Deuterium abundances

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Abstract. We discuss the measurements of deuterium abundances in high redshift quasar absorbers, in the solar system and in the interstellar medium. We present new results that indicate spatial variations of the deuterium abundance in the interstellar medium at the level of $\sim 50\%$ over scales possibly as small as $\sim 10$ pc, and discuss plausible causes for the origin of these variations.

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1 Introduction

In the early days of Big-Bang nucleosynthesis (BBN), starting with Alpher, Bethe & Gamov (1948), and until the late sixties, the primordial origin of $^4$He seemed quite plausible, but the site of formation of the other light elements remained slightly mysterious. Reeves, Audouze, Fowler & Schramm (1973) argued for cosmological deuterium, and showed that a baryonic density $\Omega_b = 0.016 \pm 0.005 h^{-2}$ (with $H_0 = 100h \text{km/s/Mpc}$) could explain the primordial abundance of $^2$D, $^3$He, $^4$He, and possibly some $^7$Li. And, following calculations by Truran & Cameron (1971), they argued that in the absence of post-Big-Bang production, deuterium is slowly destroyed during galactic evolution, as it is entirely burned to $^3$He in stars; in particular, Truran & Cameron (1971) estimated a destruction factor $\sim 2$. Reeves, Audouze, Fowler & Schramm (1973) thus argued that deuterium, if solely produced in the Big-Bang, would be a monitor of stellar formation. These ideas have been strengthened in the past twenty five years, and hardly, if at all, modified: they form the current picture of the cosmological significance of deuterium and its cosmic evolution.

Notably Epstein, Lattimer & Schramm (1976) showed that no deuterium should be produced in significant quantities in astrophysical sites other than the Big-Bang. Hence, measured abundances of deuterium would provide lower limits to the primordial abundance and consequently, an upper limit to the cosmic baryon density. It has been long recognized that the primordial abundance of deuterium represents the most sensitive probe of the baryonic density $\Omega_b$ (see e.g., Schramm, 1998; Schramm & Turner 1998).

Until the late sixties, deuterium had only been detected in ocean water, at a level $\text{D/H} \sim 10^{-4}$. In the early seventies, Black (1971) and Geiss & Reeves (1972) performed the first indirect measurement of the abundance of deuterium representative of the presolar nebula using combined solar wind and meteorite $^3$He measurements. Shortly after, Cesarsky et al. (1973) attempted a detection via the radio observation of the 21 cm and 92 cm lines of both $\text{H}_1$ and $\text{D}_1$, and Rogerson & York (1973) successfully measured for the first time the abundance of deuterium in the interstellar medium from $\text{H}_1$ and $\text{D}_1$ Lyman absorption lines. These efforts were followed by numerous new studies over the following 25 years.

During the past several years, measurements of the deuterium to hydrogen ratio in moderate to high redshift absorbers toward quasars have been obtained for the first time. These clouds are very metal-deficient, so that their deuterium content should not have been affected by astration of gas or, equivalently, the deuterium abundance measured should be close to primordial. This is in contrast with the presolar nebula and interstellar medium measurements, whose deuterium abundances show the imprint of chemical evolution on the primordial abundance.

Therefore, we now have at our disposal three samples of deuterium abundances (measured by number in comparison with hydrogen), each representative of a given epoch: BBN [primordial abundance $(\text{D/H})_{\text{QSO}}$], 4.5 Gyrs past [pre-solar abundance...
(D/H)_{pre⊙} and present epoch [interstellar abundance (D/H)_{ISM}]. Note that the inference of a primordial, pre-solar or interstellar D/H ratio from a measurement rests on the assumption of efficient mixing of the material probed by the observations.

Ultimately, we would like both to know the primordial D/H ratio and to understand the evolution of its abundance with time, in order to constrain the overall amount of star formation. As we discuss here, we have not yet reached this goal. Interstellar measurements do not always agree with each other and we argue, on the basis of very recent data, that at least part of the scatter is real; in other words, we argue that there exist some unknown processes that affect the D/H ratio in the ISM by \( \sim 30 - 50\% \) in some cases, over possibly very small scales, and we discuss a few plausible causes. In the case of the presolar nebula abundances, there also exists scatter, but at the present time, it is not clear whether it arises from chemical fractionation of deuterium and hydrogen in molecules, or from some other cause. For quasar absorption systems, the situation is not yet clear, although two remarkable measurements of Burles & Tytler (1998a,b,c,d) agree to a common value \((D/H)_{QSO} = 3.4 \pm 0.3 \times 10^{-5}\). As we have learned in the case of the ISM, the picture may very well change when new observations come in and we prefer to remain very cautious here.

In this paper, we discuss briefly the current determinations of deuterium abundances and focus on the latest results from interstellar measurements. We discuss QSO absorbers in Section 2, presolar nebula measurements in Section 3 and ISM measurements in Section 4. Section 5 discusses possible causes of spatial variations of the (D/H)_{ISM} ratio and Section 6, their consequences on other estimates of the deuterium abundance. Finally Section 7 summarizes the conclusions and discusses future directions.

2 Primordial abundance

Measurements of the D/H ratio in metal-deficient absorbers on lines of sight to distant quasars offer direct access to the primordial abundance of deuterium (Adams 1976). Although of fundamental importance with respect to Big-Bang nucleosynthesis, this measurement is particularly difficult to achieve (Webb et al. 1991). In the Lyman series of ground state absorption by atomic H\( \text{I} \) and D\( \text{I} \) the absorption of deuterium appears 82 km s\(^{-1}\) bluewards (shorter wavelengths) of the corresponding H\( \text{I} \) absorption. In realistic situations, there is only a limited range of \( b \)-values (the physical parameter that roughly defines the width of the absorption line and which is related to the temperature and the turbulent velocity) and column densities, for which the absorption due to D\( \text{I} \) can be well separated from that of H\( \text{I} \). Typically, for a single absorber and H\( \text{I} \) column densities N(H\( \text{I} \))\( \sim 10^{18} \text{ cm}^{-2} \), one would like the H\( \text{I} \) \( b \)-value to range around \( \sim 15 \text{ km s}^{-1} \), corresponding to temperatures \( \sim 10^{4} \text{ K} \) (Webb et al. 1991; Jenkins 1996). Such \( b \)-values are typical of diffuse ISM clouds, but quite atypical of quasar absorbers, in which the broadening parameter takes values above
Moreover, one rarely observes a single absorber. In particular, the Lyman $\alpha$ forest is present at high redshifts $z \geq 2$, with a large density of lines per unit redshift, so that one has to disentangle the H$\alpha$ and D$\alpha$ from the numerous neighbouring weak lines of H$\alpha$. In particular, one always runs the risk of confusion between a D$\alpha$ line and a weak H$\alpha$ line, at a redshift such that the line falls at the expected position of the D$\alpha$ line; such H$\alpha$ lines are called interlopers. As a consequence, measuring the $(D/H)_{QSO}$ ratio is a matter of statistics. Burles & Tytler (1998c,d) have estimated that about one out of thirty quasars could offer a suitable candidate for a measurement of the D/H ratio.

The first upper limit on $(D/H)_{QSO}$ was actually obtained by York et al. (1983) toward Mrk509, $z_{\text{abs}} = 0.03$ using IUE data. Several years ago, Carswell et al. (1994) and Songaila et al. (1994) reported detections of deuterium absorption toward QSO0014+813, $(D/H)_{QSO} \approx 25 \times 10^{-5}$ at $z_{\text{abs}} = 3.32$, using respectively the Kitt Peak and W.M. Keck telescopes. These authors were cautious in pointing out the possibility that the deuterium feature could actually be due to an H$\alpha$ interloper. A new analysis of the Keck data gave however $(D/H)_{QSO} \approx 19 \pm 5 \times 10^{-5}$ (Rugers & Hogan 1996). In the subsequent years, the situation has rapidly evolved. Our aim here is not to review all of these developments, and we refer the reader to excellent existing reviews (Hogan 1997; Burles & Tytler 1998c,d). As of today, there are three strong claims for a detection of D$\alpha$, namely $(D/H)_{QSO} = 3.3 \pm 0.3 \times 10^{-5}$ at $z_{\text{abs}} = 3.57$ toward QSO1937-1009 (Burles & Tytler 1998a), $(D/H)_{QSO} = 4.0 \pm 0.7 \times 10^{-5}$ at $z_{\text{abs}} = 2.50$ toward QSO1009+2956 (Burles & Tytler 1998b), and $(D/H)_{QSO} = 25 \pm 10 \times 10^{-5}$ at $z_{\text{abs}} = 0.701$ toward QSO1718+4807 (Webb et al. 1997). We therefore have two low and one high values of the $(D/H)_{QSO}$ ratio.

Here we note a few important points. From new observations of QSO0014+813, Burles, Kirkman & Tytler (1999) have demonstrated the presence of an H$\alpha$ interloper in the absorption line that had been identified as D$\alpha$, so that consequently, no $(D/H)_{QSO}$ ratio could be measured with confidence in this system. However, Hogan (1998) maintains that there is evidence for a high deuterium abundance in this system and that the probability and amount of contamination should be small, basing his arguments on statistical studies of correlations of absorbers on scales $\sim 80$ km s$^{-1}$. Songaila (1998) reports a similar finding, from statistical arguments, although based on a relatively small number of lines of sight, and derives $(D/H)_{QSO} \geq 5 \times 10^{-5}$. She also claims that the estimate of the H$\alpha$ column density of Burles & Tytler toward QSO1937-1009 is incorrect and finds for this system $(D/H)_{QSO} \geq 5 \times 10^{-5}$ (see however, Burles & Tytler 1998e).

We also note that Tytler et al. (1999) have reanalyzed the HST data of QSO1718+4807 together with IUE and Keck spectra and concluded that, for a single absorber, $(D/H)_{QSO} = 8 - 57 \times 10^{-5}$. However, they find that if a second H$\alpha$ absorber is allowed for on this line of sight, then the $(D/H)_{QSO}$ ratio becomes an upper limit, $(D/H)_{QSO} \leq 50 \times 10^{-5}$. On the other hand, using Monte-Carlo simulations of H$\alpha$ cloud distribution on the line of sight, they could check that the low $(D/H)_{QSO}$ ratios toward QSO1009+2956 and QSO1937-1009 held. Therefore the result toward
QSO1718+4807 is not yet conclusive; in particular, the HST dataset contains only Lyman α and an associated Si \textsc{iii} line and it would be extremely valuable to have data on the whole Lyman series of this absorber.

Finally, we note that Levshakov (1998, for a review) suggests that correlations in turbulent velocity on large spatial scales could seriously affect determinations of the \((D/H)_\text{QSO}\) ratio. This author, and collaborators, claim that the above high and low measurements of the deuterium abundance are consistent with a single value \(D/H \simeq 3.5 - 5.2 \times 10^{-5}\) (see also Levshakov, Tytler & Burles 1999).

This field is too young and dynamic to permit highly confident conclusions at this time, although a trend toward \((D/H)_\text{QSO} \sim 3.5 \times 10^{-5}\) seems to be emerging as indicated by the recent results of Burles & Tytler (1998a,b). Finally we stress the need for further measurements of the \((D/H)_\text{QSO}\) ratio, as they could change our understanding of the situation. This should be clear from our forthcoming discussion of the measurements of the \((D/H)_{\text{ISM}}\) ratio.

3 Pre-solar abundance

By measuring the \(^3\text{He}\) abundance in the solar wind, Geiss & Reeves (1972) determined the abundance in the protosolar nebula and hence found \((D/H)_{\text{pre}} \simeq 2.5 \pm 1.0 \times 10^{-5}\). This result was historically the first evaluation of the deuterium abundance of astrophysical significance. It was confirmed by Gautier & Morel (1997) who showed \((D/H)_{\text{pre}} = 3.01 \pm 0.17 \times 10^{-5}\). These determinations of \((D/H)_{\text{pre}}\) are indirect and linked to the solar \(^4\text{He}/^3\text{He}\) ratio and its evolution since the formation of the solar system.

Whereas in cometary water deuterium is enriched by a factor of at least 10 relative to the protosolar ratio (e.g. Bockelée-Morvan et al. 1998; Meier et al. 1998), the giant planets Jupiter and Saturn are considered to be undisturbed deuterium reservoirs, free from production or loss processes. Thus they should reflect the abundance of their light elements at the time of the formation of the solar system 4.5 Gyrs ago (Owen et al. 1986). The first measurements of the \((D/H)_{\text{pre}}\) ratio in the Jovian atmosphere have been performed through methane and its deuterated counterpart \(\text{CH}_3\text{D}\), yielding \((D/H)_{\text{pre}} = 5.1 \pm 2.2 \times 10^{-5}\) (Beer & Taylor 1973). Other molecules such as HD and \(\text{H}_2\), yield lower values: \((D/H)_{\text{pre}} \approx 1. - 2.9 \times 10^{-5}\) (Smith et al. 1989).

Recently, new measurements of the \((D/H)_{\text{pre}}\) ratio using very different methods were carried out. Two are based on the first results of the far infrared ISO observations of the HD molecule in Jupiter (Encrenaz et al. 1996) and Saturn (Griffin et al. 1996), and lead respectively to \((D/H)_{\text{pre}} = 2.2 \pm 0.5 \times 10^{-5}\) and \((D/H)_{\text{pre}} = 2.3^{+1.2}_{-0.8} \times 10^{-5}\). Note that the Encrenaz et al. (1996) value was updated to the more reliable value \((D/H)_{\text{pre}} = 1.8^{+1.1}_{-0.5} \times 10^{-5}\) by Lellouch et al. (1997). Another is based on the direct observation with HST-GHRS of both \(\text{H}_1\) and \(\text{D} \text{ i}\) Lyman α emission at the limb of Jupiter for the first time (Ben Jaffel et al. 1994; 1997).
yielding \((D/H)_{\text{pre\@\,\odot}} = 5.9 \pm 1.4 \times 10^{-5}\). The third one is an in situ measurement with a mass spectrometer onboard the Galileo probe (Niemann et al. 1996) yielding \((D/H)_{\text{pre\@\,\odot}} = 5.0 \pm 2.0 \times 10^{-5}\) [however this last value has been revised recently toward the lower part of the range, \(i.e.\ (D/H)_{\text{pre\@\,\odot}} = 2.7 \pm 0.6 \times 10^{-5}\) (Mahaffy et al. 1998)].

It is surprising that measurements that probe almost the same atmospheric region of Jupiter (\(~1\) bar level) lead to such a large scatter in the D/H ratio. Indeed, the atmospheric composition at that level is the key parameter in the ISO data analysis, the H and D Lyman \(\alpha\) spectra modeling and the Galileo mass spectrometer measurements.

It is likely that the differences between these values are due to systematic effect associated with models, such as the \(\text{CH}_4\) mixing ratio (Lecluse et al. 1996), the effect of aerosols, the effect of eddy diffusion, or in the case of the mass spectrometer data, instrumental uncertainties. Additional investigations and observations including HST-STIS and FUSE observations will help to resolve this issue.

## 4 Interstellar abundance

The first measurement of the interstellar D/H ratio was reported by Rogerson & York (1973), from \(\text{Copernicus}\) observations of the line of sight to \(\beta\) Cen, giving \((D/H)_{\text{ISM}} = 1.4 \pm 0.2 \times 10^{-5}\). In the subsequent years, many other measurements of the interstellar deuterium abundances were carried out from \(\text{Copernicus}\) and IUE observations of the Lyman series of atomic \(\text{D}\) and \(\text{H}\) (for a review, see \(e.g.\) Vidal-Madjar, Ferlet & Lemoine 1998). Because absorption by the Lyman series takes place in the far-UV, these measurements require satellite-borne instruments, and the latest observations have been performed using HST and the \(\text{Interstellar Medium Absorption Profile Spectrograph}\) (IMAPS), which afford higher spectral resolution.

In order to measure \((D/H)_{\text{ISM}}\), one can also observe deuterated molecules such as \(\text{HD},\ \text{DCN},\ etc\), and form the ratio of the deuterated molecule column density to its non-deuterated counterpart (\(\text{H}_2,\ \text{HCN},\ etc\)). More than twenty different deuterated species have been identified in the ISM, with abundances relative to the non-deuterated counterpart ranging from \(10^{-2}\) to \(10^{-6}\). Conversely, this means that fractionation effects are important. As a consequence, this method cannot currently provide a precise estimate of the true interstellar D/H ratio. Rather, this method is used in conjunction with estimates of the \((D/H)_{\text{ISM}}\) ratio to gather information on the chemistry of the ISM.

Another way to derive the \((D/H)_{\text{ISM}}\) ratio comes through radio observations of the hyperfine line of \(\text{D}\) at 92 cm. The detection of this line is extremely difficult, but it would allow one to probe more distant interstellar media than the local medium discussed below. However, because a large column density of D is necessary to provide even a weak spin-flip transition, these observations aim at molecular complexes. As a result, the upper limit derived toward Cas A (Heiles et al. 1993) \((D/H)_{\text{ISM}} \leq 2.1 \times 10^{-6}\) may as well result from a large differential fraction of D and H.
being in molecular form in these clouds, as from the fact that one expects the D/H ratio to be lower closer to the galactic center (since D is destroyed by stellar processing). The most recent result is the low significance detection of interstellar D I 92 cm emission performed by Chengalur et al. (1997) toward the galactic anticenter, giving \((D/H)_{\text{ISM}} = 3.9 \pm 1.0 \times 10^{-5}\).

Therefore, the most reliable estimate of \((D/H)_{\text{ISM}}\) remains the observation of the atomic transitions of D and H of the Lyman series in the far-UV. The relatively low resolution of the Copernicus spectra (~15 km s\(^{-1}\)) usually left the velocity structure unresolved, which could lead to significant errors. These uncertainties were reduced when HST and IMAPS echelle observations provided resolving powers high enough (3.5 to 4 km s\(^{-1}\)) to unveil the velocity structure.

Either the Lyman \(\alpha\) lines emissions from cool stars or the continua from hot stars have been used as background sources. Whereas cool stars can be selected in the solar vicinity, luminous hot stars are located further away, with distances \(\gtrsim 100\) pc. Therefore, the line of sight to hot stars generally comprises more absorbing components than cool stars. However, for cool stars, the modeling of the stellar flux is usually much more difficult than for hot stars. Moreover, lines of species such as N\(\text{I}\) and O\(\text{I}\) that lie close to Lyman \(\alpha\) cannot be observed, as the flux drops to zero on either side of Lyman \(\alpha\). Hence, in the case of cool stars, the line of sight velocity structure in H\(\text{I}\) typically has to be traced with Fe\(\text{II}\) and Mg\(\text{II}\) ions and this is usually not a good approximation. In contrast, N\(\text{I}\) and O\(\text{I}\) were shown to be good tracers of H\(\text{I}\) in the ISM (Ferlet 1981; York et al. 1983; Meyer, Cardelli & Sofia 1997; Meyer, Jura & Cardelli 1998; Sofia & Jenkins 1998) and hot stars are particularly interesting targets in that respect.

In any case, both types of background sources have offered some remarkable results. In the direction to the cool star Capella, Linsky et al. (1993; 1995) have obtained, using HST: \((D/H)_{\text{ISM}} = 1.60 \pm 0.09^{+0.05}_{-0.10} \times 10^{-5}\). On this line of sight, only one absorbing component was detected, the Local Interstellar Cloud (LIC), in which the solar system is embedded (Lallement & Bertin 1992). Several more cool stars have been observed with HST, all compatible with the Capella evaluation (Linsky et al. 1995: Procyon; Linsky & Wood 1996: \(\alpha\) Cen A, \(\alpha\) Cen B; Piskunov et al. 1997: HR 1099, 31 Com, \(\beta\) Cet, \(\beta\) Cas; Dring et al. 1997: \(\beta\) Cas, \(\alpha\) Tri, \(\epsilon\) Eri, \(\sigma\) Gem, \(\beta\) Gem, 31 Com). The most precise of these measurements has been obtained toward HR 1099 by Piskunov et al. (1997): \((D/H)_{\text{ISM}} = 1.46 \pm 0.09 \times 10^{-5}\). None of the other results is accurate enough to place any new constraints on the Linsky et al. (1993; 1995) evaluation.

Recently, new observations by HST and IMAPS have become available. HST observations of white dwarfs instead of hot or cool stars can be used to circumvent most of the afore-mentioned difficulties. White dwarfs can be chosen near the Sun and they can also be chosen in the high temperature range, so as to provide a smooth stellar profile at Lyman \(\alpha\). At the same time, the N\(\text{I}\) triplet at 1200 Å as well as the
O\textsc{i} line at 1302 Å are available. Such observations have now been conducted using HST toward three white dwarfs: G191-B2B (Lemoine et al. 1996; Vidal-Madjar et al. 1998), Hz 43 (Landsman et al. 1996) and Sirius B (Hébrard et al. 1999).

Toward G191-B2B, Vidal-Madjar et al. (1998) detected three absorbing clouds using HST-GHRS 3.5 km s$^{-1}$ spectral resolution data. Assuming that all three absorbing components shared the same (D/H)$_{\text{ISM}}$ ratio, they measured at Lyman $\alpha$ (D/H)$_{\text{ISM}}=1.12 \pm 0.08 \times 10^{-5}$. There is a clear discrepancy between this ratio and that observed toward Capella by Linsky et al. (1993; 1995). As it turns out, one of the three absorbers seen toward G191-B2B is the LIC, also seen toward Capella. Moreover, the angular separation of both targets is 7°. One should thus expect to see the same (D/H)$_{\text{ISM}}$ ratio in both LIC line of sights. When this constraint is included in the three-component fit, Vidal-Madjar et al. (1998) find that the average (D/H)$_{\text{ISM}}$ in the other two absorbers is $\sim 0.9 \pm 0.1 \times 10^{-5}$. Finally, it is important to note that Vidal-Madjar et al. (1998) re-analyzed the dataset of Linsky et al. (1993; 1995) toward Capella, using the same method of analysis as toward G191-B2B and confirmed the previous estimate. Therefore, the conclusion is that the (D/H)$_{\text{ISM}}$ ratio varies by at least $\sim 30\%$ within the local interstellar medium, either from cloud to cloud, and/or within the LIC.

Using HST-GHRS observations, Hébrard et al. (1999) detected two interstellar clouds toward Sirius A and its white dwarf companion Sirius B, one of them being identified as the LIC, in agreement with previous HST observation of Sirius A by Lallement et al. (1994). As in the case of G191-B2B, the interstellar structure of this sightline, which is assumed to be the same toward the two stars (separated by less than 4 arcsec at the time of the observation), is constrained by high spectral resolution data of species such as O\textsc{i}, N\textsc{i}, Si\textsc{ii} or C\textsc{ii}. Whereas the deuterium Lyman $\alpha$ line is well detected in the LIC with an abundance in agreement with the one of Linsky et al. (1993, 1995), no significant D\textsc{i} line is detected in the other cloud. However, the Lyman $\alpha$ lines toward Sirius A and Sirius B are not simple. Indeed an excess of absorption is seen in the blue wing of the Sirius A Lyman $\alpha$ line and interpreted as the wind from Sirius A. In its white dwarf companion, an excess in absorption is seen in the red wing and interpreted as the core of the Sirius B photospheric Lyman $\alpha$ line. A composite Lyman $\alpha$ profile could nonetheless be constructed and the (D/H)$_{\text{ISM}}$ measured in the second cloud is (D/H)$_{\text{ISM}}=0.5^{+1.1}_{-0.5} \times 10^{-5}$ (90% confidence level). The rather large error bar stems primarily from the fact that only medium resolution data were available for the Lyman $\alpha$ region.

Finally, IMAPS on the space shuttle ORFEUS-SPAS II mission was used by Jenkins et al. (1999) to observe at high spectral resolution (4 km s$^{-1}$) the Lyman $\delta$ and Lyman $\epsilon$ lines toward $\delta$ Ori. These data allowed an accurate measurement of the D\textsc{i} column density. Together with a new and accurate measurement of the H\textsc{i} column density from Lyman $\alpha$ spectra of $\delta$ Ori in the IUE archive, Jenkins et al. (1999) found the value (D/H)$_{\text{ISM}}=0.74^{+0.19}_{-0.13} \times 10^{-5}$, at a 90% confidence level (c.l.), which confirms the Copernicus result obtained by Laurent et al. (1979). Compared to Capella (Linsky et al. 1993; 1995) and HR 1099 (Piskunov et al. 1997),
this value is very low. This suggests that variations by \( \sim 50\% \) are possible in the local interstellar medium.

Using the same analysis techniques as Jenkins et al. (1999), IMAPS was also used combined with IUE archive toward two other stars, \( \gamma^2 \) Vel and \( \zeta \) Pup to yield the first results \( (D/H)_{\text{ISM}} = 2.1^{+0.36}_{-0.30} \times 10^{-5} \) and \( (D/H)_{\text{ISM}} = 1.6^{+0.28}_{-0.23} \times 10^{-5} \), respectively (Jenkins et al. 1998; Sonneborn et al. 1999). The value for \( \gamma^2 \) Vel is marginally inconsistent with the lower value toward Capella, and this disparity may be substantiated further when the error estimates become more refined. We also note that the \( \gamma^2 \) Vel result confirms previous estimates of York & Rogerson (1976), while the \( \zeta \) Pup result is only in marginal agreement with the Vidal-Madjar et al. (1977) evaluation, both made with Copernicus.

5 Interstellar D/H variations

As we have discussed, there is now firm evidence for variations of the \( (D/H)_{\text{ISM}} \) ratio, able to reach \( \sim 50\% \), over scales as small as \( \sim 10 \) pc. This fact had already been suggested by early Copernicus and IUE data, although it was not known whether this was due to the inadequacy of the data and the complexity of the problem, or to real physical effects. The dispersion of all published \( (D/H)_{\text{ISM}} \) ratios, ranging from \( 0.5 \times 10^{-5} \) to \( 4 \times 10^{-5} \), was thus not universally accepted as real (McCullough 1992). Even if some of this scatter may be accounted for by systematic errors, as we have argued above, we believe that at least part of it is real.

Actually, one should recall that time variations of the \( (D/H)_{\text{ISM}} \) ratio have already been reported toward \( \epsilon \) Per (Gry et al. 1983). They were interpreted as the ejection of high velocity hydrogen atoms from the star, which would contaminate the deuterium feature. Such an effect can only mimic an enhancement of the D/H ratio, and it is thus worth noting that in at least five cases, the \( (D/H)_{\text{ISM}} \) ratio was found to be really low: \( 0.9 \pm 0.1 \times 10^{-5} \) in two components toward G191-B2B (Vidal-Madjar et al. 1998, see Section 4); \( 0.8 \pm 0.2 \times 10^{-5} \) toward \( \lambda \) Sco (York 1983); \( 0.5 \pm 0.3 \times 10^{-5} \) toward \( \theta \) Car (Allen et al. 1992); \( 0.7 \pm 0.2 \times 10^{-5} \) and \( 0.65 \pm 0.3 \times 10^{-5} \) toward \( \delta \) and \( \epsilon \) Ori (Laurent et al. 1979), recently confirmed in the case of \( \delta \) Ori by Jenkins et al. (1999): \( (D/H)_{\text{ISM}} = 0.74^{+0.19}_{-0.13} \times 10^{-5} \) (90% c.l.). Two other lines of sight seem to give low values for the D/H ratio, albeit with larger error bars: \( 0.5^{+1.1}_{-0.5} \times 10^{-5} \) (90% c.l.) in one of the two components toward Sirius (Hébrard et al. 1999, see Section 4), \( 0.8^{+0.7}_{-0.4} \times 10^{-5} \) toward BD+28 4211 (Götz et al. 1998). All the above authors discussed possible systematics but concluded that none of the identified ones could explain such low values of \( (D/H)_{\text{ISM}} \).

Let us now discuss different plausible causes of variations:

- Molecular fractionation effects, such as the selective incorporation of D into HD, vs. H into H\(_2\), could modify the atomic D/H ratio (Watson 1973). However, the absorbers mentioned above are not molecular, with typical H\(_2\)/H\(_1\) ratios \( \leq 10^{-4} \), so that this should not be a strong effect.
Vidal-Madjar et al. (1978), and Bruston et al. (1981) have suggested that the anisotropic flux in the solar neighborhood, combined with a differential effect of radiation pressure on H\textsc{i} and D\textsc{i} atoms, would result in the spatial segregation of D\textsc{i} vs. H\textsc{i}. Indeed, all D\textsc{i} atoms in a cloud with N(H\textsc{i}) \sim 10^{18}\text{ cm}^{-2} are subject to resonant radiation pressure, whereas the inner H\textsc{i} atoms are shielded from the flux by the optically thick H\textsc{i} envelope. Therefore, provided that the cloud is not homogeneous (and radiation is anisotropic), the segregation of D\textsc{i} atoms vs. H\textsc{i} atoms induces a spatial variation in the D/H ratio. In particular, they predict that the D/H ratio would appear either higher or lower than its actual value, depending on where the line of sight crosses the cloud, assuming it is perpendicular to the direction of the net radiation flux. There is however more chance to observe the depleted region, since it is much more extended than the enriched region. These authors calculate that for a flux corresponding to 10 OB stars located at 50 pc from the cloud, deuterium atoms could diffuse to the other side in a timescale \sim 10^6\text{ yrs}. The clear signature of this mechanism would be the evidence of regional differences in the ISM.

Jura (1982) has suggested that the adsorption of D\textsc{i} and H\textsc{i} onto dust grains could be selective. In this respect, it would be interesting to study the variation of (D/H)\textsc{ISM} with gas velocity, as if there was indeed such a correlation, in much the same manner as Ca\textsc{ii}/Na\textsc{i} varies (the Routly-Spitzer effect, Routly & Spitzer 1952, Vallerga et al. 1993 and references), one might be more willing to accept the conjecture about the difference in binding of D and H to the surfaces of dust grains. We note, however, that the measurement of N(H\textsc{i}) cannot be done precisely in absorption spectra on a component by component basis, if there are more than one absorber, so that the velocity information in the D/H ratio is lost. One usually measures average D/H ratios, such as for G191-B2B. Therefore, one should measure D/O or D/N ratios as a function of velocity.

Copi, Schramm & Turner (1995), and Copi (1997) have devised a stochastic approach to chemical evolution, in which they compute the evolution of a particular region of space in Monte-Carlo fashion. This allows them to probe the scatter around the mean of correlations such as abundances vs. time/metallicity; this is in contrast to usual models of chemical evolution that only compute the mean behavior. Actually, one of their objectives was to study the spread in light elements abundances after 15 Gyrs of evolution, and they find that for deuterium, one expects a negligible scatter. However, it is difficult to apply their results to spatial variations of the (D/H)\textsc{ISM} ratio, as they were more concerned with variations at given metallicities, and thus did not introduce spatial dependence in their Monte-Carlo calculations.

Along similar lines of thought, let us see if stellar ejecta could introduce in-
homogeneities in the (D/H)$_{\text{ISM}}$ ratio. One should focus on planetary nebula (PN) ejecta and cool giant winds, as their mass input in the ISM dominates that of other stars (Pottasch 1983). Moreover, PN ejecta and cool giant winds share similar characteristics with interstellar clouds in which deuterium has been seen: PN ejecta have mass $\sim 10^{-2} - 10^{-1} M_\odot$, and speed $\sim 20 \text{ km s}^{-1}$; cool giants have mass loss $\sim 3 \times 10^{-6} M_\odot \text{yr}^{-1}$, with velocities $\sim 10 \text{ km s}^{-1}$; above interstellar clouds have mass $M \sim 10^{-2} M_\odot$ (if $n_{\text{HI}} \sim 0.1 \text{ cm}^{-3}$ and $N(\text{HI}) \sim 10^{18} \text{ cm}^{-2}$), and speed $\sim 10 - 20 \text{ km s}^{-1}$. Therefore the admixture of PN ejecta or giant wind, that are deuterium free (all D is burned to $^3$He by pre-main sequence), and interstellar unprocessed material, would result in a D/H ratio reduced by $M_\text{cloud}/(M_\text{poll} + M_\text{cloud})$, where $M_\text{poll}$ and $M_\text{cloud}$ denote the polluted and interstellar mass, respectively.

The probability that a given line of sight crosses a PN ejecta is given by the covering factor of PNe on a sphere of radius $R$, centered on the Sun. The observed density of planetary nebulae in the solar vicinity is $N_0 \sim 5 \times 10^{-8} \text{ pc}^{-3}$; this however, counts only visible nebulae, whose age is $\leq 3 \times 10^4 \text{ yr}$. Assuming that the density of nebulae of age $t$ scales as: $N = N_0 t/t_0$, where $t_0$ is the age before disappearance, one obtains the covering factor for nebulae of a given age $t$: $f \approx 7 \times 10^{-4} N_{0,-7.3} R_{50} t_{10}^2 (t/t_0)$, assuming $r \ll R$, where $r_{10}$ is the radius of the PN in units of 10 pc, $R_{50}$ is in units of 50 pc, $N_{0,-7.3}$ in units of $5 \times 10^{-8} \text{ pc}^{-3}$; $r$ is tied to the age $t$, for instance $r = 20 \text{ pc} v_{20} t_6$ ($t_6$ in units of $10^6 \text{ yrs}$), if the expansion is linear. Since the covering factor grows as $r^2 t$, one only needs to consider the largest (oldest) PNe. A rough estimate of the maximum radius of expansion can be obtained by equating the dynamic pressure of the ejecta and the ISM pressure: $r \sim 3 \text{ pc} n_{-1}^{-1/3} T_{4}^{1/3} M_{-2}^{1/3} v_{20}^{2/3}$, where $n_{-1}$ is the total density of the ambient ISM in units of $0.1 \text{ cm}^{-3}$, $T_{4}$ is the temperature in $10^4 \text{ K}$, $M_{-2}$ the ejecta mass in $10^{-2} M_\odot$. This corresponds to a covering factor $f \sim 2 \times 10^{-4}$, for an age $t \sim 10^3 \text{ yrs}$ (i.e. assuming linear expansion). Note that $r \sim 3 \text{ pc}$ roughly corresponds to the typical size of an ISM cloud.

One could reach higher covering factors in low density media, such as the solar vicinity, where $n \sim 10^{-4} \text{ cm}^{-3}$ and $T \sim 10^6 \text{ K}$ (Cox & Reynolds 1987; Ferlet 1999): in this case, the maximum radius of expansion of ejecta can become larger. However, if this latter becomes much larger than the typical size of an interstellar cloud, then the polluted mass that is effectively mixed with the interstellar material is less than the ejected mass, and the mixing becomes ineffective. Therefore, we feel that the above covering factor, $f \sim 2 \times 10^{-4}$, for $R = 50 \text{ pc}$ and $r \sim 3 \text{ pc}$, should give a reasonable estimate of the probability of contamination, within an order of magnitude.

Finally, one can perform a similar calculation for cool giant winds. Their number density is $\sim 2.5 \times 10^{-7} \text{ pc}^{-3}$; each ejects $\sim 0.3 M_\odot$ on a dynamical evolution timescale $\lesssim 10^6 \text{ yrs}$. This corresponds to a covering factor $f \sim$
$4 \times 10^{-3}$, which is substantially larger than for PNe. Although these are a qualitative estimates, the probability of contamination appears marginal, but cannot be ruled out either, and quite probably so for cool giant winds, when long pathlengths are considered.

The best signature of contamination of material of solar chemical composition by a PN ejecta, or giant wind, comes through fluorine, which usually shows $[\text{F}/\text{O}] \sim 1$ (Kaler 1982 for PNe; Joriseen, Smith & Lambert 1992 for giants); elements such as C and N are not always over-abundant. Note, however, that fluorine may also be interpreted as a signature of $\nu$-process in type II supernovae (Timmes et al. 1997, and references). Fluorine may be detected in absorption with lines of F\textsc{i} at 952Å and 954Å, although its weak universal abundance makes the detection rather difficult. Nonetheless, FUSE has access to this range, and should thus offer a possibility to test such contamination of interstellar material.

• Even though it is always much easier to destroy deuterium than to fabricate it in astrophysical systems, several processes that led to production of deuterium have been mentioned. Note that Epstein, Lattimer & Schramm (1976) showed that no realistic astrophysical system could produce deuterium by nuclosynthesis or spallation mechanisms, without, in the latter case, overproducing Li. However, photodisintegration of $^4$He can lead to production of deuterium, as exemplified by Boyd, Ferland & Schramm (1989). These authors showed that $\gamma$-ray sources associated with e.g., galactic centers and/or AGNs, could photo-disintegrate $^4$He and lead to significant production of, among others, deuterium. However, the radius of influence of such processes is usually very small; in the above case, it was found to be $\sim 10$ light years. This plus the rarity of $\gamma$-ray sources in the Galaxy, makes the contamination of interstellar abundances unlikely.

Jedamzik & Fuller (1997) have studied the possibility of photo-disintegrating $^4$He with high-redshift $\gamma$-ray bursts, and conclude that this is highly improbable due to the small radius of influence $\sim 10$ pc, a result similar to that of Boyd, Ferland & Schramm (1989). Nonetheless, Cassé & Vangioni-Flam (1998; 1999) have argued that blazars could actually influence absorbers in a significant way if the absorber is a blob of matter expelled by the central engine. Interestingly, they predict as a generic signature of photo-disintegration that odd to even atomic number element ratios should be super-solar, notably the N/O ratio. They also argue that creation as well as destruction of deuterium can occur, depending on the $\gamma$-ray spectrum.

• Jedamzik & Fuller (1995, 1997) have pointed out that primordial isocurvature baryon fluctuations on mass scales $\leq 10^5 - 10^6 M_\odot$ could produce variations by a factor 10 on these scales, and variations of order unity on galactic mass scales $\sim 10^{10} - 10^{12} M_\odot$. However, this attractive and original scenario would
not apply to $(D/H)_{\text{ISM}}$ ratios on very small spatial scales $\sim 10$ pc.

- Finally, Mullan & Linsky (1999) have argued that production of deuterium in stellar flares, by radiative capture of a proton by a free neutron, can produce a non-negligible source of non-primordial deuterium in the ISM, and possibly explain the observed variations. However, detailed estimates are still lacking for this scenario.

Finally, one should note that the above mechanisms do not agree as to whether D should be enhanced or depleted with respect to H, if any of them operates. Therefore, one cannot conclude which one of the observed interstellar abundances, if any, is more representative of a cosmic abundance that would result solely from Big-Bang production followed by star formation.

## 6 Discussion

The next question that comes to mind is the following: taking for granted that variations in the $(D/H)_{\text{ISM}}$ ratio exist, do we expect to see a similar effect in QSO absorption line systems, and if yes, how would it affect the estimate of the primordial abundance of deuterium?

To be brief, we do not know the answer to this question, mainly because the nature and the physical environment of absorption systems at high redshift may be very different from that of interstellar clouds in the solar neighborhood, and because we do not know the origin of the variation of the $(D/H)_{\text{ISM}}$ ratio.

The $(D/H)_{\text{ISM}}$ ratio is measured in interstellar clouds that typically show: $N(\text{H} I) \sim 10^{18}$ cm$^{-2}$, $n_H \sim 0.1$ cm$^{-3}$, ionization $n_{\text{HII}} \sim n_{\text{HII}}$, $T \sim 10^4$ K, size $L \sim 1$ pc, and mass $M \sim 10^{-2} M_\odot$. Although the Lyman limit systems have a similar column densities, their physical characteristics may be very different. One opinion is that these systems are associated with extended gaseous haloes, as one often finds a galaxy at the redshift of the absorber with an impact parameter $R \sim 30 h^{-1}$ kpc (Bergeron & Boissé 1991; Steidel 1993). However, it is not known whether this absorption is continuous and extends on scales $\sim R$, or whether the absorption is due to discrete clouds sufficiently clustered on the scale $\sim R$ to produce absorption with probability $\approx 1$. In particular, York et al. (1986) and Yanny & York (1992) have suggested that QSO Lyman $\alpha$ absorption (not necessarily Lyman limit systems) occur in clustered dwarf galaxies undergoing merging. In this case, one expects the absorbers to be much like galactic clouds, in particular, of small spatial extent. It is also usually believed that the QSO UV background is responsible for the ionization properties of these absorbers, in which case one typically derives low densities $n_H \sim 10^{-3}$ cm$^{-3}$, which translates into large masses $\sim 10^8 M_\odot$ (plus or minus a few orders of magnitude) if the clouds have a large radius $\sim 30$ kpc. However, there are other models for the ionization of these Lyman limit systems. For instance, Viegas & Friaça (1995) have proposed a model where Lyman limit systems originate in galactic haloes, have
sizes \(\sim\) few kpc, hydrogen densities \(n_H \sim 10^{-1}\), and the ionization results from the surrounding hot gas. Lyman limit systems are shrouded in mystery.

Despite these large uncertainties, one can establish a few interesting points. First, the depletion of deuterium by contamination of low mass stellar ejecta has been ruled out by Jedamzik & Fuller (1997). Indeed, the QSO absorbers where D has been detected have been shown to be very metal-poor. The metallicity inferred, typically \([C/H] \leq -2.0\), implies that no more than 1% of the gas been cycled through stars. We note that Timmes et al. (1997) suggest that the incomplete mixing and the smallness of the QSO beam could introduce non-negligible variations in \((D/H)_{\text{QSO}}\) ratios.

Differential radiation pressure could affect measured \((D/H)_{\text{QSO}}\) ratios if Lyman limit systems are discrete clouds, and their radius is not too large. Indeed, the primary requirement of the model of Vidal-Madjar et al. (1978) and Bruston et al. (1981), is that the radiation flux be anisotropic, and for maximum efficiency, that the line of sight cross the absorber perpendicularly to the direction of the radiation flux. As it turns out, QSO absorbers chosen for measurements of D/H ratios fulfil these criteria. In effect, these systems are selected for D/H studies if their line of sight is as trivial as possible. This means that the absorber has to be isolated, which, in geometrical terms means, for a spherical distribution, that it has to lie on the boundary. If the radiation flux arises from the central part of the spherical system, it is anisotropic on a cloud at the boundary, and moreover, the line of sight is effectively perpendicular to the flux impinging on the cloud; otherwise, one would expect multiple absorbers on the line of sight. Following Bruston et al. (1981), the diffusion velocity of deuterium atoms is: \(v_D \sim 1\,\text{pc}\,\text{Myr}^{-1}\Phi^{-1/2}_{-6} n^{-1}_{-1} T^{-1/2}_4\), for \(\Phi_{-6}\) in units of \(10^{-6}\) photons/cm\(^2\)/s/Hz, \(n_{-1}\) total density in units of \(0.1\) atoms.cm\(^{-3}\), and \(T_4\) in units of \(10^4\) K.

In the case of the York et al. (1986) model, one expects a radiation flux corresponding to \(\sim 10^2 - 10^4\) O stars, impinging on a cloud located \(\sim 1\) kpc from the center of the dwarf galaxy. This gives a diffusion velocity \(v_D \sim 0.02 - 2\) pc/Myr. Diffusion, hence segregation, can thus occur over scales of \(\sim 1\) pc, a typical cloud size, as the relevant timescale is the crossing time \(\sim 20\) Myr for a cloud circulation velocity \(\sim 50\) km/s. However, for the model developed by Viegas & Friaça (1995), the typical diffusion distance for deuterium atoms is \(\sim 1 - 10\) pc, for a flux \(\Phi_{-6} \sim 0.01 - 0.1\), sustained on a star formation timescale \(\sim 10^8\) yrs. This distance is small compared to the modeled cloud size \(\sim\) few kpc, and one thus does not expect segregation of deuterium.

Although the above numbers are very qualitative, mainly because of the uncertainties inherent to our knowledge of Lyman limit systems, one cannot rule out an effect of anisotropic radiation. It is actually interesting that the criteria according to which Lyman limit systems are chosen for D/H studies, coincide with those for a maximum effect of radiation pressure. In moderately ionized and small sized \((\sim 1 - 10\) pc\) regions, the deuterium abundance could be depleted by a factor 2.

Finally, we note that, whatever the right value of the primordial deuterium abun-
Figure 1: Deuterium abundance measurements. The different D/H evaluations are shown as a function of time (for $\Omega_0 = 1$, $q_0 = 0.5$, $H_0 = 50$ km/s/Mpc). The primordial measurements plotted (QSO) are from Burles & Tytler (1998a,b) and Songaila (1997) [high redshifts] and from Webb et al. (1997) and Tytler et al. (1999) [moderate redshift]. Pre-solar values plotted (SS) are from Gautier & Morel (1997) [solar wind] and Lellouch et al. (1997), Ben Jaffel et al. (1997) and Mahaffy et al. (1998) [Jupiter]. Interstellar values (ISM) plotted are the ones from Linsky et al. (1995) [Capella], Piskunov et al. (1997) [HR 1099], Vidal-Madar et al. (1998) [G191-B2B] and Jenkins et al. (1999) [$\delta$ Ori].

...dance, that is, either low $\sim 3.5 \times 10^{-5}$, or high $\sim 10^{-4}$, there is satisfying agreement with both Big-Bang nucleosynthesis and the predictions of other light elements abundances, and with chemical evolution and the interstellar abundances of deuterium. See, e.g., Schramm & Turner (1998) for a discussion of the agreement of a low (D/H)$_{QSO}$ with primordial $^4$He determinations (and statistical errors), and primordial $^7$Li, and its cosmological implications. High deuterium abundances are known to provide very good agreement with BBN predictions for $^4$He and $^7$Li. Although they predict significant astration of deuterium: $(D/H)_{QSO}/(D/H)_{ISM} \sim 5 - 10$, it is also known there exist viable chemical evolution models able to account for such a large destruction (e.g. Vangioni-Flam & Cassé 1995; Timmes et al. (1997); Scully et al. 1997).

7 Conclusion

The different D/H evaluations reviewed or presented here are shown in Fig. 1, as a function of (approximate) time. This figure seems to reveal a trend of decreasing deuterium abundance with time, predicted as early as 1971 (Truran & Cameron 1971). However, if one looks more closely at Fig. 1, there are discrepancies between different evaluations of deuterium abundances at similar cosmic time, which, as we have
argued in the case of ISM measurements, cannot be always accounted for in terms of measurements systematics.

Nevertheless, the trend indicated in Fig. 1 seems to show that we are converging toward a reasonable (at least understandable) picture of the cosmic history of deuterium, or Deuteronomy, in Dave Schramm’s own terms.

We have the hope that FUSE, scheduled for launch in early 1999, will sharpen this picture, and fill in the gaps to construct a curve of evolution of the abundance of deuterium vs time/metallicity. The FUSE Science Team intends to conduct a comprehensive study of the deuterium abundance in the Galaxy through Lyman series absorption of D\textsc{i} between 912 and 1187 Å. Access to a suite of lines in the series provides much stronger constraints on \(N(\text{D}\textsc{i})\) and \(N(\text{H}\textsc{i})\) than single line (\emph{i.e.}, Lyman \(\alpha\)) observations alone. The bandpass also contains a large number of lines of O\textsc{i}, N\textsc{i}, and Fe\textsc{ii} that can be used to trace the metallicity and dust content of the absorbers studied.

The primary goal of the FUSE D/H program is to link the destruction of deuterium to the physical and chemical properties of the interstellar gas. This objective is critical to successful galactic chemical evolution models since astration of deuterium, metal production, and mixing/recycling of the ISM are key ingredients in the models. FUSE observations of D/H in environments with different chemical histories will help to reveal the effectiveness of astration and its dependence upon environmental factors (\emph{e.g.} metallicity, star-formation). A study of regional variations may reveal evidence that supports the proposal about the differential effect of radiation pressure. Finally, D/H measurements in regions of low metallicity will be particularly important benchmarks for relating the high redshift D/H values to present epoch values.

FUSE will be capable of observing deuterium in distant gas clouds beyond the solar neighborhood clouds explored by \textit{Copernicus}, HST, and IMAPS. Therefore, it should be possible to search for large scale variations in D/H related to global star formation and metal gradients, as well as small scale variations in selected regions due to incomplete mixing of the interstellar gas or deuterium decrements in the ejecta of stars.

FUSE, together with HST-STIS and IMAPS, should thus give access to more precise D/H evaluations and should greatly clarify the problem of the chemical evolution of deuterium, and hence much better constrain our understanding of the primordial D/H value.

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