DEUTERIUM WITH FUSE

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Deuterium abundance measurements allow constraints to be put on the Big Bang Nucleosynthesis, the baryonic content of the Universe, and the chemical evolution of galaxies. Such measurements in a variety of astrophysical environments are one of the main objectives of the Far Ultraviolet Spectroscopic Explorer (*FUSE*) mission. The first results are presented here. Beside a tentative detection in Jupiter, deuterium absorption lines are seen toward a few extragalactic targets and tens of interstellar sight lines. In the local interstellar medium (within 100 pc), it is likely that the D/H and D/O ratios have both a single value. They may present spatial variations beyond the Local Bubble.

1 Introduction

Deuterium is believed to be produced in appreciable quantities only in primordial Big Bang nucleosynthesis (Reeves et al. 1973) and destroyed in stellar interiors (*e.g.*, Epstein et al. 1976); it is thus a key element in cosmology and in galactic chemical evolution (see *e.g.* Vangioni-Flam & Cassé 1995; Prantzos 1996). The primordial abundance of deuterium is one of the best probes of $\Omega_B h^2$, the baryonic density of the Universe divided by the critical density. The abundance of deuterium (D/H, measured by number in comparison with hydrogen) is expected to decline during Galactic evolution at a rate that is a function of the star formation rate; standard models predict a factor of 2 to 3 decrease in the deuterium abundance in 15 Gyrs (see *e.g.*, Galli et al. 1995; Tosi et al. 1998). Hence, any abundance of deuterium measured at any metallicity should provide a lower limit to the primordial deuterium abundance.

Three samples of D/H measurements may be performed, each representative of a given epoch, at look-back times of ~14 Gyrs (in primordial intergalactic clouds, $(D/H)_{prim}$), 4.5 Gyrs (protosolar, $(D/H)_{pre\odot}$), and 0.0 Gyrs (interstellar medium, $(D/H)_{ISM}$). These deuterium abundance measurements allow constraints to be put on Big Bang Nucleosynthesis and Galactic chemical evolution (Fig. 1). Although the evolution of the deuterium abundance seems to be qualitatively understood, measurements of D/H at similar redshifts show some dispersion and indicate that additional processes may be important in shaping the abundance of deuterium. That fact has led to the development of non-standard models, which propose, for example, larger astration factors (*e.g.*, Vangioni-Flam et al. 1994) or non-primordial deuterium production (see Lemoine et al. (1999) for a review).

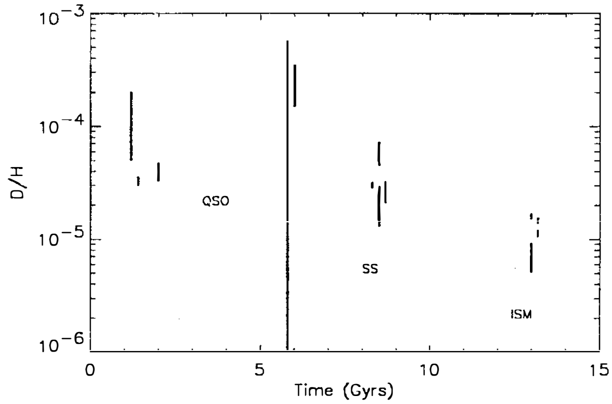

Figure 1: **Deuterium evolution.** $(D/H)_{prim}$ measurements in high and moderate z QSO absorbants, $(D/H)_{pre\odot}$ in the Solar System, and $(D/H)_{ISM}$ in the interstellar medium. This figure is taken from Lemoine et al. (1999).

The determination of the deuterium abundance in a variety of astrophysical environments is one of the main objectives of the Far Ultraviolet Spectroscopic Explorer (*FUSE*). The spectral resolution of *FUSE* is $\sim$15 km s^{-1} and its bandpass is 905-1187 Å. This spectral window is very rich in atomic (H I, D I, O I, N I...), ionic (O VI, Fe II, Si II...), and molecular transitions (H_2, HD, CO...). In the Lyman series of atomic H I and D I, the absorption of deuterium appears 82 km s^{-1} blueshifted from the corresponding H I absorption. Thus, *FUSE* provides a unique capability for observing all of the strong H I and D I Lyman series transitions, except Lyman α (λ 1216 Å).

FUSE is a mission developed for NASA by the Johns Hopkins University, in collaboration with the space agencies of Canada (CSA) and France (CNES), who share the observing time. The satellite was successfully launched on 1999 June 24. Cycle 1 of the observations started in December 1999 and Cycle 3 is currently on-going. Science observations temporarily ceased between December 2001 and February 2002 because of the failure of the second of four reaction wheels; the satellite was returned to full operations when the team developed a new guidance system. At the date of late April 2002, *FUSE* have performed more than 2000 different observations, including more than 1600 public ones (the proprietary period is 6 months for most of the spectra).

This review presents the first observations performed by *FUSE* as part of the deuterium program, together with the first results concerning the interstellar D I. Details of the *FUSE* instrument and on-orbit performance have been given by Moos et al. (2000) and Sahnow et al. (2000). More information on *FUSE* is available on the web at `http://fuse.pha.jhu.edu`.

2 Primordial abundance

Measurements of the D/H ratio in low-metallicity intergalactic absorbers on lines of sight to distant quasars offer direct access to the primordial abundance of deuterium. Through the latest years, few measurements of $(D/H)_{prim}$ were performed in high redshifts ($z > 2.5$) absorbers using large ground-based telescopes (see Burles (2002) in this issue).

Snapshot Surveys were performed by *FUSE* with short observations of several tens of AGNs and QSOs to check far ultraviolet flux levels and suitability of the objects as background continuum sources for extended integrations. The goal was to select few targets for measurements of the D/H ratio in high velocity halo clouds and low redshift ($z < 0.3$) absorption systems.

Few Lyman limit systems and high velocity clouds with D I detections have been identified. The *FUSE* long-time exposures are currently analysed through profile fitting and equivalent widths, together with HST and radio complementary observations. High spectral resolution HST data are mandatory for these sight lines which present multi-components structures. The first D/H measurements obtained are slightly higher than the measurements related to the interstellar medium (see Section 4) but the uncertainties are still being worked out.

3 Pre-solar abundance

This *FUSE* program focus on determining the $(D/H)_{pre\odot}$ ratio in Jupiter. The Jovian D/H problem can be tackled three ways: (1), from deuterium and hydrogen emissions at the planetary limb, at Lyman α with HST or at Lyman β with *FUSE*; (2), from CH_3D and CH_4 molecular observations; (3), from HD and H_2 observations, in the *ISO* or *FUSE* wavelength ranges or from *in situ* Galileo measurements. The same atmospheric models should provide the same D/H ratio regardless the technique used. The *FUSE* Solar System Team is working on such models, which should provide a reference value for the D/H ratio at the time the solar system was formed, 4.5 Gyrs ago.

Up to now, D I at the Jupiter limb has been tentatively detected with *FUSE*. From several planetary limb pointings, a weak emission feature is seen on the blue wing of the H I brightening, at the position predicted for D I. The signal is however perturbed by the backround geocoronal and Io torus effects. Thorough analysis of these parasite signals should be performed before claiming a D I detection at Lyman β.

4 Interstellar abundance

The interstellar medium is the astrophysical site that has allowed the most comprehensive investigations of deuterium abundances. This is also the site for the first *FUSE* results.

Prior to *FUSE*, deuterium has been observed in the interstellar medium using different methods: radio measurements of its 92 cm hyperfine transition (Blitz & Heiles 1987; Chengalur et al. 1997), observations of deuterated molecules (Lubowich et al. 2000; Caux et al. 2002), Balmer series analyses (Hébrard et al. 2000, O'Dell et al. 2001), and Lyman series absorption (Ferlet et al. 1996; Linsky 1998). The most accurate measurements are obtained through Lyman absorption-line observations in the far-ultraviolet (far-UV) spectral range; by observing hydrogen and deuterium directly in their atomic form, far-UV Lyman series absorption-line measurements provide accurate column density determinations that are not dependent on ionization or chemical fractionation effects. The first measurement of the $(D/H)_{ISM}$ ratio was reported by Rogerson & York (1973) toward β Cen, using *Copernicus*: $(D/H)_{ISM} = 1.4 \pm 0.2 \times 10^{-5}$. Since then, many other $(D/H)_{ISM}$ measurements have been performed using different instruments (*Copernicus*, *IUE*, *IMAPS*, *HST*) and the derived values show significant dispersion around the β Cen one.

For example, an average value $(D/H)_{ISM} = 1.50(\pm 0.10) \times 10^{-5}$ ($1\,\sigma$) has been derived for the Local Interstellar Cloud (Lallement & Bertin 1992) by Linsky (1998) from the comparison of 12 nearby sight lines, but several other lines of sight show values outside this range (*e.g.*, Laurent et al. 1979; York 1983; Allen et al. 1992; Vidal-Madjar et al. 1998; Hébrard et al. 1999; Jenkins et al. 1999; Sonneborn et al. 2000). This dispersion may result from spatial variations due to some unknown physical processes or underestimation of systematic errors. There is still considerable debate on this issue which final resolution may have implications for understanding the physics of the interstellar medium, as well as the chemical evolution of the Galaxy and the baryonic density of the Universe inferred from D/H measurements.

Several tens of targets were observed by *FUSE* within the local interstellar medium. These observations significantly increase the amount of lines of sight available for local deuterium abundance determinations. The goal is to determine to what extent the D/H ratio varies within a few hundred parsecs from the Sun.

D I absorptions lines are clearly detected in a large part of these observations, together with other species (O I, N I, FeII...). Results for 7 lines of sight (white dwarfs and sub-dwarfs) were recently published: Feige 110 (Friedman et al. 2001), WD 2211−495 (Hébrard et al. 2002), HZ43A (Kruk et al. 2002), WD 0621−376 (Lehner et al. 2002), G191−B2B (Lemoine et al. 2002), BD +28° 4211 (Sonneborn et al. 2002), and WD 1634−573 (Wood et al. 2002), with an overview by Moos et al. (2002). Several techniques were used to determine the column densities from the multiple interstellar absorption lines detected (Moos et al. 2002): profile fitting, single-component curves of growth fitted to the measured equivalent widths, and analysis of the apparent optical depths of the weak lines. The final results are the combination of the individual analyses which were performed in six different laboratories in USA and France. We have adopted results and errors that we believe are conservative and reliably account for both statistic and systematic uncertainties. Note that most of the *FUSE* H I lines from these targets lie on the flat part of the curve of growth; therefore, H I column densities were derived from archives Lyman α observations with HST or IUE.

The weighted mean of the D I/H I ratio for the five *FUSE* targets with reliable H I column densities is D/H$= 1.52\,(\pm 0.08) \times 10^{-5}$ $(1\,\sigma)$, without significant variation from one sight line to the other. Thus, the *FUSE* studies support the idea that the D/H ratio is constant out to a distance of about 100 pc. On Fig. 2, the *FUSE* results are plotted together with previous D/H measurements, from HST, IMAPS, or *Copernicus*. It is likely that D/H does present spatial variations beyond about 100 pc.

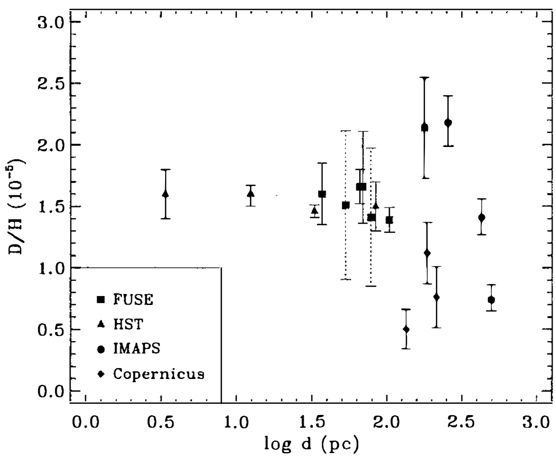

Figure 2: **D/H ratio vs. distance.** No significant variations appear at distances < 100 pc, but it is likely that there are variations at larger distances. This figure is taken from Moos et al. (2002); see that paper for references.

However, H I column density measurements from Lyman absorption lines fits have been proved to be subject to systematic errors due to the possible presence of broad, weak extra absorbing components (Linsky & Wood 1996; Lemoine et al. 2002; Vidal-Madjar & Ferlet 2002), presumably arising from the heliosphere. Indeed, one of the challenges of D/H measurements is to evaluate simultaneously H I and D I column densities, which differ by about 5 orders of magnitudes. This could lead to systematic errors due to the fact that all lines from the same species may lie on the non-linear part of the curve of growth, or that there may be clouds seen in H I but without D I detectable counterpart.

An alternative may be to use the D I/O I ratio as a proxy to D I/H I. Many of the difficulties inherent to D/H measurements could be avoided by measuring D/O (*e.g.* Timmes et al. 1997): indeed, the average D/O ratio in the ISM is ofthe order of a few percent, instead of a few 10^{-5} for D/H, and many O I absorption lines with different oscillator strengths are present in the *FUSE* bandpass. Furthermore, O I is believed to be a good tracer of H I in the Galactic disk (Meyer et al. 1998) since both species have nearly the same ionization potential (the ionization of H I, D I, and O I are locked together by high charge transfer; Jenkins et al. 2000); neutral forms of these species dominate over ionized states in the diffuse interstellar medium. Moreover, D/O is sensitive to astration, both from D destruction and O production.

For targets at distances lower than 100 pc, within the Local Bubble (Ferlet 1999), *FUSE* results show a constancy in the D/O ratio (Moos et al. 2002). A *FUSE* survey of D/O in the local interstellar medium by Hébrard et al. (2002) that includes additional sight lines also reaches the same conclusion (see Fig. 3), contrary to the bahaviour of the D I/N I ratio. The discrepancy probably arises from O I being a better tracer of H I than N I, because of ionization effects (Jenkins et al. 2000). The weighted mean of D/O and the standard deviation of the mean are $(D/O)_{LISM} = 3.84\,(\pm 0.17) \times 10^{-2}$.

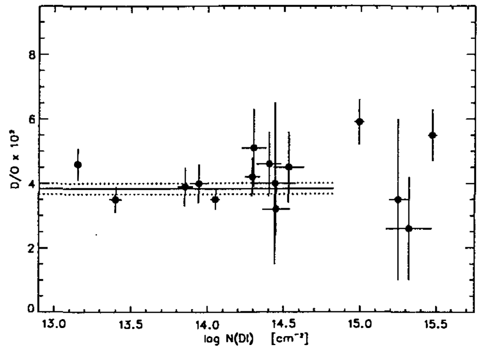

Figure 3: **D/O vs.** N**(D I).** The weighted mean of the 11 local values [$\log N(\mathrm{DI}) < 14.8$] is $(D/O)_{LISM} = 3.84\,(\pm 0.17) \times 10^{-2}$. All the plotted error bars are $1\,\sigma$.

The D/O constancy in the LISM agrees with that of $(D/H)_{LISM}$. Indeed, the only possibility to have both D/O stability and D/H variations would be that D/H and O/H vary precisely in the same way for D/O to remain constant. That seems unlikely since (i) O/H appears to be uniform in the ISM over paths of several hundreds parsecs (*e.g.* Meyer et al. 1998; André et al. 2002), and (ii) astration should lead to an anti-correlation of D I and O I abundances. The stability of D/O in the LISM appears rather as a strong argument which supports both D/H and O/H spatial stability in the LISM. We note however that D I and O I anti-correlation is not detected over limited metallicity range sampled by these *FUSE* sight lines (see Fig. 4).

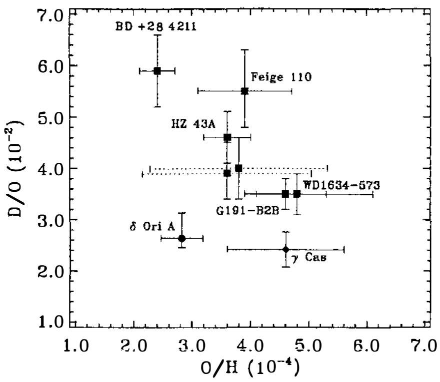

Figure 4: **D/O vs. O/H.** There is no evidence for a dependence of D/O on O/H over the limited metallicity range sampled. This figure is taken from Moos et al. (2002).

By assuming the value O/H $= 3.43(\pm0.15) \times 10^{-4}$ found by Meyer (2001), the *FUSE* D/O result implies D/H $= 1.32(\pm0.08) \times 10^{-5}$ $(1\,\sigma)$. This value is slightly lower than the average *FUSE*-value reported above.

First *FUSE* results obtained for log N(D I) ≥ 15 and $d \geq 100$ pc (see Fig. 3) suggest that D/O variations may occur at larger column densities (larger pathlengths). Such a trend is expected if oxygen depletion onto dust grains increases for denser clouds (Cartledge et al. 2001). Indeed, present *FUSE* results refer only to the gaseous phase, and approximately 30-40 per cent of the total interstellar oxygen is probably in the solid phase (Meyer et al. 1998; Sofia & Meyer 2001; Allende Prieto et al. 2001). Obviously, D/O studies should be extended to more distant lines of sight.

These distant sight lines will be observed through D I Lyman absorption lines; however, some of them could probe dense molecular clouds in which H_2 and HD molecules will be observed through multiple absorption lines in the *FUSE* band pass. Indeed, the high sensivity of *FUSE* allows denser clouds to be observed (Ferlet et al. 2000), in which most of the deuterium and hydrogen are expected to be in their molecular form. Thus, D/H can be obtained from the HD/H_2 ratio without strong model-dependant uncertainties. Up to now, HD is detected in more than 100 lines of sight with *FUSE*.

Acknowledgments

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