astro-ph/9612020
Invited talk at the *HST User's Meeting*
Baltimore, Sept.12-13, 1996

Deuterium abundance and cosmology

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Abstract. We review the status of the measurements of the deuterium abundance from the local interstellar medium to the solar system and high redshifts absorbers toward quasars. We present preliminary results toward a white dwarf and a QSO. We conclude that the deuterium evolution from the Big Bang to now is still not properly understood.

1 Introduction

It is well accepted that deuterium is only produced in significant amount during primordial nucleosynthesis (BBN, see e.g. the proceedings of the ESO Symposium *The Light Element Abundances*, 1995, Crane Ed., Springer). Moreover, D is thoroughly destroyed in stellar interiors. Hence, any abundance of deuterium measured at any metallicity should provide a lower limit to the primordial deuterium abundance. Deuterium is thus a key element in cosmology and in galactic chemical evolution (see e.g. Audouze & Tinsley 1976; Gautier & Owen 1983; Vidal-Madjar & Gry 1984; Boesgaard & Steigman 1985; Olive et al. 1990; Pagel 1992; Vangioni-Flam & Cassé 1994; Prantzos 1996). Indeed, its primordial abundance is the best tracer of the baryonic density parameter of the Universe Ω_B, and the decrease of its abundance along the galactic evolution should trace the amount of star formation (among others).

The first, although indirect, measurement of the deuterium abundance of astrophysical significance was carried out through ^{3}He evaluation in the solar wind, leading to D/H$\simeq 2.5\pm1.0\times10^{-5}$ (Geiss & Reeves 1972), a value representative of 4.5 Gyrs ago. The first measurements of the interstellar D/H ratio, representative of the present epoch, were reported shortly thereafter (Rogerson & York 1973). Their value of D/H$\simeq 1.4 \pm 0.2 \times 10^{-5}$ has since then nearly not changed, whatever the availability of adequate instrumentation was. For more than a decade, these interstellar abundances have been used to constrain BBN in a direct way.

However, abundances measured at lower metallicities are less contaminated by the effect of galactic evolution. This is the reason why the deuterium abundance is now being chased in high redshift absorbers on quasar lines of sight: the composition of these clouds of very low metallicity should reflect the actual primordial deuterium value.

In the following, we discuss the different measurements of the deuterium abundance, following an anti-chronological order: in the ISM, in the pre-solar nebula, and in high redshift absorbers. We conclude eventually that many aspects of the evolution of deuterium in the Universe are yet unknown.

2 Interstellar observations

There are several methods to measure the interstellar abundance of deuterium (see Vidal-Madjar 1991, Ferlet 1992). One of them is to observe deuterated molecules such as HD, DCN, *etc*... and to form the ratio of the deuterated molecule column density to its non-deuterated counterpart (H_2, 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, and that, as a consequence, this method cannot provide a precise estimate of the true interstellar D/H ratio; rather, this method is used in conjunction with estimates of the interstellar D/H ratio to gather information on the chemistry of the ISM.

Another way to derive the D/H ratio comes through radio observations of the hyperfine line of D I at 92cm. The detection of this line is however extremely difficult, and no firm detection has ever been reported. The detection of this line would allow 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$\leq 2.1 \times 10^{-6}$ 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 in stellar processing).

Finally, the only way to derive a reliable estimate of the interstellar D/H ratio is to observe the atomic transitions of D and H of the Lyman series in the far-UV, in absorption in the local ISM against the background continuum of cool or hot stars. These observations have been performed using the Copernicus and the IUE satellites, and now the Hubble Space Telescope. Both types of target stars present pros and cons.

2.1 Cool stars

The main advantage of observing cool stars is that they can be selected in the vicinity of the Sun. This results in low H I column densities, and "trivial" to nearly "trivial" lines of sight. In effect, due to the low atomic weight of H I and D I, to the D I–H I -82km/s isotopic shift, and to the abundance of H I in the local medium, the D I line cannot be detected at Lyman α in the wing of the H I line for H I column densities larger than 10^{19} cm^{-2}. Also, the presence of several interstellar components with different b-values may imply a large error on the H I column density if these components are unresolved. For this reason, deriving the H I column density has always been the limiting factor of accurate D/H ratios measurements. Note that the spectral resolutions of Copernicus and IUE were respectively 15 and 30 km s^{-1}, and, as a consequence, a non-trivial line of sight, even in the local ISM, would generally go unresolved. Eventhough HST–GHRS now offers a spectral resolution of 3.5 km s^{-1}, the thermal width of the D I line in the local ISM is $\simeq 8$ km s^{-1}, so that one has to observe lines of heavier species (thinner lines) to fully use the resolving power of HST, and build up a coherent line of sight velocity structure. This is one of the first difficulties inherent to the "cool stars" approach: the detailed structure of the line of sight could be found only through the observation of the FeII and the MgII ions, which are unfortunately present in both HI and HII regions and thus may not trace properly the HI gas. In particular, species like NI and OI could not be observed (see below).

Moreover, the chromospheric Lyman α emission line has to be modeled to set the continuum for the interstellar absorption. Such a procedure necessarily introduces systematic errors.

Nevertheless, this method has provided the most precise measurement of the local D/H ratio in the direction of Capella, using HST–GHRS: $(\mathrm{D/H})_{\alpha Aur} = 1.60 \pm 0.09^{+0.05}_{-0.10} \times 10^{-5}$ (Linsky et al. 1993, 1995), assuming no systematics.

In that unique case, the possible systematics due to the chromospheric line profile are probably well reduced because the observations of that spectroscopic binary were made at two different phases of the system when the two stellar chromospheric lines were placed very differently in the velocity space owing to the stars motion within the system. The result is that very different and independent observations were consistent with only one interstellar absorption and two chromospheric line profiles simply shifted from one epoch to the other. Capella is also unique in the local ISM by revealing apparently a simple line of sight with a single component. If true, although this could always be debated (see below), the confidence in the column densities evaluation could be relatively high.

Several more cool stars have been observed with HST since then (Linsky et al. 1995: Capella, Procyon; Linsky & Wood 1996: α Cen A, α Cen B; Piskunov et al. 1996: HR 1099, 31 Com, β Cet, β Cas; Dring et al. 1997: α Tri, ϵ Eri, σ Gem, β Gem). Although all compatible with the Capella evaluation, none of these results is precise enough to place any new constraints on this evaluation.

2.2 Hot stars

Hot stars are unfortunately located further away from the Sun, so that one always has to face a high HI column density and often a non-trivial line of sight structure. In these cases, DI could not be detected at Lyα, and one has to observe higher order lines, *e.g.* Lyγ, Lyδ, Lyϵ; hence these measurements have primarily come through Copernicus observations. The stellar continuum is however smooth at the location of the interstellar absorption and, moreover, the NI triplet at 1200 Å as well as other NI lines are available to probe the velocity structure of the line of sight. In particular, NI and OI were shown to be excellent tracers of HI in the ISM (Ferlet 1981; York et al. 1983). The interstellar void identified in the direction to hot stars in the Canis Majoris tunnel (Gry et al. 1995) has allowed HST observations of DI at Lyα, but no further constraints have resulted so far.

2.3 Present status

All published D/H ratios are collected in fig. 1, distinguishing hot stars from cool stars observations (all references except Allen et al. 1992 can be found in Vidal-Madjar 1991, Ferlet 1992; note that the most recent cool stars estimations from HST are not included). The D/H ratios range from $\sim 5 \times 10^{-6}$ to $\sim 4 \times 10^{-5}$. A large scatter is clearly detected in fig. 1 and represents differences of the D/H ratio in the local ISM, that may be as large as a factor $\simeq 4$ over scales as small as a few parsecs. The essential question is: do these variations really exist?

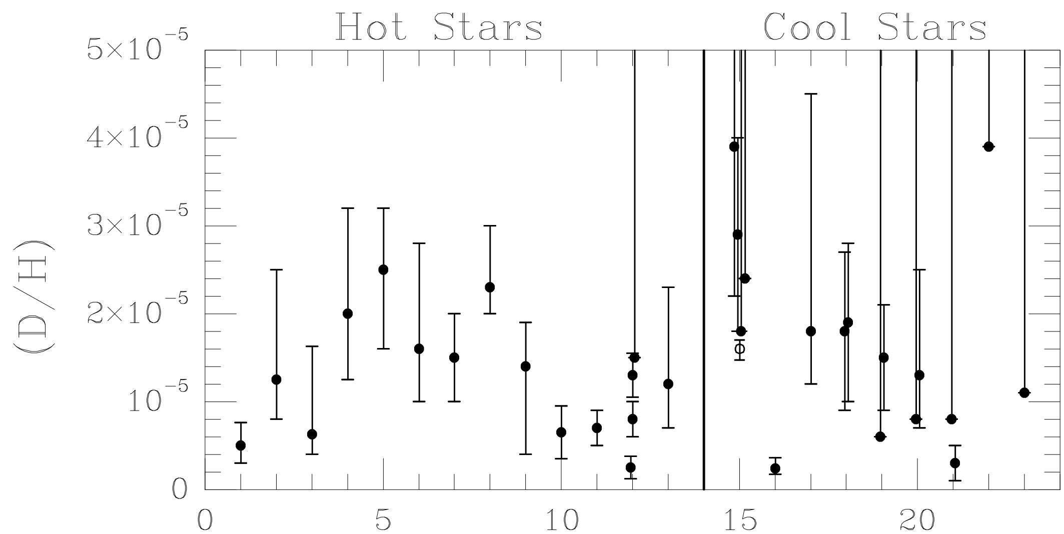

Figure 1: Measurements of the D/H ratio in the local ISM. The left hand-side box collects data obtained toward hot stars, while the right hand-side one shows cool stars observations. The x-axis has no physical significance, and merely labels the different stars. Data points next to each other, within less than 1 x-axis unit, correspond to the same target star. The open circle represents the Linsky et al. (1993, 1995) measurement using HST toward Capella. All other data points come from Copernicus or IUE observations.

Unfortunately, one cannot answer this question and at the same time be perfectly objective. On one hand, note that the Linsky et al. (1993, 1995) measurement does not agree with any of the previous D/H measurements toward Capella. However, one cannot ignore this measurement of unprecedented quality. On the other hand, one could use the observed scatter between different measurements toward a same star to get a rough estimate of the systematics; such an estimate does not seem to be able to account for the large scatter of fig. 1 for all the other stars. Finally, it could be tempting – but also very arbitrary – to claim that the systematics associated with IUE and Copernicus observations are large, that they account for the observed discrepancies, and that only the Linsky et al. (1993, 1995) value should be kept. Although undoubtedly of great quality, the Capella measurement comes through the modeling of the chromospheric emission line of an unresolved binary system and the detection of only one absorbing component on the line of sight, through MgII and FeII observations. As mentioned above, it could well be that HI media, shifted from the Local Cloud by a few km s^{-1} went unnoticed in MgII and FeII although they would play an important role in the HI saturated profile. Such systematics were not considered by Linsky et al. (1993, 1995).

To answer to the reliability of the observations shown in fig. 1, one has to re-analyze all these data in a consistent way, looking for possible undetected systematics. One has to recall as an example that time variations of the D/H ratio have already been reported toward ϵ Per (Gry et al. 1983), which were interpreted as due to the ejection of high velocity hydrogen atoms from the star. This perturbation can only enhance the D/H ratio. It is worth noting that in at least four cases the D/H ratio was found to be really low: $0.7 \pm 0.2 \times 10^{-5}$ and $0.65 \pm 0.3 \times 10^{-5}$ toward δ and ϵ Ori (Laurent et al. 1979); $0.8 \pm 0.2 \times 10^{-5}$ toward λ Sco (York 1983) and $0.5 \pm 0.3 \times 10^{-5}$ toward θ Car (Allen et al. 1992). In each cases, authors discussed in details possible systematics but concluded that none of the identified ones could explained these low nearby ISM D/H values.

Finally, note that various explanations to these possible fluctuations of the D/H ratio have been put forward as early as Vidal-Madjar et al. (1978), Bruston et al. (1981) as a selective radiation pressure effect. More recently, even the very possibility of measuring the D/H ratio was questionned as a consequence of possible stochastic velocity fields with finite correlation lengths in the interstellar medium (Levshakov et al. 1996). The consequence could be that any evaluation made through line profile analysis assuming Voigt profiles, can lead to very different evaluations of the D/H ratio for a unique assumed one. This has been discussed by Jenkins (1996) who shows that with a sample of lines presenting different oscillator stengths, it is possible to evaluate correctly the column densities whatever the velocity distribution of the cloud is. Such a situation is fortunately often the case in the Copernicus studies of the D/H ratio. This is however a long-standing problem.

To try to make some progress, we have inaugurated the use of a new type of targets that should solve many of the intrinsic difficulties of the problem, namely nearby white dwarfs.

2.4 Actual prospects

Observing white dwarfs has many advantages. Such targets can be chosen near to the Sun, circumventing the main disadvantage of hot stars, and they can also be chosen in the high temperature range, so as to provide a smooth stellar profile at Lyα. At the same time, the NI triplet at 1200Å as well as the OI line at 1302Å would be available, allowing thus an accurate sampling of the line of sight. Such observations have now been conducted using HST toward two white dwarfs: G191–B2B (Lemoine et al. 1996; Vidal-Madjar et al. 1997) and Hz43 (Landsman et al. 1996).

In the case of Hz43, the structure of the line of sight appears trivial at a first glance, *i.e.* it only consists of the Local Cloud. The D/H ratio as well as the HI column density are consistent, in the single-cloud hypothesis, with those of the Local Cloud obtained by Linsky et al. (1993, 1995). However, due to the relative faintness of this target, the NI triplet was observed at medium resolution only, and other interstellar components cannot be ruled out as of now. Obviously this target looks very promising, providing these first observations be complemented with higher resolution, higher signal-to-noise ratio data.

In the case of G191–B2B, data were obtained in Cycles 1 and 5 at high resolution ($\simeq$3.3 km s^{-1}) for Lyα, NI 1200Å, OI 1302Å, SiII 1304Å, MgII 2800Å, FeII 2343Å and SiIII 1206Å. The line of sight velocity structure coherent in all these lines (about 15, including thoses observed at lower resolution) comprises one HI region – the Local Cloud observed toward Capella – together with two HII regions; we refer to these components as blue, white and red, according to their positions along the wavelength scale. Both HII regions are clearly seen in SiIII, but their presence is also felt in strong lines such as HI Lyα and OI 1302Å. The analysis in terms of column densities is still underway, but it seems already clear that the column density ratio of the blue to the red component varies from ion to ion. In particular, if the D/H ratio for the red component common to the G191–B2B and Capella sight-lines (these stars are separated by only 8^o on the sky) is forced to be that found by Linsky et al. (1993, 1995), then the D/H ratio for the blue component appears significantly lower.

In fig. 2 are superposed the G191–B2B spectra obtained at the highest resolution of Ech-A of the GHRS, all plotted in velocity space to allow an easy comparison of the different absorption features. In both NI and SiII lines, at least two components are obviously present. However, only one of them (at about +9 km s^{-1}, dotted line) is detected in the SiIII line (the feature near +29 km s^{-1} is stellar), while a third component close to +13 km s^{-1} is needed to fit the SiIII line. The existence of this third component is further confirmed in the OI line in order to deepen enough the OI absorption feature between both NI and SiII components. Freezing then the velociy separations and *b*-values, it is possible to fit the DI line. The stricking result is that the D/H ratio varies by at least a factor of three between the two extreme blue and red components, which are better constrained. If one assumes that D/H is 1.6×10^{-5} in the red component (which corresponds to the Capella one), a value certainly compatible with the total HI content on that line of sight and with the known NI abundance (Ferlet 1981), then the D/H ratio in the blue component has to be of the order of 5.5×10^{-6}. Furthermore, if one considers that OI is a better tracer of the HI and DI gas than NI because of its nearly identical ionization potential, then the D/H ratio in the blue component should be even lower!

It is interesting to note that again D/H values clearly below 10^{-5} seem to be required by the observations, suggesting again real D/H variations in the local ISM. We have revealed a contamination of the HI interstellar absorption toward G191–B2B by residuals atoms of neutral hydrogen from two HII regions. It is not unlikely that this effect is also present in other lines of sight, in particular toward Capella. The observation of the whole Lyman series, possible with the FUSE mission planned in 1998, will allow to better evaluate this effect. New HST–GHRS observations toward another white dwarf are presently underway.

3 The D/H evaluations in the solar system

The pre-solar value for the deuterium abundance has traditionally been derived from meteorites and lunar soil: D/H=$2.6\pm1.0 \times 10^{-5}$ (Geiss 1993). The giant planets Jupiter and Saturn are considered to be undisturbed deuterium reservoirs, free from production or losses processes, preserving the abundance of their light elements since the formation of the solar system 4.5 billion years ago (Owen et al. 1986). The first measurements of the D/H ratio in the Jovian atmosphere have been performed through methane and its deuterated counterpart CH_3D yielding D/H=$5.1\pm2.2\times10^{-5}$ (Beer & Taylor 1973). Abundant molecules like H_2 were also used yielding lower values: D/H=$2.1\pm0.4\times10^{-5}$ (Trauger et al. 1973). More recent molecular measurements, also model-dependent, gives D/H=$2.5\pm0.7 \times 10^{-5}$ (Gautier & Owen 1983).

Recently, new important measurements of the D/H ratio implying very different methods were carried out. One is based on the far infrared ISO observation of the HD molecule in Jupiter (Encrenaz et al. 1996) and leads to D/H=$2.2\pm0.5 \times 10^{-5}$, although some systematics are suspected. Another is based on the direct observation with HST–GHRS of both HI and DI

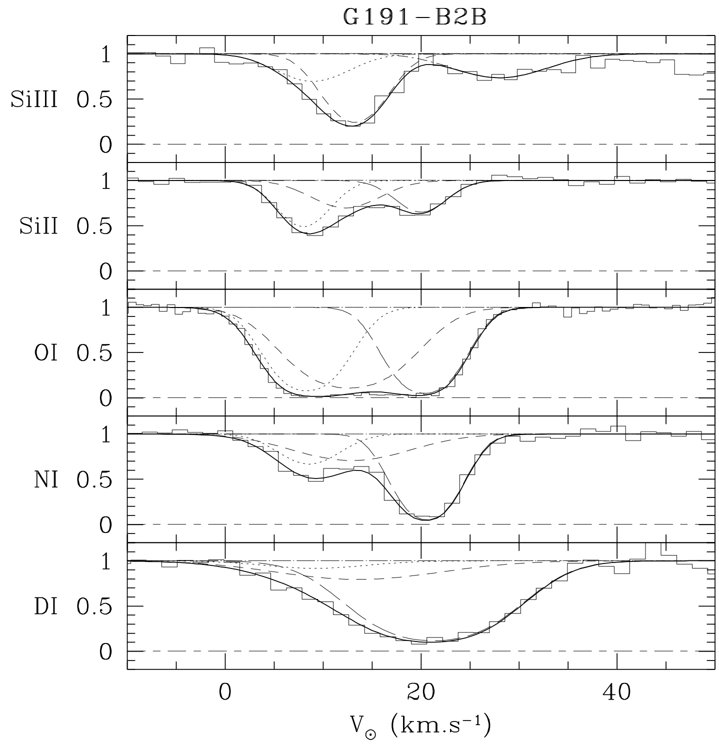

Figure 2: Are superposed in velocity space the absorption features seen in the different species indicated on the left hand side of the figure. Two obvious components are seen in SiII and NI. However, a third component in between the two others is imposed by the SiIII and OI lines. The two components at the shortest wavelengths, seen in SiIII, are HII regions, while the component at ∼20 km s^{-1} is the Local Cloud, an HI region. It is clear that the D/H ratio cannot be the same in the red and the blue component (see text). Also, it is obvious that deducing lines of sight velocity structure for D/H evaluations from ionized species could be extremely misleading.

Lyman α emission at the limb of Jupiter for the first time (Ben Jaffel et al. 1994, 1996). The last one is an in situ measurement with a mass spectrometer onboard the Galileo probe (Niemann et al. 1996). These two latter yield similar ratios: $5.9\pm1.4\times10^{-5}$ and $5.0\pm2.0\times10^{-5}$ respectively.

These last values are higher than the meteoritic one (Geiss 1993) and the other Jovian ones (see e.g. Bjoraker et al. 1986) by $\sim 2\sigma$. That may call to a reconsideration of the pre-solar abundance of deuterium since systematics may be inherent to each observational approach (see e.g. Lecluse et al. 1996).

4 Lines of sight toward QSOs

4.1 Observations

A very promising approach to evaluate the D/H ratio was initiated a few years ago by observing directly with large ground based telescopes the Lyman lines redshifted in the visible part of the spectrum (see e.g. Carswell et al. 1987; Webb et al. 1991). These lines are seen in absorption in QSOs spectra produced by the absorption of HI gas present in the intergalactic medium in front of the QSOs. The most favorable case for detection of deuterium is provided in Lyman limit systems, whose HI column densities typically range between $\sim 10^{16} - 10^{19}$ cm^{-2} and HI b-values are > 15 km s^{-1}. The mass and size of these clouds are essentially unknown by several orders of magnitudes.

The very interesting point of this approach is that one may probe directly a primordial cloud (*i.e.* a very low metallicity system), and thus have direct access to the primordial D/H value. On the other hand, the difficulty is twofold: *i)* the relative faintness of the sources renders these observations very difficult; *ii)* the number of absorbers per unit redshift and per unit column density increases with decreasing column density, so that there is always the possibility that the observed deuterium feature would be in fact a mimicking low-column density HI absorber. The advent of very large telescopes can at least partly overcome the first point. Space-based UV telescopes, such as HST, offer the possibility of observing absorbers at low redshift, where the probability of contamination is greatly reduced. Note as well that there is a large scatter of metallicity with redshift, so that there are many low-redshift absorber candidates that are truly metal-poor (see Timmes et al. 1996). Thus, one can hope that a large number of measurements of the deuterium abundance in distant extragalactic objects, using both types of instrumentation, will yield its primordial abundance.

As for today, the different reported estimations are summarized in table 1. For high redshift QSOs absorption systems, they are obtained from observations with the 10m Keck1 or the 4m Kitt Peak telescopes; for the lower redshift system, data are from HST. Most were made with typical spectral resolutions of 8 km s^{-1} and signal-to-noise ratios at the DI Lyα line which vary from ~ 10 to as high as ~ 75. Actually, only three detections of deuterium rather than upper limits are claimed, in complete disagreement with each other (1σ random error in table 1), giving either a high ($\sim 2 \times 10^{-4}$, Rugers & Hogan 1996a, 1996b) or a low ($\sim 2.5 \times 10^{-5}$, Tytler et al. 1996) D/H ratio.

The generic method employed in these studies is as follows. Metal lines such as CIV, SiIV, MgII are used to determine the velocity structure in the redshift region where DI is being chased. Taking this velocity structure into account, all the Lyman series up to the Lyman limit and the limit itself are then fitted for estimating the HI column density and b(HI). In general, the high order lines yield an estimate of b, while the Lyman limit yields an estimate of N(HI); if damping wings are present in Lyα, they give also strong constraints on N(HI). But one has to recall that again the usual limiting factor in determining the D/H ratio is the evaluation of N(HI). Whenever D is detected at Lyα, the estimate of D/H is rather secure if all the above steps have been successfully completed *i.e.* the velocity structure is in good agreement between the metal lines and the HI lines, b and N(HI) have been accurately determined.

Although there is always the possibility that the DI line be in fact an HI interloper, the actual DI detections were claimed on the basis of the following arguments. It is known (or believed) that the distribution of b-values in Lyman limit systems shows a cut-off around (and

Table 1: D/H measurements in absorption systems toward QSOs.

QSO	z_{abs}	D/H	Ref.
Q0014+8118	3.320	$\leq 2.5 \times 10^{-4}$	1,2
Q0014+8118	3.320	$1.9 \pm 0.5 \times 10^{-4}$	3
Q1009+2956	2.504	$2.5 \pm 0.5 \times 10^{-5}$	4
Q1937−1009	3.572	$2.3 \pm 0.3 \times 10^{-5}$	5
Q1202−0725	4.672	$\leq 1.5 \times 10^{-4}$	6
Q0420−3851	3.086	$> 2. \times 10^{-5}$	7
Q1937−1009	3.572	$> 4. \times 10^{-5}$	8
Q0454−2203	0.482	$< 1. \times 10^{-5}$	9

Ref. 1 Songaila et al. 1994; 2 Carswell et al. 1994; 3 Rugers & Hogan 1996; 4 Burles & Tytler 1996; 5 Tytler et al. 1996; 6 Wampler et al. 1996; 7 Carswell et al. 1996; 8 Songaila et al. 1996; 9 Webb et al. 1997.

below) $b \sim 15$ km s^{-1}. In the three claimed detections, the b-value for the DI line was found in the order of ~ 10 km s^{-1}, with b(DI)/b(HI)$\sim 1/\sqrt{2}$ which corresponds to a pure thermal case. Moreover, the probability for interloping was estimated to be $< 0.1\%$.

Three caveats can at least be identified in this type of analysis, the magnitude of which are yet unknown. First, as already metionned, ionized metal species do not trace correctly the HI gas. Hence, one should imagine that the redshift of HI absorbers do not match those derived from metal lines (see a stricking example of such a situation in figure 3). Furthermore, there could be substantial substructure in these HI clouds, with no hope of tracing them from either HI or ionized metal lines. An interesting study would be to observe these clouds at higher resolution ($<$ 8km s^{-1}) in OI (NI is not expected to be detectable in these very metal-poor clouds). Second, the estimate of N(HI) from the Lyman limit is not reliable if the residual flux below the limit is uncertain, or is contaminated by instrumental noise (Songaila et al. 1996). Third, the asumption of Voigt profiles in the analysis could be extremely misleading as suggested by Levshakov & Takahara (1996), particularly in the case of QSOs for which the number of available absorption metallic lines is greatly reduced.

To increase the general confusion toward what should be considered as **the** primordial D/H value, a 2σ upper limit D/H$< 1. \times 10^{-5}$ has been very recently set from HST observations of a z_{abs}=0.4823 absorber (Webb et al. 1997; table 1). These data were gathered in Cycles 5 and 6 at $\Delta\lambda \sim 16$ km s^{-1}, and signal-to-noise ratios $\sim 5-8$. They cover the Lyman limit, Lyϵ, Lyδ, Lyγ, Lyα, SiIII; further ground-based observations of MgII were collected at the Cerro Tololo International Observatory; see figure 3. The generic method outlined above was followed to derive D/H, although no MgII is seen in the system. Deuterium is not detected at Lyα. But the position of the HI absorber at Lyα is accurately known from the other lines, and precludes any deuterium absorption, whence the strong limit. This result could nevertheless be modified if substructure were present (this study is underway).

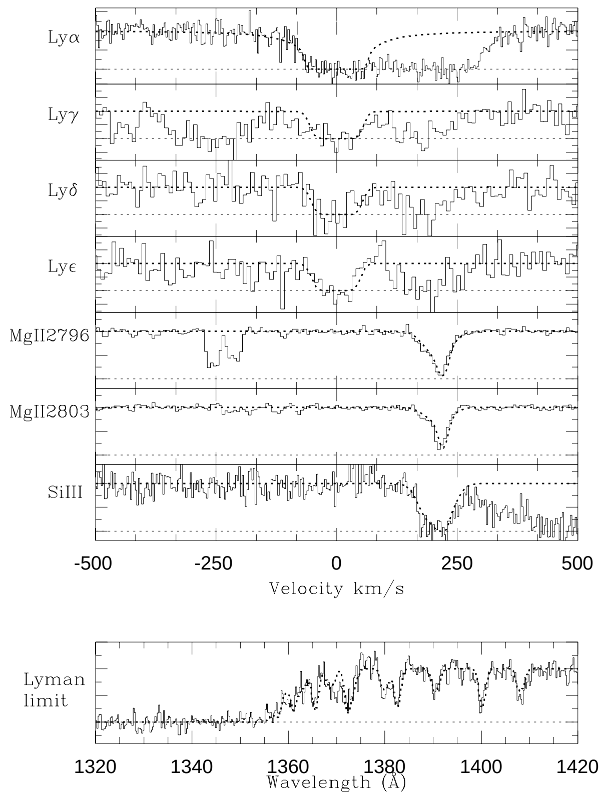

Figure 3: Exemples of spectra of the z=0.482264, z=0.483036, and z=0.483304 absorbers toward Q0454-2203, observed with HST–GHRS and FOS at Lyα, Lyγ, Lyδ, Lyϵ, Ly limit, and SiIII; the MgII spectrum was collected at CTIO. The system at 0 km s^{-1} is the one in which D/H has been evaluated to be $< 1. \times 10^{-5}$. Contrary to the other more complex system at about +200 km s^{-1}, it is not seen in either MgII nor SiIII and thus presents a low metallicity (<1/100 solar).

4.2 Who's wrong, who's right?

If the result of Webb et al. (1997) is observationally confirmed toward some other QSOs, then there will be definitely something rotten in some remote kingdom... No model of chemical evolution is able to account for an increase of the deuterium abundance with metallicity. In that situation, we will thus have to assume either the distribution of cosmic deuterium is strongly inhomogeneous, or such a low value is the result of a strong contamination by deuterium-poor gas. However, it is not so easy to deplete deuterium without producing metals, although a particular configuration of the line of sight aiming through a stellar wind contaminated region could do the job. A remote possibility is to produce significant amount of deuterium in some still unknown astrophysical site... Keeping these remarks in mind, let us discard this result from the following discussion, because too perturbing!

We now assume that Tytler et al. (1996) is right, *i.e.* the primordial deuterium abundance is low, $\sim 2.5 \times 10^{-5}$ as prefered by Hata et al. (1996). It is then easy to argue that the high deuterium abundances sometimes measured are due to interlopers, eventhough their expected small probability of occurence, eventhough the claimed detected signature of D I b-value. In order to match a low primordial deuterium abundance with other light elements, one would have to accomodate either large systematics in the determination of the primordial ^{4}He mass fraction, or, equivalently, further light degrees of freedom (equivalent to neutrino flavors) at BBN. The reader is refered to Copi et al. (1996a) for a discussion of this point. The ensuing chemical evolution of deuterium would be rather straightforward, possibly involving infall to avoid too much deuterium destruction.

Let now assume that Tytler et al. (1996) is wrong, *i.e.* the high values of D/H are the correct primordial ones. Although in excellent agreement with the primordial abundances of ^{7}Li and ^{4}He (Cardall & Fuller 1996), such high values would lead to several other problems. The implied low baryonic density parameter Ω_B would strengthen the so-called "baryon cluster catastrophy". The chemical evolution of deuterium would be quite difficult to account for, as it would require an astration factor ~ 15 over ~ 10Gyrs when standard models destroy D by no more than a factor ~ 3. Moreover, most models already overproduce ^{3}He after 10Gyrs of evolution. Since D is converted to ^{3}He in stellar interiors, a high D/H ratio would make this situation worse. However, Scully et al. (1996) have developped a promising new model which could resolve these problems.

Finally, let put everyone right and happy. The deuterium abundance seen in one absorber or the other, or both, could have been strongly affected by some unknown mechanism (e.g. Timmes et al 1996; Jedamzik & Fuller 1996). However there is, up to now, no compelling mechanism able to reconcile the observed values. As well and after all, there might not be a unique primordial deuterium abundance. For instance, the presence of isocurvature baryon fluctuations at BBN would affect the yields differently in different regions. However, it seems that Copi et al. (1996b) and Jedamzik & Fuller (1996) do not quite agree on wether or not such fluctuations of an amplitude and a scale large enough to explain the variations of D/H at high redshifts can be made compatible with the high degree of isotropy of the Cosmic Microwave Background (CMB).

Last, the remaining possibility is that no one is right (Levshakov & Takahara 1996). For sure, that would be fun and will ask for many more observations!

5 Conclusion

The previous discussion is very well summarized in figure 4. The different – and discordant – D/H evaluations are shown as a function of time, with no a priori bias to select one over another. Some of the differences are too large to be accounted for. It is clear that all measurements cannot be correct and some still unknown systematics should be identified. Certainly each one will find its preferred value in each domain, but our impression is that for the moment we are far from having understood the whole story.

As a matter of fact, if the variations of the D/H ratio in the local interstellar medium are illusory, then one could quote as an average of the published values: $(D/H)_{ISM} \simeq 1.3 \pm 0.4 \times 10^{-5}$. The rather large error bar arises from a subjective although conservative viewpoint. On the

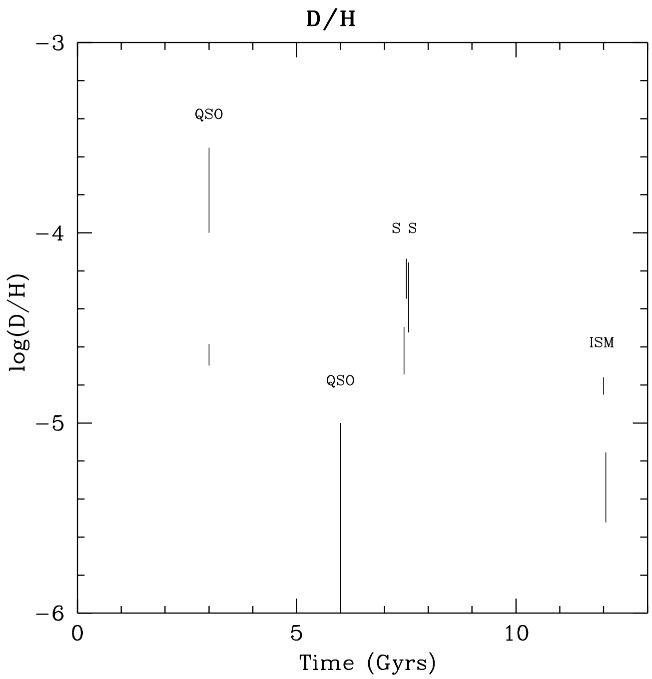

Figure 4: The different D/H evaluations are shown approximately as a function of the epochs in the Universe when they are relevant. All the scatter is not shown but merely the main trends. For the ISM, the Capella value along with possible significant low values; in the solar system, the standard and recent values; for the QSOs, the most extreme cases at high redshifts and the only measurement at lower redshift.

contrary, if D/H does vary in the ISM, one has to understand why; until then, *no measurement of the D/H ratio in the ISM or the IGM should be quoted as reliable.* Moreover, one should expect these variations to be larger in reality. The actual value might in fact be very different from what is observed if these variations are systematic, *i.e.* act in one way only; this in turn would heavily bear on the chemical evolution of deuterium. It also appears that the upper bound on Ω_B is obtained from BBN predictions through the interstellar abundance of deuterium: this bound would have to be removed until the variations and their cause are properly understood.

There is a hope that the FUSE mission will solve these problems from 1998. It will probe the ISM further than the local medium, up to extragalactic low-redshift objects. It will look for gradients of the deuterium abundance with galactocentric distance and with galactic height in the halo. These dedicated studies with FUSE should greatly clarify the problem of the chemical evolution of deuterium.

In other words, when some important observable is evaluated:

One measurement is nice

Few measurements are a crisis

Many more measurements could be fun

Acknowledgments. The study of the interstellar D/H ratio toward white dwarves with HST has been initiated by A.V-M and R.F. Subsequently, several French and US collaborators were included. M.L. acknowledges support by the NASA, DoE, and NSF at the University of Chicago. We thank C. Copi, D. Schramm, J. Truran, M. Turner and D. York for useful discussions.

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