ATOMIC DEUTERIUM/HYDROGEN IN THE GALAXY

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Abstract. An accurate value of the deuterium/hydrogen (D/H) ratio in the local interstellar medium (LISM) and a better understanding of the D/H variations with position in the Galactic disk can provide essential information on the primordial D/H ratio in the Galaxy at the time of the protosolar nebula, and the amount of astration and mixing in the Galaxy over time. Recent measurements have been obtained with UV spectrographs on FUSE, HST, and IMAPS using hot white dwarfs, OB stars, and late-type stars as background light sources against which to measure absorption by D and H in the interstellar medium along the lines of sight. Recent analyses of FUSE observations of seven white dwarfs and subdwarfs provide a weighted mean value of D/H = $(1.52 \pm 0.08) \times 10^{-5}$ $(15.2 \pm 0.8$ ppm), consistent with the value of $(1.50\pm0.10) \times 10^{-5}$ $(15.0 \pm 1.0$ ppm) obtained from analysis of lines of sight toward nearby late-type stars. Both numbers refer to the ISM within about 100 pc of the Sun, which samples warm clouds located within the Local Bubble. Outside of the Local Bubble at distances of 200 to 500 pc, analyses of far-UV spectra obtained with IMAPS indicate a much wider range of D/H ratios between 0.8 to 2.2 ppm, providing information on inhomogeneous astration in the Galactic disk.

1. Why are Accurate Measurements of the D/H Ratio Important?

Measurements of D/H, the number ratio of deuterium in all forms to hydrogen in all forms, are important for at least two reasons. First, an accurate measurement of the primordial ratio, $(D/H)_{\text{prim}}$, counts the number of baryons in the universe to determine the ratio $\Omega_B$ of the baryon density to the closure density, and tests our assumptions concerning nucleosynthesis during the first 100–1,000 seconds of the universe (e.g.,Burles et al. 2001). Deuterium is our best probe of primordial nucleosynthesis because theory predicts that D was formed only in the very early universe, D is the easiest isotope to be destroyed by nuclear reactions in stars (astration), and $\Omega_B$ is a very sensitive single-valued function of $(D/H)_{\text{prim}}$. The best approximation to $(D/H)_{\text{prim}}$ would be an accurate measurement of D/H in gas where there has been little chemical fractionation or star formation, as indicated by very low metal abundances, but such measurements remain difficult.

Second, measurements of D/H in different locations in our Galaxy will provide an accurate test of the assumptions underlying Galactic chemical evolution models. A major problem in astrophysics is understanding how galaxies evolve and, in particular, how the chemical element abundances evolve. In broad overview, we know that stars form out of gas clouds and over time they destroy D, create metals, and return some of this deuterium-poor and metal-rich material to the ISM by winds and supernova explosions. The detailed rates for these processes depend on the
initial stellar masses. Thus with time D/H should decrease and metal abundances should increase. Theoretical models for Galactic chemical evolution rest on many assumptions that measurements of D/H in different environments can test. In particular, the temporal and spatial scales for mixing in the ISM are poorly known and likely depend on the magnetic field, which is also poorly known.

2. What is the Best Way of Measuring D/H?

While I believe that the most accurate D/H measurements are obtained from interstellar H and D Lyman line absorption in warm interstellar gas, I first summarize the various techniques that have been used to measure D/H in the Galaxy:

Deuterated molecules in cold interstellar clouds: HDO/H$_2$O $\geq$ 1000 ppm* and other deuterated molecules also show very high abundances. Since deuterated molecules are more tightly bound than nondeuterated molecules, the small difference in the binding energies divided by $kT$ can be large at cold temperatures (10–20 K). For example, the reaction HD + H$_2$O $\leftrightarrow$ HDO + H$_2$ at low temperatures leads to HDO/H$_2$O $\gg$ D/H. Carbon molecule chemistry also creates huge overabundances of the deuterated molecules.

HD/H$_2$ in the ISM: In cold clouds nearly all D is tied up in HD molecules, so HD/H$_2$ measures D/H. Measurement of the HD J = 1 $\rightarrow$ 0 pure rotation line (112 $\mu$m) in the Orion Bar (Wright et al., 1999) by the ISO spacecraft gives D/H = 10 $\pm$ 3 ppm. This value for D/H may not be representative of the gas, however, since HD is not self-shielded like H$_2$ and will have a higher photodissociation rate from stellar and diffuse UV radiation.

Balmer-α line in the Orion Nebula: Hebrard et al. (2000) first detected narrow deuterium Balmer-α and Balmer-β emission lines. Accurate measurements of the D/H ratio from the Balmer lines is difficult, however, because the D Balmer lines are fluorescent lines pumped by the hot star continuum, whereas the H Balmer lines are recombination lines (cf. O’Dell et al., 2001).

Hyperfine structure line: The most recent search for the 92 cm (327 MHz) deuterium line in the ISM toward the Galactic anticenter yields a possible detection (Chengalur et al., 1997) with D/H = 39 $\pm$ 10 ppm.

D/H in the Sun: A search for D Balmer-α emission at –1.785 Å relative to H Balmer-α (Beckers, 1975) gives an upper limit of D/H < 0.25 ppm. This very low value for D/H is consistent with the burning of D deep in the convective zone and the mixing of this D-depleted gas throughout the solar atmosphere.

* I express D/H ratios in parts per million (ppm) in **bold face** to facilitate intercomparisons.
D/H in the solar system: In his review paper, Robert et al. (2000) list for D/H in comets 300 ppm, meteorites 80–1000 ppm, Jupiter and Saturn 25 ppm, Uranus and Neptune 60 ppm. The standard explanation is that the initially highly deuterated water and other molecules become less deuterated with time by isotopic exchange with H$_2$ at warmer temperatures. Terrestrial water also started with a very high D/H ratio and subsequently reached its present ratio of HDO/H$_2$O = 150 ppm via partial isotopic re-equilibrium with warm H$_2$.

3. Measuring D/H with UV Spectra from HST

The Goddard High Resolution Spectrograph (GHRS) and the Space Telescope Imaging Spectrograph (STIS) instruments on HST with resolution of $\leq 3$ km s$^{-1}$ are providing beautiful spectra of interstellar Lyman-$\alpha$ absorption with which to measure the column densities N(D I) and N(H I) and thus D/H. Several serendipitous results have already emerged from this analysis.

Virtues of this approach:
- Since no molecules are present in the warm ($T \approx 7,000$ K) ISM clouds, there is no chemical fractionation and the fractional ionization of H and D are the same. Thus N(D I)/N(H I) equals the D/H ratio in these warm clouds.
- For lines of sight through the LISM, N(H I) $\sim 10^{18} - 10^{20}$ cm$^{-2}$ and N(D I) $\sim 10^{13} - 10^{15}$ cm$^{-2}$. Thus for either Lyman-$\alpha$ or higher Lyman series lines, the D line has measurable opacity while the corresponding H line is not too optically thick to absorb completely the D line located at $-82$ km s$^{-1}$. The “horizon” set by the H I column density at which the saturated core of the interstellar H absorption is as wide as 82 km s$^{-1}$ is $6 \times 10^{18}$ cm$^{-2}$ for Lyman-$\alpha$, $4 \times 10^{19}$ cm$^{-2}$ for Lyman-$\beta$, and larger for the higher Lyman lines.

Problems with this approach:
- For many lines of sight, overlapping velocity components may permit one to measure (D/H)$_{total}$, but not D/H for each component separately.
- Low column density cloudlets of hydrogen that are Doppler shifted with respect to the main interstellar absorption feature add to the saturated H Lyman line absorption but have insufficient opacity to be detected in lines of D or any metal. When not included in the analysis, this “invisible” hydrogen can lead to large errors in N(H I) and thus the D/H ratio (Lemoine et al., 2002).

As an example of the complexities in the data analysis and the serendipitous results that have emerged from measuring the D/H ratio for the lines of sight to the nearby stars, I summarize recent studies (cf. Linsky and Wood 1996 and Wood et al. 2001) of the short (1.3 pc) lines of sight to the triplet $\alpha$ Centauri system: A (a G2 V star like the Sun), B (a K2 dwarf), and C (Proxima Centauri, an M dwarf).
• The interstellar Fe II and Mg II resonance lines formed in the lines of sight to these stars show absorption at only one velocity, indicating that there is only one warm cloud, the so-called G (or Galactic Center) Cloud along this simple line of sight. However, the central velocity of the H Lyman-α absorption is redshifted by 2.2 km s\(^{-1}\) relative to the D Lyman-α and metal line absorption, indicating the presence of a second red-shifted absorber in the H line.

• Additional absorption on the red side of the H Lyman-α absorption profile (see Fig. 1) is due to the “hydrogen wall” in the heliosphere produced by the interaction and charge exchange of inflowing LISM neutral H with outflowing solar wind protons near the heliopause (e.g., Zank \textit{et al.} 2001). \(N(\text{H I})_{\text{wall}} \sim 0.0004 \times N(\text{H I})_{\text{Gcloud}}\), which is sufficient to explain the additional H absorption but insufficient to provide measurable D or metal line absorption. If the H wall absorption is not included in the analysis, then the inferred \(N(\text{H I})\) would be a factor of 2 too large and the inferred D/H ratio a factor of 2 too small.

• Additional absorption on the blue side of the H Lyman-α absorption profile of α Cen A and B (see Fig. 1) is due to hydrogen wall absorption in their astrospheres produced by the interaction of LISM neutral H with their ionized stellar winds. The blue shift relative to the interstellar absorption results from viewing the decelerated H wall from the outside. The near absence of H wall absorption in the astrosphere of Proxima Centauri indicates a very low mass loss rate for this star. Studies of astrospheric absorption toward a number of nearby stars allowed Wood \textit{et al.} (2002a) to infer stellar mass loss rates as small as \(10^{-15} M_{\odot} \text{yr}^{-1}\), and to estimate the mass loss rate of the young Sun, which is important for understanding the evolution of the Martian atmosphere.

• Lemoine \textit{et al.} (2002) and Vidal-Madjar and Ferlet (2002) have argued that systematic errors in deriving \(N(\text{H I})\) from saturated Lyman line absorption are much larger than previously assumed, leading to very uncertain D/H values. Large systematic errors can indeed be present, but in several well studied examples independent measurements of \(N(\text{H I})\) inferred from the shape of the Lyman continuum absorption are in excellent agreement with the Lyman-α absorption results. Since the two diagnostic techniques are very different and the Lyman-α and Lyman continuum optical depths differ by a factor of \(10^6\), the agreement in \(N(\text{H I})\) to better than 10% using the two techniques indicates that the systematic errors for these lines of sight are not large. Linsky \textit{et al.} (2000) summarized the close agreement between the two different techniques for the lines of sight to the white dwarfs HZ 43 and G191-B2B, and for groups of late-type and white dwarf stars located within a few degrees of each other with lines of sight through the same clouds. Examples include the HZ 43, 31 Com, and GD 153 group, and the Capella and G191-B2B pair.

• Analysis of Lyman-α absorption for 12 sightlines through the LIC yield a mean value of \(D/H = 15.0 \pm 1.0\) ppm (Linsky, 1998) and no trend with distance to the target star (up to 100 pc) or Galactic longitude. Other investigators have also analyzed GHRS and STIS data using different approaches. For example,
Figure 1. Comparison of the observed Lyman-α profiles toward α Cen B and Proxima Centauri. The dashed line is the interstellar absorption predicted from the observed D and metal lines. The extra absorption on the red side of the interstellar absorption (same for both stars) is due to the H wall in the heliosphere. The extra absorption on the blue side (different for the two stars and a function of the mass loss rate) is due to the H wall in the astrospheres. From Wood et al., (2001).

Vidal-Madjar et al. (1998) confirmed that the D/H ratio for the Capella line of sight through the LIC is consistent with the mean LIC value. The G191-B2B line of sight has generated more controversy, although Vidal-Madjar et al. (1998), Lemoine et al. (2002), and Sahu et al. (1999) agree that D/H in the LIC component is consistent with the mean value. They disagree, however, on the value of D/H in the one or two other velocity components along the line of sight to this star located only $69^{+19}_{-12}$ pc away.

4. Structures in the Local Interstellar Medium

The D/H ratio is unlikely to be constant throughout the Galaxy. Prime candidates for different D/H ratios are those locations where the gas has been confined for a long time and the gas composition has been altered by stellar mass loss of astrated material with limited mixing with the gas in the rest of the Galaxy. We do not know a priori what these structures are, but as a start we should measure the D/H ratio in ISM gas located in identifiable structures in our local region of the Galaxy.
The Galactic halo extends for many kiloparsecs (kpc) above and below the Galactic plane and likely consists primarily of hot gas with low metal abundances. A prime goal of the Far Ultraviolet Spectrograph Explorer (FUSE) mission is to measure D/H in sightlines through the halo, but there are no results available to report. The thin disk of the Galaxy, in which most giant molecular clouds are located and star formation occurs, has a vertical scale height of 325 pc and a radial scale height \( \sim 4000 \) pc. The D/H ratios measured toward OB stars in the thin disk by the Copernicus satellite and the IMAPS instrument will be discussed below.

The Sun is located inside a region of very low density called the Local Cavity. Steir et al. (1999) have modelled the contours of the Na I absorption that likely delineate the outer edge of hot low density gas \((\log T = 6.0–6.1)\) called the Local Bubble (LB), which extends outward by 100–200 pc from the Sun. It is likely that the LB fills most or all of the Local Cavity, but this is not yet demonstrated. The LB was likely formed by the winds and supernovae explosions of stars in the Scopius-Centaurus Association as the 26 km s\(^{-1}\) flow vector is from the center of the Association. The age of the LB is a few million yr and the gas within it is likely well mixed and could be D-poor and metal-rich given its origin.

Within the LB are a number of small clouds consisting of warm, partially ionized gas (see Fig. 2). The Sun is located within but close to the edge of the Local Interstellar Cloud (LIC). First identified from its kinematics by Lallement and Bertin (1992), the LIC was modelled by Redfield and Linsky (2000) as roughly spherical with dimensions of 5–8 pc, \( T \approx 7,000 \) K, and \( n_{\text{total}} \approx 0.2 \) cm\(^{-3}\). Within the LIC, D/H and the depletions of Mg and Fe appear to be constant. Located near the LIC are at least nine other warm clouds with similar temperatures but a wide range of metal depletions, indicating that grains in some clouds have been evaporated by shocks. The ionization fractions of H and He in the LIC are consistent with steady-state equilibrium for which the photoionization is from nearby stars (primarily \( \epsilon \) CMa), the UV background, and an assumed UV radiation field formed at the boundary between warm clouds and the hot surrounding gas (cf. model 17 in Slavin and Frisch, 2002 and Wood et al., 2002b).

5. FUSE Measurements of D/H Along the Lines of Sight to Nearby Hot White Dwarf Stars

The FUSE spacecraft obtains spectra of stars and extragalactic sources in the far–UV (910–1180 Å) with about 20 km s\(^{-1}\) resolution. For a description of the satellite and its capabilities see Moos et al. (2000) and Sahnow et al. (2000). A major goal of the FUSE observing program is to measure D/H in local and more distant interstellar gas. The first results of this program are published in a series of eight papers appearing in the May 2002 issue of ApJ Supplements. Moos et al. (2002) summarize the results obtained from analyses of the lines of sight to five white dwarfs (HZ 43, G191-B2B, WD 0621-376, WD 1634-573, and WD 2211-495) located at distances of 37–69 pc within the LB and to two subdwarfs (Feige 110
and BD +28° 4211) located at distances of 104–179 pc outside of the LB. White
dwarfs are useful targets because they have a bright continuum with few stellar
absorption lines, relatively simple lines of sight, and no stellar winds.

The basic approach taken in analyzing these spectra is to fit Voigt (convolved
Doppler and damping) profiles to the interstellar absorption seen in the FUSE and
STIS spectra to determine the number of absorption components and the total
column densities for H, D, and important metals. One complication is that the
FUSE spectra have insufficient spectral resolution to determine \( N(H\text{ I}) \) from the
shapes of the higher Lyman lines, so \( N(H\text{ I}) \) is better determined from the Lyman-\( \alpha \)
profile or EUVE measurements of the Lyman continuum absorption. Uncertainties
in the FUSE line spread function and velocity scale also complicate the analysis.
The possible presence along the line of sight of hot hydrogen absorbers with low
column densities increases the uncertainty in \( N(H\text{ I}) \) and thus \( D/H \).

An example of this work is the line of sight to G191-B2B analyzed by Lemoine et al.
(2002). The line of sight to this hot DA white dwarf (log \( T_{\text{eff}} = 54,000 \text{ K, } \log g = 7.4 \)) has 3 ISM velocity components: 19.6 km/s (LIC), 11.5 km/s, and 7.4 km/s. The
inclusion of uncertainties in \( N(H\text{ I}) \) from the possible presence of hot H absorbers
and uncertainties in the stellar Lyman line shapes against which the interstellar

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**Figure 2.** A schematic view of the Local Interstellar Cloud (LIC) and two other clouds as viewed from the North Galactic Pole. The Sun is located just inside the LIC toward the G cloud. Arrows designate the ISM flow direction. The star \( \epsilon \) CMa is a major source of the photoionizing radiation. From Wood et al., (2002b).
TABLE I
FUSE results for D/H from D/O and O/H

| Number Ratio                        | 5 sightlines inside LB | All 7 sightlines |
|-------------------------------------|------------------------|------------------|
| D I/O (FUSE LISM)                   | $(3.76 \pm 0.20) \times 10^{-2}$ | $(3.99 \pm 0.19) \times 10^{-2}$ |
| O/H (Sun)                           | $(4.90 \pm 0.56) \times 10^{-4}$ | $(4.90 \pm 0.56) \times 10^{-4}$ |
| D/H (ppm)                           | $18.4 \pm 2.3$         | $19.5 \pm 2.5$   |
| D/H (O_{gas}/O_{tot} = 0.80)       | $14.7 \pm 1.8$         | $15.6 \pm 2.0$   |
| O I/H (ISM)                         | $(3.43 \pm 0.15) \times 10^{-4}$ | $(3.43 \pm 0.15) \times 10^{-4}$ |
| D/H (ppm)                           | $12.9 \pm 0.8$         | $13.7 \pm 0.8$   |
| O I/H (FUSE LISM)                   | $(3.94 \pm 0.35) \times 10^{-4}$ | $(3.03 \pm 0.21) \times 10^{-4}$ |
| D/H (ppm)                           | $14.8 \pm 1.5$         | $12.1 \pm 1.0$   |

absorption is measured leads to log N(H I) = 18.18 ± 0.18 (2 σ) and (D/H)$_{tot}$ = 16.6$^{+9}_{-6}$ ppm.

For all seven lines of sight typical uncertainties in N(D I) are ±10% (1σ), but the values of N(H I) obtained from EUVE, GHRS, STIS, or IUE spectra are typically uncertain by ±17% (1σ). The weighted mean D/H = 15.2 ± 0.8 ppm and the range in D/H values is 14–21 ppm. The line of sight with the highest D/H = 21.4 ± 4.1 ppm is Feige 110, which is located outside of the LB. D/H for the other six lines of sight cluster closely about 15 ppm.

An alternative and perhaps more accurate way of determining D/H is from measurements of D/O and O/H. Oxygen is a good proxy for hydrogen as the ionization potentials for O I and H I are nearly the same and their ionization equilibria are closely tied by charge exchange reactions. The presence of many optically thin O I lines in the FUSE spectrum leads to typical uncertainties in N(O I) of ±10%. Typical uncertainties in D/O are ±15%, and for the five white dwarfs inside the LB the weighted mean value is D/O = 0.0376 ± 0.0020 (±5%). The usually cited value is O I/H I = (3.43 ± 0.15) $\times 10^{-4}$ (Meyer, 2002) for the ISM at distances of 200–1000 pc. I take the new solar value of O/H = (4.90 ± 0.56) $\times 10^{-4}$ from Allende Prieto et al. (2001), who use their three-dimensional time-dependent hydrodynamical model solar atmospheres to analyze the [O I] 6300 Å line. Table I summarizes the D/H ratios derived using the measured D/O ratios and either the O/H ratio for the Sun (assuming 0% or 20% depletion of oxygen to grains in the ISM), the Meyer (2002) value for the ISM gas, or the FUSE values for the LISM gas. For nearly all of these cases, the inferred D/H value is consistent with the directly measured value of D/H = 15.2 ± 0.8 ppm.
6. What have We Learned about D/H in the Galaxy?

- Within the Local Bubble (out to 100 pc or more from the Sun), D/H probably has a single value (i.e., the local ISM is well mixed). The measurements of D/H summarized in Table II lead me to conclude that the best value for D/H in the Local Bubble is \((D/H)_{LB} = 15 \pm 1\) ppm.

- Table III and Figure 3 summarize the D/H measurements of gas beyond the LB, including measurements toward two hot subdwarfs by FUSE, to three O stars by Copernicus, to three O stars by the IMAPS experiment, and the mean of four quasar sightlines studied with the Keck telescope. These results show a wide range of D/H = 5–22 ppm in the Galactic disk.

- If we adopt the most recent quasar sightline value of D/H = 30 ± 4 ppm (O’Meara et al., 2001) as an approximate value for \((D/H)_{prim}\), then the deuterium astration in the Local Bubble, \((D/H)_{prim}/(D/H)_{LB} = (30 \pm 0.4)/(15 \pm 1) = 2.0 \pm 0.4\). The range of deuterium astration in the Galactic disk from the data in Table III is then 1.35–6.0.

- Theoretical estimates of deuterium astration over the lifetime of our Galaxy are \(\leq 3\) (Tosi et al., 1998) and appear to be inconsistent with the wide range of observed astration values. However, the models make a number of assump-
Figure 3. A summary of D/H measurements obtained with HST (asterisks), FUSE inside the LB (diamonds), FUSE outside of the LB (triangles), Copernicus (squares), IMAPS (circles), and Keck (upside down triangles) with distance d in units of parsecs. The three quasar lines of sight studied with Keck are not plotted at their correct distances. The dashed lines refer to the mean D/H values inside the Local Bubble and for the quasar lines of sight.

...tions that may not be valid. For example, the young Galaxy has primordial D/H and no metals, and the infalling gas from the halo has primordial or near-primordial abundances. Each ring of the Galaxy (several kpc wide) is assumed to be well mixed, and the gas is not mixed with gas in other rings. If the D/H results beyond the Local Bubble are valid, the Galactic chemical evolution models are overly simplified. The next generation of Galactic chemical evolution models must include episodic star formation (star bursts) with rapid mass loss and supernovae events and more realistic mixing scenarios.

- All Galactic chemical evolution models predict that D/H and metal abundance should be anti-correlated, but the initial results from FUSE do not show this. Rather, there appears to be a weak positive correlation between D/H and O/H. Analysis of D/H and O/H for more lines of sight is needed.

- \((D/H)_{\text{prim}} \approx (D/H)_{\text{QSO}} = 30 \pm 4\) ppm is consistent with the primordial abundance of He and \(^7\)Li according to present models of Big Bang nucleosynthesis (e.g., [Burles et al. 2001]). The ratio of baryons to photons is \(\eta_\gamma = (5.5 \pm 0.5) \times 10^{-10}\), and the ratio of the baryon density to the closure density, \(\Omega_B = 0.041 \pm 0.009\). Big bang nucleosynthesis theory looks basically right.
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