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What the D/O ratio tells us about the interstellar abundance of deuterium?

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Abstract. The ionization balances for HI, OI and DI being locked together by charge exchange, the deuterium-to-oxygen ratio is considered to be a good proxy for the deuterium-to-hydrogen ratio, in particular within the interstellar medium. As the DI and OI column densities are of similar orders of magnitude for a given sight line, comparisons of the two values are generally less subject to systematic errors than comparisons of DI and HI. Moreover, D/O is additionally sensitive to astration, because as stars destroy deuterium, they should produce oxygen. D/O measurements are now available for tens of lines of sight in the interstellar medium, most of them from *FUSE* observations. The D/H and D/O ratios show different pictures, D/H being clearly more dispersed than D/O. The low, homogeneous D/O ratio measured on distant lines of sight suggests a deuterium abundance representative of the present epoch that is about two times lower than this measured within the local interstellar medium.

Keywords. ISM: abundances; Galaxy: abundances; cosmology: cosmological parameters; ultraviolet: ISM

1. Introduction

In the Big Bang standard model, deuterium is produced in significant amounts only during the Big Bang nucleosynthesis. Among the elements created in BBN, the abundance of deuterium is the most sensitive to the baryonic density of the Universe. As deuterium is destroyed in stellar interiors, its abundance D/H is expected to continuously decrease, from its primordial value $(D/H)_{prim}$ to the value characteristic of the present epoch, $(D/H)_{PE}$. This $(D/H)_{PE}$ ratio is measured within the interstellar medium and should be characteristic of cosmic material after ~ 14 Gyrs of Galactic evolution.

$(D/H)_{PE}$ is a key ratio. It serves as a reference baseline for $(D/H)_{prim}$, providing a lower limit for $(D/H)_{prim}$. It also yields important constraints for chemical evolution models of the Galaxy. The depletion factor due to astration, $f_{ev} = (D/H)_{prim} / (D/H)_{PE}$, depends on the star formation and infall rates, and possibly other processes such as early Galactic wind. Models predict values around $f_{ev} \simeq 1.5$ (e.g. Chiappini *et al.* 2002). In addition, $(D/H)_{PE}$ can be studied more thoroughly than the other deuterium abundances, because it is measured in the interstellar medium. Several tens of sight lines suitable for high quality deuterium abundance measurements are available, and potentially, small sample size should not be an issue.

The determination of the canonical value of $(D/H)_{PE}$ has been the subject of considerable debate over the years. Numerous measurements have been performed through Lyman absorption-line observations in the far-ultraviolet spectral range. By observing hydrogen and deuterium directly in their atomic form, they provide accurate column density determinations that are not dependent on ionization or chemical fractionation. Among them, the ratio $D/H = 1.6 \times 10^{-5}$ measured toward Capella (Linsky *et al.* 1995) has often been used as a benchmark of $(D/H)_{ISM}$. Although it has been performed in a particular cloud, namely the Local Interstellar Cloud (Lallement & Bertin 1992), it has been taken as the canonical $(D/H)_{PE}$ value by numerous theoretical studies of the chemical evolution of the Galaxy. However, several lines of sight observed with *Copernicus* revealed values outside this range (see, e.g., Laurent *et al.* 1979; York 1983). It was uncertain whether the dispersion was the signature of spatial variations in $(D/H)_{ISM}$, or due to unknown systematic errors. The *FUSE* mission has brought significant progress on these issues. Tens of targets observed with *FUSE* have allowed D/H and D/O ratios to be measured in the the interstellar medium.

2. D/O as a proxy for D/H

One of the challenges of D/H measurements is to evaluate for the same line of sight the HI and DI column densities, N(HI) and N(DI), which differ by about five orders of magnitude. Such a large difference is a potential source of systematic errors. For example, all lines from the same species may lie on the non-linear part of the curve of growth, or HI column densities may be detectable in clouds for which DI are below the detection limit (see, e.g., Linsky & Wood 1996, Lemoine *et al.* 2002, or Vidal-Madjar & Ferlet 2002).

Many of the difficulties associated with obtaining accurate D/H ratios may be avoided by measuring the deuterium-to-oxygen ratio, D/O (Timmes *et al.* 1997, Hébrard & Moos 2003). First of all, the D/O ratio is of order of a few percent rather than $\sim 10^{-5}$ as for D/H. Many OI and DI transitions with different oscillator strengths are present in the *FUSE* bandpass, allowing measurement of N(OI) and N(DI) over a wide range of values. OI is believed to be a good tracer of HI in the nearby Galactic disk (Meyer et al. 2001; André *et al.* 2003; Cartledge *et al.* 2004). The neutral forms of oxygen and hydrogen likely dominate over their ions for many sight lines in the diffuse interstellar medium. In any case, because both species have nearly the same ionization potential, their ionization balances are strongly coupled to each other by charge exchange reactions (Jenkins *et al.* 2000). Thus, no corrections from ionization models are required, and we can use $N(\mathrm{DI})/N(\mathrm{OI})$ for D/O. Finally, D/O is particularly sensitive to stellar activity, because of both deuterium destruction (deuterium is burned in stellar interiors at temperatures as low as 6×10^6 K) and oxygen production (oxygen is mainly produced by type II supernovae). Hence, spatial variations of the deuterium abundance due to different astration rates at different locations would translate in even higher D/O spatial variations.

3. Deuterium within the Local Bubble

The first published *FUSE* $(D/H)_{ISM}$ results focussed on the local interstellar medium (e.g. Moos *et al.* 2002; Friedman *et al.* 2002; Hébrard *et al.* 2002; Lemoine *et al.* 2002; Sonneborn *et al.* 2002). These early studies have shown that $(D/H)_{ISM}$ likely presents a single value in the Local Bubble. Oliveira *et al.* (2003) reported $(D/H)_{LB} = (1.52 \pm 0.07) \times 10^{-5}$ from *FUSE* data only. Wood *et al.* (2004) included previous LB measurements, and reported $(D/H)_{LB} = (1.56 \pm 0.04) \times 10^{-5}$. The Local Bubble is a $\sim$ 100 pc-size low-density cavity which includes the LIC in which the Solar System is embedded, and other interstellar clouds (e.g. Snowden *et al.* 1998). The spectral resolution of *FUSE* is too low to distinguish these different individual clouds. However, as the $(D/H)_{ISM}$ integrated along the studied sight lines show no variations, it seems secure to conclude that the different clouds probed within the LB present an homogeneous $(D/H)_{ISM}$ ratio.

The homogeneity of the deuterium abundance in the different interstellar clouds within the LB was also shown from *FUSE* D/O measurements (Hébrard & Moos 2003). D/O was found to be constant within the Local Bubble, with the averaged value $(D/O)_{LB} =$

$(3.84{\pm}0.16){\times}10^{-2}$ (see Figure 1, left panel). This homogeneity of $(D/O)_{LB}$ argues against variations of D/H in the LB. Indeed, the only possible way for a stable D/O together with a varying D/H would be for D/H and O/H to be correlated. Moreover, they would have to precisely vary in such a way that D/O remains constant. That seems unlikely for two different reasons: (i) O/H appears to be uniform in the interstellar medium over paths of several hundred parsecs (Meyer *et al.* 2001; André *et al.* 2003; Cartledge *et al.* 2004), and (ii) astration processes should lead to an anti-correlation of DI and OI abundances.

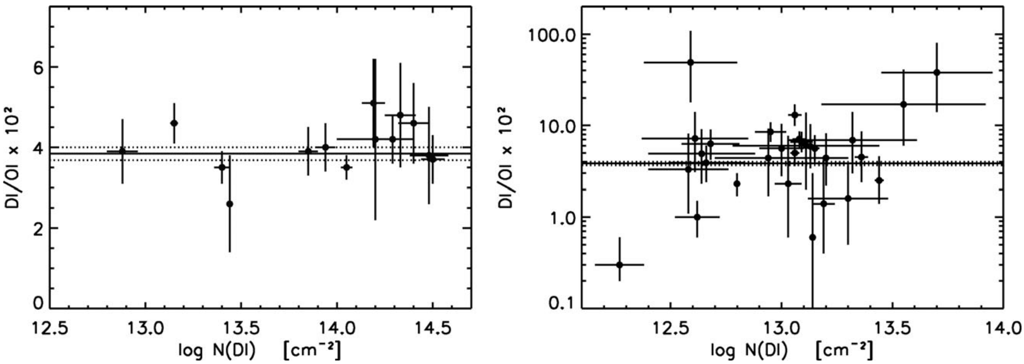

Figure 1. D/O in the Local Bubble from *FUSE* (left) and HST (right) measurements.

Using the interstellar O/H ratio from Meyer (2001), the $(D/O)_{LB}$ ratio translates into $(D/H)_{LB} = (1.32{\pm}0.08){\times}10^{-5}$. According to the error bars, this result is $2.5\,\sigma$ lower than the direct $(D/H)_{LB}$ measurement reported above, which is significant. The explantion is unlikely to be due to the O/H used to translate D/O into D/H, as Oliveira *et al.* (2005) found a $(O/H)_{LB}$ ratio in good agreement with the O/H ratio measured in more distant interstellar medium by Meyer (2001). Whatever is the explanation, the homogeneity of the local D/O measurements implies that the spatial variations of D/H in the Local Bubble must be extremely small, if any (Hébrard & Moos 2003).

It seems now that the homogeneity of the deuterium abundance within the Local Bubble has reached consensus. One can note however the N(DI) and N(OI) measurements reported within 100 pc by Redfield & Linsky (2004), using HST data. The corresponding D/O ratios are plotted in Figure 1 (right panel). A wide dispersion appears of about 2 orders of magnitude. Apparently, the *FUSE* and HST studies produce opposite conclusions. It is unlikely that a malicious systematic effect disturbs the *FUSE* measurements in a way that erases actual variations. More probably, the HST measurements are perturbed in a random way by uncontroled systematics. The probable cause is the N(OI) measurements, performed with the λ1302Å saturated transition in the HST spectra, whereas N(OI) is measured from unsaturated lines in the *FUSE* bandpass. Hébrard *et al.* (2005) and Friedman *et al.* (2006) have shown examples of systematic effects on column densities due to saturated lines.

4. Deuterium in the distant interstellar medium

Whatever the true $(D/H)_{LB}$ is, 1.32×10^{-5} or 1.56×10^{-5}, it now appears clear that this ratio should not be considered as a canonical value for $(D/H)_{ISM}$. $(D/H)_{LB}$ is not representative of the cosmic material at the present epoch. Indeed, in addition to the early *Copernicus* results reported above, *FUSE* has provided extra clues for a significant dispersion in $(D/H)_{ISM}$ beyond the Local Bubble (Friedman *et al.* 2002; Hoopes

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et al. 2003; Wood *et al.* 2004; Williger *et al.* 2005; Hébrard *et al.* 2005; Friedman *et al.* 2006; Oliveira & Hébrard 2006; Oliveira *et al.* 2006; Dupuis *et al.* 2009). It is difficult to decide which one of the different values is representative of the present epoch, and even if a canonical value for $(D/H)_{ISM}$ does exist. There is certainly no reason to preferentially adopt $(D/H)_{LB}$.

If a $(D/H)_{ISM}$ canonical value exists, the best way to determine it might be to measure deuterium along the long lines of sight with high column densities. More material is probed, and thus localized anomalies are likely to be averaged out. Following that approach, Hébrard & Moos (2003) reported a trend mainly based on D/O: the deuterium abundance is lower for the most distant lines of sight and the highest column densities. This trend was reinforced since then by the additional *FUSE* results, as shown on the left panel of Figure 2. This figure plots the lines of sight from Hébrard & Moos (2003) and all the subsequent *FUSE* measurement published after and quoted above. It does not include the HST measurements presented in Redfield & Linsky (2004). On this plot, the local D/O is homogeneous; the distant D/O is also homogeneous, but with a value about two times lower. There are just two lines of sight with high D/O (Oliveira *et al.* 2006), but the OI column density is here possibly affected by saturation, as shown in the cases discussed in Hébrard *et al.* (2005) and Friedmand *et al.* (2006).

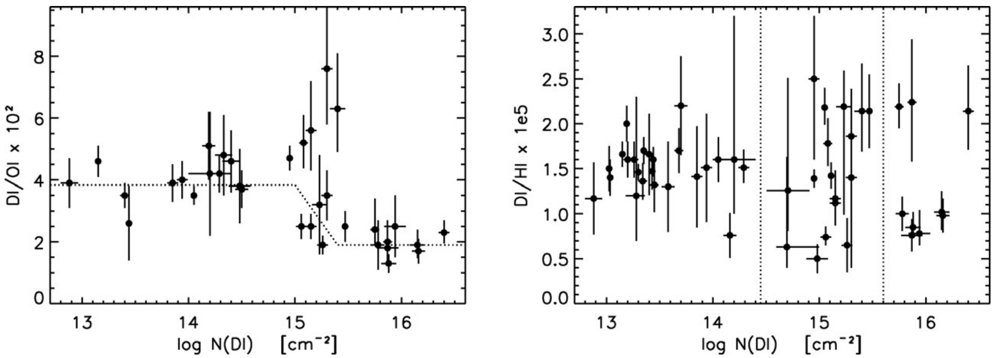

Figure 2. D/O and D/H as a function of DI column density.

This trend could suggest that the local deuterium abundance might be abnormally high, whereas the actual value of $(D/H)_{PE}$ may be significantly below 1×10^{-5} (Hébrard & Moos 2003). On the other hand, following an idea proposed by Jura (1982) and updated by Draine (2004; 2005), Wood *et al.* (2004) argued that deuterium can be preferentially depleted onto dust grains. This would imply total $(D/H)_{ISM}$ ratios larger than those measured in the gas phase, and a $(D/H)_{PE}$ value significantly larger than 2×10^{-5}. Thus, presently, two possibilities are proposed for the present-epoch deuterium abundance.

5. Two scenarios for $(D/H)_{PE}$

If deuterium is significantly depleted onto dust grains, $(D/H)_{PE}$ can only be measured in interstellar clouds in which all deuterium has been released in the gas phase by recent shocks. Assuming this is the case for the few high $(D/H)_{ISM}$ values measured to date, Linsky & Wood (2004) claimed $(D/H)_{PE} = (2.3 \pm 0.4) \times 10^{-5}$. Following this idea, this value was updated to $(D/H)_{PE} \geqslant (2.3 \pm 0.2) \times 10^{-5}$ by Linsky *et al.* (2006), and to a similar vaue $(D/H)_{PE} \geqslant (2.0 \pm 0.1) \times 10^{-5}$ using a Bayesian approach by Prodanovic *et al.* (2009). According to this scenario, lower D/H ratios are found for the sight lines which probe primarily interstellar clouds that have not been recently shocked. That may explain the three D/H regimes apparently seen by Linsky *et al.* (2006). Locally, the D/H is homogeneous but lower than $(\mathrm{D/H})_{\mathrm{PE}}$ because the Local Bubble has been shocked recently, but not recently enough, so that part of the deuterium has been incorporated in the solid phase. At intermediate column densities, D/H shows variations, depending on the nature of the clouds, which may or may not have been shocked. Thirdly, at the largest column densities, deuterium is on average significantly depleted in the interstellar clouds probed, except for a few recently shocked clouds.

However, this third regime presenting an homogeneous, low D/H was not confirmed by subsequent *FUSE* measurements. This is shown in right panel of Figure 2, which includes all the measurements available now. The two vertical lines show the limits of the three regimes, as presented in Linsky *et al.* (2006). Rather than a 3-regime picture, this plot shows an homogeneous D/H ratio locally, and an increasing dispersion together with the increasing column density.

Moreover, the D/O measurements are difficult to fit with the depletion scenario. Indeed, D/H and D/O measurements are presently available for 9 distant targets (i.e. clearly outside the Local Bubble): HD 195965 and HD 191877 (Hoopes *et al.* 2003), LSS 1274 (Hébrard & Moos 2003; Wood *et al.* 2004), JL 9 (Wood *et al.* 2004), PG 0038+199 (Williger *et al.* 2005), HD 90087 (Hébrard *et al.* 2005), LSE 44 (Friedman *et al.* 2006), HD 41161 and HD 53975 (Oliveira & Hébrard 2006). The χ^2 are 35.8 for D/H and 5.9 for D/O, for 8 degrees of freedom. Thus, D/O measurements show less dispersion than D/H. Here again, it is difficult to guess a malicious effect able to erase actual variations in the deuterium abundance. In fact, the D/O measurements suggest a different scenario than the “depletion” hypothesis. In Figure 2 (left panel), D/O is homogeneous, with values near 3.8×10^{-2} for $\log N(\mathrm{DI}) \leqslant 15$, i.e. in the Local Bubble, and is homogeneous with about two times lower value for $\log N(\mathrm{DI}) \geqslant 15.5$. The intermediate region ($15 \leqslant \log N(\mathrm{DI}) \leqslant 15.5$) appears more as a transition between these two different plateaus than a particular regime in itself. The lines of sight showing high D/H show low D/O (Williger *et al.* 2005; Friedman *et al.* 2006; Oliveira & Hébrard 2006).

The values of D/O for sight lines to distant targets are homogeneous, around $(2.0 \pm 0.5) \times 10^{-2}$. Because these lines of sight probe large amounts of material, this ratio may be characteristic of the present epoch. If so, it would imply $(\mathrm{D/H})_{\mathrm{PE}} = (7 \pm 2) \times 10^{-6}$. Then, the reason for a high local D/H value is uncertain; the possibility of unknown deuterium enrichment process(es) or local infall of less evolved material must be considered. One can note that Cartledge *et al.* (2004) invoked local infall to possibly explain their O/H measurements.

6. Conclusions

The “depletion argument” and the “D/O argument” lead to two different values for $(\mathrm{D/H})_{\mathrm{PE}}$: $\sim 2.3 \times 10^{-5}$ and $\sim 7 \times 10^{-6}$, respectively. As shown in Figure 3, the high $(\mathrm{D/H})_{\mathrm{PE}}$ would imply a low deuterium destruction through astration, even possibly no destruction at all. Conversely, the low $(\mathrm{D/H})_{\mathrm{PE}}$ would imply larger depletion factors f_{ev}, especially in the latest stages of the Universe evolution.

It appears clearly that the local value 1.5×10^{-5} should no longer be considered as a canonical value for $(\mathrm{D/H})_{\mathrm{PE}}$. Up to now, neither the “depletion” nor the “D/O” hypothesis (or both of them) can be firmly ruled out. Their is no hope of extra deuterium measurements in the distant interstellar medium, as *FUSE* now stopped operations. In addition, it won’t be possible to probe deuterium on column densities larger than those detected with *FUSE*, as the denser ones are at the limit where unsaturated deuterium

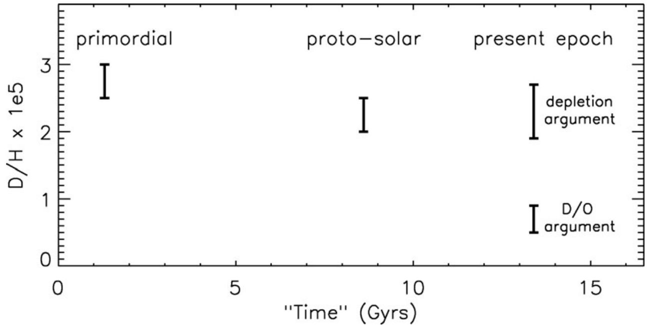

Figure 3. Deuterium abundance as a function of time after BBN.

lines are detectable. Additional deuterium measurements are thus unlikely to provide new constraints on this issue for a while.

References

André, M. K., Oliveira, C. M., Howk, J. C., *et al.* 2003, ApJ, 591, 1000
Cartledge, S., Lauroesch, J. , Meyer, D., & Sofia, U. 2004, ApJ, 613, 1037
Chiappini, C., Renda, A., & Matteucci, F. 2002, A&A, 395, 789
Dupuis, J., Hébrard, G., Oliveira, C., Moos, H. W., & Sonnentrucker, P., 2009, ApJ, 690, 1045
Friedman, S. D., Howk, J. C., Chayer, P., *et al.* 2002, ApJS, 140, 37
Friedman, S. D., Hébrard, G., Tripp, T. M., *et al.* 2006, ApJ, 638, 847
Hébrard, G., Lemoine, M., Vidal-Madjar, A., *et al.* 2002, ApJS, 140, 103
Hébrard, G. & Moos, H. W. 2003, ApJ, 599, 297
Hébrard, G., Tripp, T. M., Chayer, P., *et al.* 2005, ApJ, 635, 1136
Hoopes, C. G., Sembach, K. R., Hébrard, G., *et al.* 2003, ApJ, 586, 1094
Lallement, R. & Bertin, P. 1992, A&A, 266, 479
Laurent, C., Vidal-Madjar, A., & York, D. G. 1979, ApJ, 229, 923
Lemoine, M., Vidal-Madjar, A., Hébrard, G., *et al.* 2002, ApJS, 140, 67
Linsky, J. L., Diplas, A., Wood, B. E., *et al.* 1995, ApJ, 451, 335
Linsky, J. L. & Wood, B. E. 1996, ApJ, 463, 254
Linsky, J. L., Draine, B. T., Moos, H. W., *et al.*, 2006, ApJ, 647, 1106
Meyer, D. M. 2001, XVIIth IAP Colloquium, Paris, Edited by R. Ferlet *et al.*, p. 135
Moos, H. W., Sembach, K. R., Vidal-Madjar, A., *et al.* 2002, ApJS, 140, 3
Oliveira, C. M., Hébrard, G., Howk, J. C., *et al.* 2003, ApJ, 587, 235
Oliveira, C. M. & Hébrard, G., 2006, ApJ, 653, 345
Oliveira, C. M., Moos, H. W., Chayer, P., & Kruk, J. W. 2006, ApJ, 642, 283
Prodanovic, T., Steigman, G., & Fields, B. D. 2009, arXiv:0910.4961
Redfield, S. & Linsky, J. L. 2004, ApJ, 602, 776
Snowden, S. L., Egger, R., Finkbeiner, D. P., *et al.* 1998, ApJ, 493, 715
Sonneborn, G., André, M., Oliveira, C., *et al.* 2002, ApJS, 140, 51
Timmes, F. X., Truran, J. W., Lauroesch, J. T., & York, D. G. 1997, ApJ, 476, 464
Vidal-Madjar, A. & Ferlet, R. 2002, ApJ, 571, L169
Williger, G., Oliveira, C., Hébrard, G., Dupuis, J., Dreizler, S., & Moos, H. W. 2005, ApJ 625, 210
Wood, B. E., Linsky, J. L., Hébrard, G., *et al.* 2004, ApJ, 609, 838
York, D. G. 1983, ApJ, 264, 172

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