi 1987) and they obviously contribute to the enrichment of intergalactic gas in galaxy clusters (e.g. Renzini et al. 1993); also, other systems like blue compact dwarf galaxies may suffer such selective winds (e.g. Kunth & Ostlin 2000 for a review). However, the important point is that all these assumptions have generic observational consequences that concern not only $D$ but other elements as well, and which will be discussed in Sect. 3.

At this point, we note that the low column densities of LLSs imply that these systems have not have formed stars and metals themselves, but they have been contaminated by nearby star forming regions. In that case, the $D$ vs. $Z$ curves in Fig. 1 constitute lower limits to the absorber abundances of $D$ at a given metallicity, the true value depending on the degree of mixing between the two systems. Obviously, in that case it would be even more difficult to obtain substantial $D$ depletion at low metallicities.

## 3. Discussion

The number of $D$ observations in high redshift systems is too small at present to allow for statistically significant conclusions about chemical evolution. Still, it is interesting to see whether any inferences can be made from the available data (taken at face value) about the evolutionary status of those systems and/or the primordial $D$ abundance.

We note that the solutions of Eq. (1) and Fig. 1 concern the ratio $D/D_{\rm P}$ and not the absolute abundance $D/H$, whereas observations concern the latter quantity. Obviously, the higher the true primordial $D_{\rm P}/H$ value, the more difficult is to deplete $D$ down to the observed $D/H$ values at high redshift. This is illustrated in the upper panel of Fig. 2, where all $D/H$ values (concerning high $z$ clouds, the proto-solar nebula and the local ISM) have been normalised to $D_{\rm P}/H = 4 \times 10^{-5}$. Although that value is still quite modest (i.e. with respect to the high primordial values of $D_{\rm P}/H > 10^{-4}$ reported by e.g. Webb et al. 1997), it is obvious that all "standard" models systematically fail to reproduce the high redshift data, by more than 3 $\sigma$ in the case of the systems H S0105+1619 (*triangle*) and Q 2206-197 (*hexagone*).

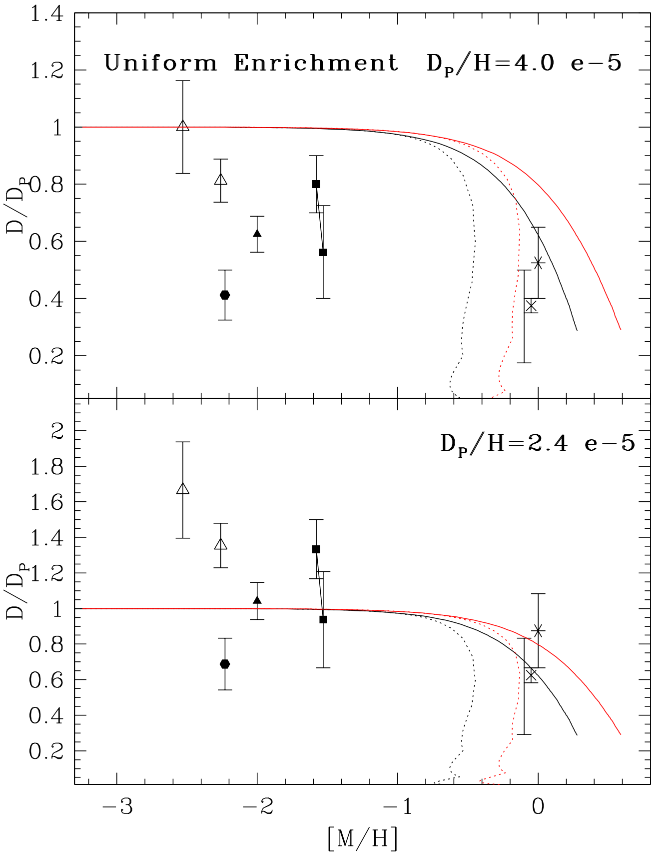

**Fig. 2.** Deuterium vs. metallicity evolution, compared to observations of high redshift regions, the protosolar nebula and the local ISM. Data in both panels are: at high redshift from O'Meara et al. (2000, *triangles*), D'Odorico et al. (2001, *square*), Levshakov et al. (2001, *square*) and Pettini & Bowen (2001, *hexagon*) with *open symbols* corresponding to LLS and *filled symbols* to DLAs; in the proto-solar nebula from Geiss (1998, *asterisk*); the local ISM from Linsky (1998, *cross*) and from recent IMAPS and FUSE observations (Sonneborn et al. 2000; Vidal-Madjar 2001, range indicated by *vertical error bar*). In the *upper panel* data is normalised to a primordial $D$ value $D_{\rm P}/H = 4 \times 10^{-5}$ and in the *lower panel* to $D_{\rm P}/H = 2.4 \times 10^{-5}$ (see text). Model curves in both panels are the same with those in the middle panel of Fig. 1.

In the lower panel of Fig. 2 all data are normalised to $D_{\rm P}/H = 2.4 \times 10^{-5}$, the weighted primordial $D$ value found by averaging over the available measurements of high column density systems alone (*filled symbols*). The data agree with the theoretical curves in that case within $2\sigma$ in all cases. In our view, this is the most reasonable interpretation of the data at present, suggesting that DLAs have a undergone "normal" chemical evolution with negligible $D$ depletion and reveal the true primordial $D/H$ value (which may lay in the $2{-}3 \times 10^{-5}$ range); as pointed out in Pettini & Bowen (2001) the difficulty of determining the HI column density in LLS renders the $D/H$ evaluation in those systems prone to systematic errors and thus less reliable.

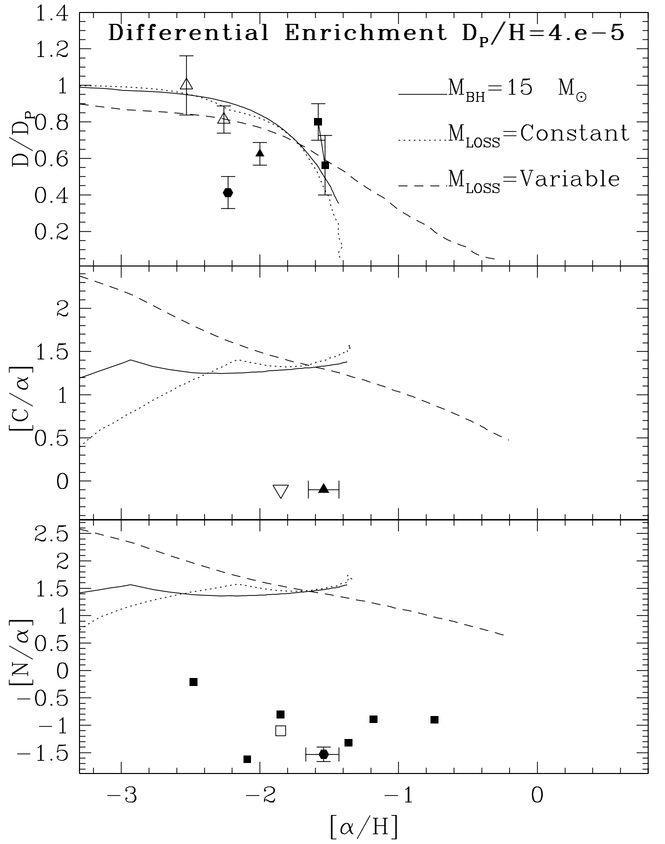

**Fig. 3.** *Top:* deuterium vs. metallicity evolution, compared to observations of high redshift regions. Data are the same as Fig. 2, normalised to $D_P/H = 4 \times 10^{-5}$. Curves correspond to "non-standard" models, the same as in the bottom panel of Fig. 1. *Middle:* [C/$\alpha$] vs. metallicity evolution. Curves correspond to the same models as in the top panel; here and in the bottom panel *filled symbols* represent abundance ratios where Si is the $\alpha$ element while *open symbols* correspond to O. Data point for $z = 4.46$ DLA (*lower limit* for C/Si) is taken from Dessauges-Zavadsky et al. (2001) and for HS 0105+1619 (*upper limit* for C/O) from O'Meara et al. (2001). *Bottom:* [N/$\alpha$] vs. metallicity evolution. Curves correspond to the same models as in the top panel. Data for DLAs are from Centurion et al. (1998, *filled squares*), Dessauges-Zavadsky et al. (2001, *filled hexagon*) and O'Meara et al. (2001, *open square*).

We note that such low primordial $D$ values are compatible with the pre-solar value of $D/H = 2.1 \pm 0.5 \times 10^{-5}$ (Geiss 1998) and suggest that in the solar neighborhood $D$ has been virtually undepleted up to the Sun's formation, probably due to slow infall of primordial gas; such a slow infall is necessary in order to explain the local G-dwarf metallicity distribution, as argued in several places (e.g. Prantzos & Silk 1998; Tosi et al. 1998).

On the other hand, if one assumes that the slightly higher $D/H$ values of LLS reflect the true primordial $D$ abundance and that there is a trend of decreasing $D$ with metallicity, then "non-standard" models have to be used to explain the data, taken at face value. This is seen in the top panel of Fig. 3, where it is assumed that $D_P/H = 4 \times 10^{-5}$. The data point of Pettini & Bowen (2001) is difficult to reproduce even with extreme assumptions about the system's history. However, the common feature of *all models* obtaing substantial $D$ depletion at low metallicities through astration is that they have to minimize the amount of (metal-rich) ejecta from massive stars while keeping the $D$-free ejecta of intermediate mass stars (either through "selective winds" or a skewed IMF). As a result, typical nucleosynthetic products of intermediate mass stars, like C and N, should be particularly abundant in that case, as originally suggested by Jedamzik & Fuller (1997). This is illustrated in the middle and bottom panels of Fig. 3, where the corresponding C/$\alpha$ and N/$\alpha$ ratios are found to be at least 10 times solar (where "alpha" stands for O or Si). In our calculations we adopted the metallicity dependent yields of Woosley & Weaver (1995) for massive stars and of Van den Hoek & Groenewegen (1997) for intermediate mass stars, which include Hot-Bottom Burning (HBB) and find substantial nitrogen production in the 4–8 $M_\odot$ stellar mass range.

The available data on C abundances in DLAs do not allow at present a useful comparison to model predictions, since there is only one lower limit for the $z = 4.466$ DLA towards the QSO APM BR J0307-4945 (Dessauges-Zavadsky et al. 2001); since the column density of the cloud towards the QSO HS 0105+1619 is $\log(N_{\rm HI}) = 19.42$, this cloud could be marginally considered as a DLA, in which case the upper limit on its C/O ratio (*open symbol* in the middle panel of Fig. 3) is clearly incompatible with the values of the "non-standard" senarii. On the other hand, there are several observations of N/Si in DLAs (Centurion et al. 1998; Dessauges-Zavadsky et al. 2001) which show no particular enhancement of nitrogen, as can be seen in Fig. 3 (bottom panel). N/Si is considerably lower than solar in these systems, even if one takes into account ionisation corrections which could enhance that ratio (e.g. Pilygin 1999 and references therein). Taken at face value, the data do not favour the "non-standard" senario of chemical evolution developed in this section. One could argue, however, that HBB has not taken place in intermediate mass stars of such low metallicity systems and that nitrogen has not to be necessarily enhanced. Indeed, the occurence (as a function of stellar mass) and the amount of HBB are still matters of debate (e.g. Lattanzio 1998 for a review). It turns out then that carbon observations become crucial, since a large C/Si (or C/O) ratio is always expected, independently of the occurence of HBB.

In summary, C/$\alpha$ *and/or* N/$\alpha$ (where $\alpha$ stands for alpha-elements like O, Ne, Mg, Si, S etc.) should be particularly enhanced in high redshift systems *if* their $D$ has been indeed substantially depleted through astration. The only way to avoid the overproduction of *both* C/$\alpha$ and N/$\alpha$ is to assume that in intermediate mass stars of such low metallicities the third dredge-up, (bringing C from the He-burning shell to the stellar envelope), is supressed (see Lattanzio 1998 and references therein).

The results of Fig. 3 also suggest that if the primordial $D$ value is much higher than $D_P/H \sim 4 \times 10^{-5}$, then it is extremely difficult to intepret the high redshift data by any model invoking only astration in order to deplete $D$. A possible loophole in that argument concerns the astration of $D$ by a first generation of superheavy ($M > 1000\ M_\odot$) stars, which would eject in the ISM only their hydrogen-burning products ($D$ free and He-rich) through stellar winds before collapsing to black holes; this senario is advocated in Jedamzik & Fuller (1997) and cannot be refuted by current observations, since the yields and the IMF of such stars are unknown. We note that this scenario could accomodate both a high primordial $D$ and a low primordial He, since the currently determined values of those elements in low metallicity systems would result from the action of those stars and would not reflect directly the corresponding primordial values. In that case the observational determination of primordial He abundance (through the linear regression of He/H vs. O/H in low metallicity dwarf galaxies, e.g. Izotov & Thuan 1998) would become much less straightforward.

We also note that the apparent dispersion of $D$ measurements in high $z$ absorbers (a factor of ~2) is comparable to the one observed in the local ISM (e.g. Vidal-Madjar 2001), which has not received a satisfactory explanation up to now. However, the reality of the dispersion at high $z$ is not established yet, and even if it were the case, a different explanation would probably be required, in view of the vastly different spatial scales involved.

## 4. Summary

In this paper we argue that in any "standard" model of galactic chemical evolution, i.e. with a "reasonable" IMF covering the whole stellar mass range and assuming no preferential enrichment by low-mass stars, substantial $D$ depletion (>20%) can be obtained only at metallicities $[\mathrm{M/H}] > -1$; this conclusion is independent of the adopted SFR, infall or outflow prescriptions.

In the light of this argument, the recent observations of $D/H$ vs. metallicity in several high redshift absorbers are best understood if the primordial $D$ value is in the range $D_\mathrm{P}/H \sim 2{-}3 \times 10^{-5}$, as suggested by O'Meara et al. (2000) and Pettini & Bowen (2001) on the basis of $D/H$ observations in DLAs. We note that this range points to a baryonic density ($\Omega_\mathrm{B} h^2 = 0.019{-}0.026$) similar to that obtained by recent estimates based on the CMB anisotropy measurements (Wang et al. 2001).

Slightly higher values ($D/H \sim 4 \times 10^{-5}$) are found in Lyman limit systems. Such values are barely compatible with CMB estimates and, if taken at face value, suggest a trend of decreasing $D$ abundance with metallicity. We argue that special assumptions, like differential enrichment of DLAs, are required to explain the data in that case (see also Fields et al. 2001). A clear test of such a differential enrichment would be an excess of products of low mass stars like C and/or N in those systems (if they have depleted $D$ by astration alone, as assumed here). Currently available data of N/Si in DLAs do not favour such a "non-standard" scenario, but observations of C/Si are crucial in order to definitively eliminate it.

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