ATOMIC DEUTERIUM/HYDROGEN IN THE GALAXY

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Abstract. An accurate value of the D/H ratio in the local interstellar medium (LISM) and a better understanding of the D/H variations with position in the Galactic disk and halo are vitally important as they provide information on the primordial D/H ratio in the Galaxy at the time of the primitive nebulae, and the amount of starbirth and mixing in the Galaxy over time. Recent measurements have been obtained with UV echelle spectroscopy on FUSE, STIS, and IMACS 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 eleven white dwarfs and subdwarfs provide a weighted mean value of D/H = (1.52 ± 0.08) × 10−5 (15.2 ± 0.6 ppm), consistent with the value of (1.56 ± 0.10) × 10−5 (15.6 ± 1.0 ppm) obtained from analysis of lines of sight toward nearby late-type stars. Both number 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 700 pc, analyses of the UV spectra obtained with the IMACS instrument indicate a much wider range of D/H ratios between 0.8 to 3.2 ppm. This portion of the Galactic disk provides information on inhomogeneous situation in the Galaxy.

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 three reasons. First, an accurate measurement of the primordial ratio, (D/H)_{prim}, counts the number of baryons in the universe to determine the ratio Q_{baryo} 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). Since present theories of primordial nucleosynthesis indicate that D was formed only in the very early universe and D is the easiest isotope to be destroyed by nuclear reaction in stars (ation), D is a unique fossil for study by astrophotonomists. D is the best isotope to study because most authors agree that there are no significant sources of D after 1,000 seconds, and Q_{baryo} is a very sensitive single-valued function of (D/H)_{prim}. While one expects that the best approximation to (D/H)_{prim} would be an accurate measurement of D/H in an environment where there has been little chemical reaction or star formation as measured by very low metal abundances, such measurements remain difficult.

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 to understand how galaxies evolve with time 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 while our 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.

3. 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 absorptions in warm interstellar gas, I first summarize the various techniques that have been used to estimate D/H in the Galaxy:

Deuterated molecules in cold interstellar clouds: HDO/H₂O > 100 ppma and other deuterated molecules also show very high abundances. Since deuterated molecules are more tightly bound than nondeterated 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 + H₂ -> HD + H₂ at low temperatures leads to HDO/H₂O > D/H. Carbon molecule chemistry also creates huge overabundances in the deuterated molecules.

H/D in the ISM: In cold clouds nearly all D is tied up in HD molecules, so HD/H₂ measures D/H. Measurement of the HD J = 1 - 0 pure rotation line (112 μm) in the Orion Bar (Wright et al., 1999) by the ISO spacecraft gives D/H > 10 ± 3 ppm. This is a sensible value, but HD is not self-shielded like H₂ and thus will have a higher photodissociation rate from stellar and diffuse UV radiation fields.

Balmer line in the Orion Nebula: Hébert et al. (2000) first detected narrow D Balmer-a and Balmer-f emission line. 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 (217 MHz) deuterium line in the ISM toward the Galactic anticenter yields a possible detection (Chung et al., 1997) with D/H = 39 ± 10 ppm.

* I express D/H ratio in parts per million (ppm) to easily intercompare different data sets.
D/H in the Sun: A search for D Balmer-α emission at ~1.765 Å relative to H Balmer-α (Beckers, 1975) gives an upper limit of D/H < 0.28 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.

D/H in the solar system: In their review, Robert et al. (2000) list for D/H in comets 100 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 H₂ at warmer temperatures. Terrestrial water also started with a very high D/H ratio and subsequently reached its present ratio of HD/HD₃O = 190 ppm via partial isotopic re-equilibrium with warm H₂.

3. Measuring D/H with UV Spectra from HST

The Goddard High Resolution Spectrograph (GIRS) and the Space Telescope Imaging Spectrograph (STIS) instruments on HST are providing beautiful spectra of interstellar Lyman-α absorption with resolution of ≤ 3 km s⁻¹ with which the column densities N(D I) and N(H I) and thus D/H are measurable. Several interesting surprises have emerged from this analysis.

Virtues of this approach:
- Since no molecules are present in the warm (T ≈ 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) is the D/H ratio in these warm clouds.
- For lines of sight through the LISM, N(H I) = 10¹⁵ – 10²⁶ cm⁻² and N(D I) ≈ 10¹⁴ – 10¹⁵ cm⁻². Thus for either Lyman-α or higher Lyman series lines, the D line has measurable opacity while the corresponding H line is too optically thick to absorb completely the D line located at ~62 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 x 10¹⁴ cm⁻² for Lyman-α, 4 x 10¹⁵ cm⁻² for Lyman-β, 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/Hₙeav but not D/H for each component separately.
- Low column density clouds 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 as 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 (Lemine 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. Linzky and Wood, 1996, and Wood et al., 2001) of the short (1.3 pc) lines of sight to the triple α 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 only at one velocity, indicating that there is only one warm cloud, the so-called G (for 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 redshifted absorber in the H line.

- Additional absorption at the red side of the H Lyman-α absorption profile (see Figure 1) is due to the "hydronen 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 et al., 2001). N(H I)\(_{wall}\) \approx 0.0004 \times N(\Omega)\(_{LISMa}\), 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(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 Figure 1) is due to hydrogen wall absorption in their atmospheres produced by the interaction of LISM neutral H and their innermost stellar winds. The blue shift relative to the interstellar absorption results from viewing the de-energized H wall from the outside. The near absence of H wall absorption in the atmosphere of Proxima Centauri indicates a very low mass loss rate for this star. Studies of atmospheric absorption toward a number of nearby stars allowed Wood et al. (2002a) to infer stellar mass loss rates as small as \(10^{-18} M_\odot y^{-1}\), and to estimate the mass loss rate of the young Sun, which is important for understanding the evolution of the Martian atmosphere.

- Lemontes et al. (2002) and Vidal-Madjar and Forain (2002) have argued that systematic errors in deriving N(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(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\(^5\), the agreement in N(H I) to better than 10% using the two techniques indicates that the systematic errors for these lines of sight are not large. Linzky et al. (2000) summarized the close agreement between the two different techniques for the lines of sight to the white dwarfs HD 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 HD 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 ± 1.8 ppm (Linsky, 1998) and no trend with distance to the target star (up to 100 pc) or Galactic longitude. Other investigators have also analyzed GREGIS and STIS data using different approaches. For example, 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 GJ91-BB line of sight has generated most controversy, although Vidal-Madjar et al. (1998), Leone 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 ± 13 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 evolved stars 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 kpc's above and below the Galactic plane and is generally assumed to consist primarily of hot gas with low metal abundances. A prime goal of the FUSE mission (Far Ultraviolet Spectrograph Explorer) is to measure D/H in sightlines through the halo, but there are as yet no results available to report. The thin disk of the Galaxy, in which most gaseous molecular clouds are located and star formation occurs, has a vertical scale height of 325 pc and a radial scale height of 4000 pc. The D/H ratios measured toward OB stars in the thin disk by the Copernicus satellite and the IRAS instrument will be discussed below.

The Sun is located inside a region of very low density called the Local Cavity. Shull et al. (1999) have moulded the contours of the Na I absorption that likely delineates the outer edge of hot ionized gas (log $T = 6.5-6.6$) called the Local Bubble (LB), which extends outwards from the Sun for 100-200 pc. 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 supernova explosions of stars in the Scorpio-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 years and the gas within it is likely well mixed and could be D poor and metal rich given its origin.

Within the LB set a number of small clouds consisting of warm, partially ionized gas (see Figure 2). The Sun is located within just close to the edge of the Local INTERstellar Cloud (LIC). First identified from its kinematics by Lallement and Petit (1992), the LIC was modelled by Redfield and Liang (2000) as roughly spherical with dimensions of 5-4 pc, $T \approx 7000$ K, and $n_{\text{H}} \approx 0.2$ cm$^{-3}$. Within the LIC, D/H and the depletions of Mg and Fe appear to be constant. Near the LIC and at least twice other warm clouds with similar temperatures, but a wide range of metal depletions, indicating that the 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 C subtypes), the UV background, and an assumed UV radiation field focused at the boundary between warm clouds and the hot surrounding gas (cf. model 17 in Steiner and Frisch, 2002, and Wood et al., 2002).

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 (110-1280 Å) with about 20 km s$^{-1}$ resolution. For a description of the satellite and its capabilities see Moos et al. (2000) and Shull et al. (2000). A major goal of the FUSE observing program is to measure D/H in local and distant interstellar gas. The first results of this program will be published in a series of eight papers to appear in the May 2002 issue of ApJ. The results obtained from analyses of the lines of sight to five white
dwarfs (HZ 43, G191-B2B, WD 0621-176, 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 104-175 pc outside of the LB. White dwarfs are useful targets because they have a bright continuum with few stellar absorption lines against which to measure the ISM absorption, relatively simple line of sight, and no stellar winds to complicate the analysis.

The basic approach taken in analyzing these spectra is to fit Voigt profiles to the interstellar absorption seen in the FUSE and STIS spectra to infer 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 I) from the shapes of the higher Lyman lines, and N(H I) is better determined from the Lyman-α 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 I) and thus ΔV I.

As an example of this work, I summarize the analysis of the line of sight to G191-B2B by Lemoine et al. (2002). The line of sight to this hot DA white dwarf (log T eff = 54, 008 K, log g = 7.4) has 3 ISM velocity components: 19 km s⁻¹ (L27), 11.5 km s⁻¹, and 7.4 km s⁻¹. The inclusion of uncertainties in N(H I) from the possible presence of hot H absorbers and uncertainties in the best-fit Lyman line
<table>
<thead>
<tr>
<th>Number Ratio</th>
<th>S sightlines inside LB</th>
<th>All 7 sightlines</th>
</tr>
</thead>
<tbody>
<tr>
<td>D/H (FUSE LISM)</td>
<td>0.076 ± 0.020</td>
<td>0.038 ± 0.019</td>
</tr>
<tr>
<td>O/H (Sun)</td>
<td>(2.2 ± 1.1) × 10⁻⁴</td>
<td>(5.2 ± 1.1) × 10⁻⁴</td>
</tr>
<tr>
<td>D/H (ppm)</td>
<td>18.6 ± 4.3</td>
<td>28.7 ± 6.3</td>
</tr>
<tr>
<td>D/H (Q_{OII}/O_{III} = 0.75)</td>
<td>16 ± 4</td>
<td>15 ± 2</td>
</tr>
<tr>
<td>O/H (ISM)</td>
<td>(3.4 ± 0.5) × 10⁻⁴</td>
<td>(0.43 ± 0.15) × 10⁻⁴</td>
</tr>
<tr>
<td>D/H (ppm)</td>
<td>17.6 ± 4.8</td>
<td>13.7 ± 6.9</td>
</tr>
<tr>
<td>O/H (FUSE LISM)</td>
<td>(3.9 ± 0.25) × 10⁻⁴</td>
<td>(3.03 ± 0.21) × 10⁻⁴</td>
</tr>
<tr>
<td>D/H (ppm)</td>
<td>14 ± 1.5</td>
<td>12.8 ± 0.6</td>
</tr>
</tbody>
</table>

Grades against which the interstellar absorption is measured leads to log N(HI) = 13.18 ± 0.13 (2 σ) and D/H_{sun} = 16 ± 2 ppm.

For all seven lines of sight typical uncertainties in N(DII) are ±10% (1σ), but the values of N(H I) obtained from EUVE, GHRS, STIS, or FUSE 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 = 11.42±4.1 ppm is Feige 110, which is located outside of the L.B. 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 H as the ionization potentials for O I and H I are nearly the same and the ionization equilibria are closely tied to each other by charge exchange reactions. The presence of many optically thin O I lines in the FUSE spectrum lead to typical uncertainties in O/H of ±10%. Typical uncertainties in D/O are ±15%, and for the five white dwarfs inside the L.B. the weighted mean value is D/O = 0.040 ± 0.0025 (±5%). The usually cited value of O/H = (3.43 ± 0.15) × 10⁻⁴ in the ISM at 200-1000 pc (Meyer, 2002). However, about 25% of oxygen may be tied up in grains, so O_{grains}/O_{ISM} = 0.75 in the ISM and probably variable. Table 1 summarizes the D/H ratios derived using D/O and O/H under different assumptions.

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 measured in Table 1 lead me to conclude that the best value for D/H in the Local Bubble is (D/H)_{LB} = 15±1 ppm.
### Table 2

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Published value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>HST-like stars with (10 pc)</td>
<td>15.8±1.9</td>
<td>Limy (1998)</td>
</tr>
<tr>
<td>FUSE (5 sightlines inside 10 R)</td>
<td>15.2±0.8</td>
<td>Moor et al. (2002)</td>
</tr>
<tr>
<td>FUSE (D0 and D5 in LISM)</td>
<td>14.8±1.5</td>
<td>Moor et al. (2002)</td>
</tr>
<tr>
<td>FUSE (Do, solar</td>
<td>19.5±0.1</td>
<td>Moor et al. (2002)</td>
</tr>
<tr>
<td>FUSE (Do, solar</td>
<td>146±3.1</td>
<td>Moor et al. (2002)</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Star</th>
<th>Dn</th>
<th>DM</th>
<th>Instrument</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>BD+28°4211</td>
<td>196</td>
<td>13.9±1.0</td>
<td>FUSE</td>
<td>Sembach et al. (2002)</td>
</tr>
<tr>
<td>δ Car</td>
<td>135</td>
<td>0.0±3.6</td>
<td>Copernicus</td>
<td>Aller et al. (1992)</td>
</tr>
<tr>
<td>Feige 110</td>
<td>180</td>
<td>21.0±4.1</td>
<td>FUSE</td>
<td>Joshua et al. (2002)</td>
</tr>
<tr>
<td>γ Cas</td>
<td>188</td>
<td>13.6±2.5</td>
<td>Copernicus</td>
<td>Fink et al. (1985)</td>
</tr>
<tr>
<td>ζ Boo</td>
<td>156</td>
<td>7.6±3.5</td>
<td>Copernicus</td>
<td>Beck (1985)</td>
</tr>
<tr>
<td>ζ Per</td>
<td>258</td>
<td>21.0±2.3</td>
<td>IMACS</td>
<td>Stoneham (2000)</td>
</tr>
<tr>
<td>ζ Cru</td>
<td>450</td>
<td>14.2±1.5</td>
<td>IMACS</td>
<td>Stoneham (2000)</td>
</tr>
<tr>
<td>δ Cru</td>
<td>500</td>
<td>7.6±2.0</td>
<td>IMACS</td>
<td>Jenkins et al. (1999)</td>
</tr>
<tr>
<td>ε CrA</td>
<td>204</td>
<td>30±2</td>
<td>IMACS</td>
<td>O'Meara et al. (2001)</td>
</tr>
</tbody>
</table>

- Table III and Figure 3 summarize the D/H measurements of gas beyond the L3, including measurements toward two hot subdwarfs by FUSE, to three O stars by Copernicus, to three O stars by the IMACS experiment, and the mean of four quasar sightlines studied with the Keck telescope. These results show a wide range of D/H = 2.2 ppm in the Galactic disk.
- If we adopt the most recent quasar sightline value of D/H = 3.0±4 ppm (O'Meara et al., 2001) as an approximate value for (D/H)_{sun}, then the des- terium abundance in the Local Bubble, (D/H)_{LB} = (D/H)_{sun} - (5±0.3)(15±2) = 2.0±0.4. The range of deuterium abundance in the Galactic disk from the data in Table III then becomes 1.35–6.0.
- Theoretical estimates of deuterium abundance over the lifetime of our Galaxy are < 3 (Toom et al., 1998) and appear to be consistent with the wide range of observed abundance values. However, the models make a number of assumptions that may not be valid. For example, the young Galaxy has primordial D/H and no metals, and the inflating gas from the halo has primordial or near-primalordial 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 ratios 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 supernova 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)$_{meas} = (D/H)$_{SOF} = 30.4 \pm 4$ ppm is consistent with the primordial abundance of He and $^1$H according to present models of Big Bang nucleosynthesis (e.g., Burles et al., 2001). The ratio of baryons to photons is $\eta = (5.5 \pm 0.5) \times 10^{-10}$, 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.

Acknowledgements

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References


