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 questions as they provide 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 ± 0.8 ppm), consistent with the value of $(1.50 \pm 0.10) \times 10^{-5}$ (15.0 ± 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 the IMAPS instrument indicate a much wider range of D/H ratios between 0.8 to 2.2 ppm. This portion of the Galactic disk provides information on inhomogeneous astration 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, $(\mathrm{D/H})_{\mathrm{prim}}$, counts the number of baryons in the universe to determine the ratio Ω_{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). 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 reactions in stars (astration), D is a unique fossil for study by archeoastronomers. D is the best isotope to study because most authors agree that there are no significant sources of D after 1,000 seconds, and Ω_{B} is a very sensitive single-valued function of $(\mathrm{D/H})_{\mathrm{prim}}$. While one expects that the best approximation to $(\mathrm{D/H})_{\mathrm{prim}}$ would be an accurate measurement of D/H in an environment where there has been little chemical fractionation 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,

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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: $HDO/H_2O \geq$ **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 $HD + H_2O \leftrightarrow HDO + H_2$ at low temperatures leads to $HDO/H_2O \gg D/H$. 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 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 H_2, and thus will have a higher photodissociation rate from stellar and diffuse UV radiation fields.

Balmer-α line in the Orion Nebula: Hébrard *et al.* (2000) first detected narrow D 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 ± 10** ppm.

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* I express D/H ratios in parts per million (ppm) to easily intercompare different data sets.

D/H in the Sun: A search for D Balmer-α emission at -1.785 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.

D/H in the solar system: In their review, 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_2O = **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 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 surprizes have 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) is the D/H ratio in these warm clouds.
- For lines of sight through the LISM, N(H I) $\approx 10^{18} - 10^{20}$ cm^{-2} and N(D I) $\approx 10^{13} - 10^{15}$ cm^{-2}. Thus for either Lyman-α 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 6×10^{18} cm^{-2} for Lyman-α, 4×10^{19} 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 $(D/H)_{total}$, 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 serendipidous 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 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 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 Figure 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 *et al.*, 2001). $N(\mathrm{H\,I})_{\mathrm{Hwall}} \approx 0.0004 \times N(\mathrm{H\,I})_{\mathrm{Gcloud}}$, 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(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 astrospheres produced by the interaction of LISM neutral H and 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 *et al.* (2002a) to infer stellar mass loss rates as small as $10^{-15} M_{\odot} y^{-1}$, and to estimate the mass loss rate of the young Sun, which is important for understanding the evolution of the Martian atmosphere.
- Lemoine *et al.* (2002) and Vidal-Madjar and Ferlet (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 10^6, 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. Linsky *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.

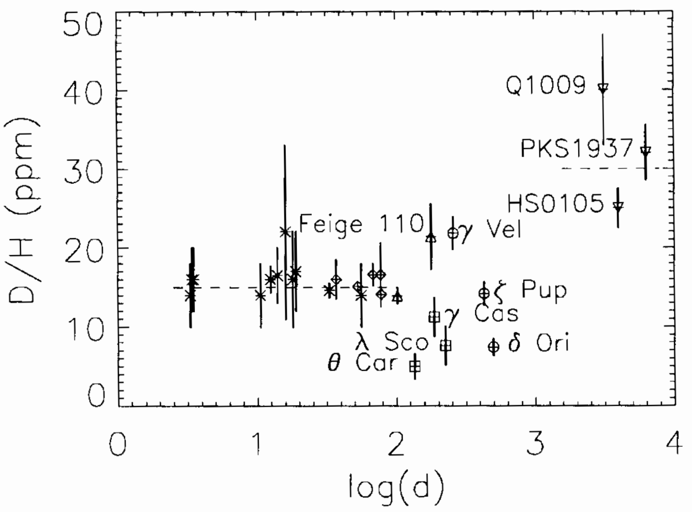

Figure 1. Comparison of the observed Lyman-α profiles toward α Cen B and Proxima Centauri. The dashed line is the interstellar absorption predicted from the observed D and metal lines. The extra absorption on the red side of the interstellar absorption (same for both stars) is due to the H wall in the 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).

- Analysis of Lyman-α absorption for 12 sightlines through the LIC yield a mean value of D/H = **15.0± 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, 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 controvery, 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 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 giant molecular clouds are located and star formation occurs, has a vertical scale height of 325 pc and a radial scale height $\approx$ 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. Sfeir *et al.* (1999) have modelled the contours of the Na I absorption that likely delineates the outer edge of hot low density gas ($\log T = 6.0$–6.1) called the Local Bubble (LB), which extends outward 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 supernovae explosions of stars in the Scorpius-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 are a number of small clouds consisting of warm, partially ionized gas (see Figure 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 $n_{\mathrm{total}} \approx 0.2$ cm^{-3}. Within the LIC, D/H and the depletions of Mg and Fe appear to be constant. Near the LIC are at least nine 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 ϵ 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 will be published in a series of eight papers to appear 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

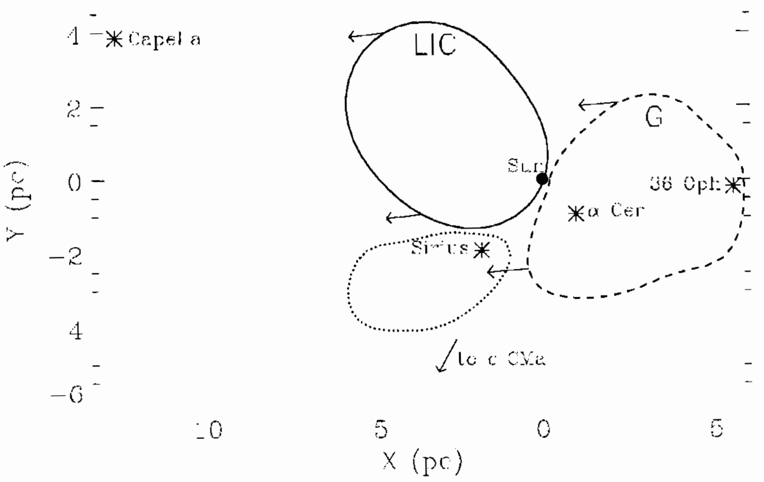

Figure 2. A schematic view of the Local Interstellar Cloud (LIC) and two other clouds as viewed from the North Galactic Pole. The Sun is located just inside the LIC toward the G cloud. Arrows designate the ISM flow direction. The star ϵ CMa is a major source of the photoionizing radiation. From Wood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

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 against which to measure the ISM absorption, relatively simple lines 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 D/H.

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 ($\log T_{\rm eff} = 54,000$ K, $\log g = 7.4$) has 3 ISM velocity components: 19.6 km s^{-1} (LIC), 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 stellar Lyman line

TABLE I

FUSE results for D/H from D/O and O/H

Number Ratio	5 sightlines inside LB	All 7 sightlines
DI/OI (FUSE LISM)	0.076 ± 0.0020	0.0399 ± 0.0019
O/H (Sun)	$(5.2 \pm 1.1) \times 10^{-4}$	$(5.2 \pm 1.1) \times 10^{-4}$
D/H (ppm)	**19.5±4.1**	**20.7±4.3**
D/H ($O_{gas}/O_{tot} = 0.75$)	**14.6±3.1**	**15.5±3.2**
OI/HI (ISM)	$(3.43 \pm 0.15) \times 10^{-4}$	$(3.43 \pm 0.15) \times 10^{-4}$
D/H (ppm)	**11.8±0.8**	**13.7±0.9**
OI/HI (FUSE LISM)	$(3.94 \pm 0.35) \times 10^{-4}$	$(3.03 \pm 0.21) \times 10^{-4}$
D/H (ppm)	**14.8±1.5**	**12.1±0.8**

shapes against which the interstellar absorption is measured leads to $\log N(\mathrm{HI}) = 18.18 \pm 0.18$ ($2\ \sigma$) and $(\mathrm{D/H})_{\mathrm{tot}}$ = **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 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 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 = 0.040 ± 0.0020 (±5%). The usually cited value of OI/HI = $(3.43 \pm 0.15) \times 10^{-4}$ in the ISM at 200–1000 pc (Meyer, 2002). However, about 25% of oxygen may be tied up in grains, so $O_{gas}/O_{tot} \approx 0.75$ 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 summarized in Table II lead me to conclude that the best value for D/H in the Local Bubble is $(\mathrm{D/H})_{\mathrm{LB}}$ = **15± 1** ppm.

TABLE II

D/H in the Local Bubble measured by different techniques

D/H Measurements	Published value	Reference
HST (solar-like stars with 100pc)	**15.0±1.0**	Linsky (1998)
FUSE (5 sightlines inside LB)	**15.2±0.8**	Moos *et al.* (2002)
FUSE (D/O and O/H in LISM)	**14.8±1.5**	Moos *et al.* (2002)
FUSE (D/O, solar O/H)	**19.5±4.1**	Moos *et al.* (2002)
FUSE (D/O, solar O/Hx0.75)	**14.6±3.1**	Moos *et al.* (2002)

TABLE III

D/H measurements beyond the Local Bubble

Star	D(pc)	D/H	Instrument	Reference
BD+28°4211	104	**13.9±1.0**	FUSE	Sonneborn *et al.* (2002)
θ Car	135	**5.0±1.6**	Copernicus	Allen *et al.* (1992)
Feige 110	180	**21.4±4.1**	FUSE	Friedman *et al.* (2002)
γ Cas	188	**13±2.5**	Copernicus	Ferlet *et al.* (1980)
λ Sco	216	**7.6±2.5**	Copernicus	York (1983)
γ^2 Vel	258	**21.8±2.0**	IMAPS	Sonneborn *et al.* (2000)
ζ Pup	430	**14.2±1.5**	IMAPS	Sonneborn *et al.* (2000)
δ Ori A	500	**7.4±1.0**	IMAPS	Jenkins *et al.* (1999)
4 QSOs		**30±4**	Keck	O'Meara *et al.* (2001)

- 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 $(\mathrm{D/H})_{\mathrm{prim}}$, then the deuterium astration in the Local Bubble, $(\mathrm{D/H})_{\mathrm{prim}}/(\mathrm{D/H})_{\mathrm{LB}} = (30 \pm 0.4)/(15 \pm 1) = 2.0 \pm 0.4$. 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 ≤ 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 assumptions 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

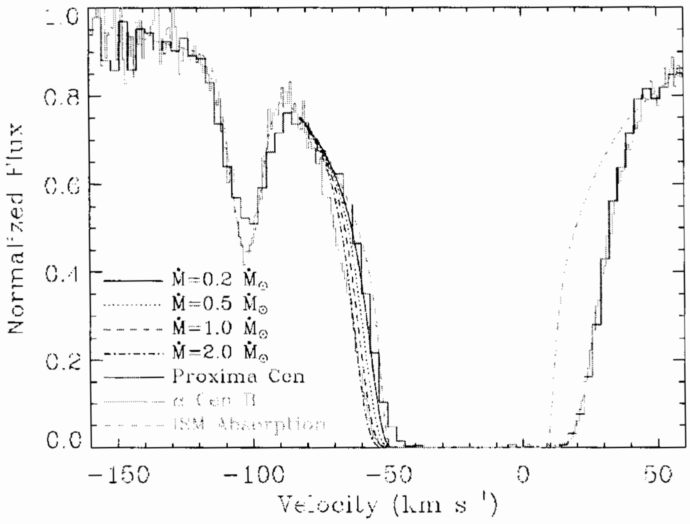

Figure 3. A summary of D/H measurements obtained with HST (*asterisks*), FUSE inside the LB (*diamonds*), FUSE outside of the LB (*triangles*), Copernicus (*squares*), IMAPS (*circles*), and Keck (*upside down triangles*). The three quasar lines of sight studied with Keck are not plotted at their correct distances. The dashed lines refer to the mean D/H values inside the Local Bubble and for the quasar lines of sight.

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.
- $(\mathrm{D/H})_{\mathrm{prim}} \approx (\mathrm{D/H})_{\mathrm{QSO}} = \mathbf{30 \pm 4}$ 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 $\eta = (5.5 \pm 0.5) \times 10^{-10}$, and the ratio of the baryon density to the closure density, $\Omega_\mathrm{B} = 0.041 \pm 0.009$. Big bang nucleosynthesis theory looks basically right.

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