Carnegie Observatories Astrophysics Series, Vol. 4:
Origin and Evolution of the Elements, 2003
ed. A. McWilliam and M. Rauch (Pasadena: Carnegie Observatories,
http://www.ociw.edu/ociw/symposia/series/symposium4/proceedings.html)

D/H as a Measure of Chemical Inhomogeneity in our Galaxy

JEFFREY L. LINSKY
JILA/University of Colorado and NIST, Boulder, CO, USA

Abstract

Accurate measurements of interstellar deuterium abundances along lines of sight extending out to several hundred parsecs by FUSE and other instruments is making D/H a useful tool for understanding Galactic chemical evolution. We find that the gas inside of the Local Bubble is chemically homogeneous, but that large variations in D/H beyond the Local Bubble are real and challenge present concepts of chemical evolution. A new set of models is needed that will include spatially dependent infall of relatively unprocessed material, depletion of D onto grains, and appropriate mixing timescales.

1.1 Tools of the trade

Since accurate measurements of the deuterium abundances are important for understanding the early history of the Universe and Galactic chemical evolution, investigators have pursued a variety of techniques to measure D/H in different locations. As reviewed by Linsky (2003), these techniques include the study of (1) deuterated molecules in cold interstellar clouds, (2) HD/H_2 in the ISM, (3) deuterium Balmer-α emission in the Orion Nebula, (4) 92 cm emission from the hyperfine transition line of D I in the ISM, (5) D/H in the solar photosphere, (6) D/H in comets, meteorites, and planetary atmospheres, and (7) deuterium Lyman line absorption in warm interstellar gas. The last technique has proven to be the most accurate because in the warm ($T \sim 7,000$ K) component of the ISM there are very few molecules, depletion of H and D onto grains is minimal, and the ionization equilibria of D and H are very similar. Thus measurements of the D I and H I column densities, N(D I) and N(H I), directly provide the D/H total abundance ratio. However, the factor of 10^5 difference in the abundances of D and H means that the interstellar H Lyman lines are all very optically thick, whereas the D Lyman lines are optically thin. Thus this technique must be applied with care as the extremely thick Lyman lines of H may contain unresolved absorption components not seen in lines of any other element and small errors in the assumed background continuum can result in large errors in the H column density and thus the D/H ratio.

Analysis of Lyman line absorption along many lines of sight toward different stars have demonstrated the following requirements for accurate D/H measurements:

High S/N: Signal/noise ≥ 30 is highly desirable especially for column densities N(H I) $< 10^{19}$ cm^{-2} when the wings of the Ly-α line are not yet strong and N(H I) must be measured from the outer edges of the absorption line core.

Knowledge of the line of sight: The low mass H and D lines are broadened primarily by thermal motions and thus provide little information on the velocity structure along the line of sight. The intrinsically narrow lines of heavier ions like Mg II and Fe II provide information on the Doppler motions (systematic and turbulent) along the line of sight. It is important to include this information to the analysis of the very saturated H lines since small errors in the nonthermal broadening of these lines due to not including the Doppler shifts of H I along the line of sight can translate into very large errors in N(H I).

High spectral resolution: To disentangle the velocity structure along a line of sight, spectral resolution comparable to the spacing of the velocity components is required. Welty et al. (1996) showed that even resolutions of 0.3–1.0 km s^{-1}, are inadequate to fully resolve the interstellar velocity structure observed with the Ca II K line. It is likely that the velocity structure for warm interstellar H I gas will have similar velocity structure. Since the thermal width of the H I lines is about 10 km s^{-1}, the inferred D/H ratio will be an average value for the line of sight. It is essential, however, to include the velocity structure when deriving N(H I) from the shape of the interstellar absorption. A resolution better than 5 km s^{-1} is needed to measure N(H I) from the shape of the outer edges of the interstellar absorption.

Low N(H I): Since the H and D Lyman lines are separated by only 82 km s^{-1}, there will be a "horizon" for each Lyman line set by the value of N(H I) when the interstellar H absorption becomes so broad that the D line cannot be observed. The horizon is 5×10^{18} cm^{-2} for Ly-α and 3×10^{19} cm^{-2} for Ly-β. While HST can observe the Ly-α line, the Far Ultraviolet Spectrometer Explorer (FUSE) is needed to study Ly-β and the higher Lyman lines which have more distant horizons. Depending on the value of N(H I) along the line of sight and how accurately it can be measured, various strategies have been employed to measure D/H bny measuring N(D I) from different lines than are used for measuring N(H I) and by using proxies like N(O I) for estimating N(H I) (see below). Also, N(H I) can be measured from the Lyman continuum absoprtion observed, for example, by EUVE.

Knowledge of the "continuum": For hot white dwarfs, subdwarfs, and OBA stars, the stellar Lyman lines are absorption features, while for late-type stars the Lyman lines are in emission. Since the interstellar absorption is broad, one cannot simply interpolate the intrinsic stellar flux from the emission outside of the Lyman line cores, but instead one must compute the stellar line shape using a model atmosphere program or estimate the line shape from comparison with other stars line the Sun. The former approach typically used for the hotter stars requires that one know the stellar parameters accurately, while the latter approach typically used for late-type stars requires that one know the intrinsic shape of the line in the comparison star. Both approaches are sources of systematic error in the inferred D/H ratio.

Knowledge of the heliosphere and astrosphere: The interaction via charge exchange between the ionized solar (or stellar) wind and the inflowing partially ionized ISM gas leads to additional neutral H absorption. The heliospheric absorption is redshifted relative to the ISM for all viewing angles and the astrospheric absorption is blueshifted (cf. Wood et al. 2002a). Since the heliospheric and astrospheric absorption in H I is not very optically thick, there is negligible absorption in D and metal lines. The heliospheric and astrospheric absorption can be very important because it broadens the total absorption in the H Lyman lines. If not properly modelled,

Table 1.1. *Moderate and high resolution UV spectroscopic instruments.*

Instrument	Spectral Range (Å)	Resolution (km s^{-1})	D/H Target Stars	Observing Dates
Copernicus	900–3150	15	11 OB, 6 FGK	1972–1981
IUE/SWP-HI	1170–1950	25	2 GK	1978–1996
HST/GHRS	1170–3200	3.5	15 FGK, 1 A, 1 WD	1990–1997
ORFEUS	912–1410	30	1 sdO	1993, 1996
IMAPS	930–1150	4.0	3 O	1993, 1996
HST/STIS	1170–3200	3.0	1 K, 1 B, 3 WDs	1997–2010?
FUSE	912–1180	20	8 WDs, 5 OB	1998–?
HST/COS	1150–3200	15		2005?

this extra absorption would appear to be interstellar, raising the inferred N(H I) and thereby lowering the inferred D/H ratio for the line of sight.

The problem is H: For most Galactic lines of sight studied so far, the errors in N(H I) usually exceed those in N(D I), since the H lines are very optically thick. Also, the hard to estimate systematic errors usually exceed random measurement errors. One should keep this in mind when using D/H measurements reported in the literature.

Table 1.1 lists the various satellites and instruments that have been used to measure D/H using UV and far-UV spectrographs. The fourth column of the table lists the target stars observed giving their spectral types and whether they are a white dwarf (WD) or subdwarf (sd). D/H values are published for the ISM along these lines of sight, but for some of the older data sets (especially IUE) the D/H values are not very accurate and will not be used later in this paper.

1.2 D/H, D/O, and D/O inside of the Local Bubble

The Sun is located in a portion of the Galactic disk known as the Local Bubble (LB). The LB extends for 50–200 pc in different directions with its outer edge defined by a "wall" of relatively cold material seen as NaI absorption (Sfeir et al. 1999). Most of the material inside of the LB is very low density hot gas ($\log T \approx 6.0$) that is likely produced by the winds of hot stars and the ejecta of supernovae in the Sco-Cen Association. The interstellar gas flows past the Sun at 28.1 km s^{-1} from the direction $l = 12.4°$, $b = +11.6°$ (Frisch et al. 2002), which is close to the center of the Sco-Cen Association.

Located inside of the LB are a number of warm ($T \sim 7{,}000$ K) partially ionized clouds with total densities about 0.2 cm^{-3}. One such cloud is the Local Interstellar Cloud (LIC) first identified by line of sight interstellar velocities toward nearby stars that are consistent with a single vector (Lallement & Bertin 1992). The Sun is located just inside of the LIC, because the flow of neutral He inside the heliosphere is consistent with the LIC flow vector and no absorption at the predicted LIC velocity is seen toward stars in the Galactic Center direction. The LIC is roughly spherical in shape with dimensions 4.7 x 6.8 pc, $N_{HI} = 2.1 \times 10^{18}$ cm^{-2}, and $n_{HI} \approx 0.10$ cm^{-3} (Redfield & Linsky 2000).

Table 1.2 summarizes the D/H measurements towards stars located inside of the LB.

Table 1.2. *Measurements of D/H inside the Local Bubble.*

DI/HI (ppm)	Instrument Used	Targets	Location	Reference
15 ± 1	HST/GHRS	11 GK, 1 WD	inside LIC	Linsky (1998)
14.7 ± 1.8	HST/GHRS	15 GK, 2 WD	< 100 pc	Linsky (1998)
16.0 ± 2.5	FUSE	WD1634-573 (DO)	37 pc	Wood et al. (2002b)
15.1:	FUSE	WD2211-495 (DA)	53 pc	Hébrard et al. (2002)
16.6 ± 1.4	FUSE	HZ43A (DA)	68 pc	Kruk et al. (2002)
$16.6^{+4.5}_{-3.0}$	FUSE	G191-B2B (DA1)	69 pc	Lemoine et al. (2002)
14.1:	FUSE	WD0621-376 (DA)	78 pc	Lehner et al. (2003)
$15.1^{+3.9}_{-3.3}$	FUSE	GD 246 (WD)	79 pc	Oliveira et al. (2003)

Since the photoionization continua of H and D overlap, the selfshielding of D I and H I to far ultraviolet radiation is the same, their ionization equilibria are the same, and the ratio of column densities, N(D I)/N(H I), will give the number density ratio DI/HI and thus D/H. The first column in the table lists the measured values of DI/HI in parts per million (ppm). The HST results were obtained from the analysis of the Lyman-α line profiles observed towards G and K stars mostly with the GHRS. The DI/HI ratios in Linsky (1998) are the weighted means for lines of sight to 12 stars with velocity components consistent with the LIC velocity vector, and for lines of sight to 17 stars with velocity components for many clouds located inside of the LIC. The listed uncertainties are for the means ratios and do not give the variance in the individual lines of sight. Also listed are DI/HI values for lines of sight toward 6 white dwarfs located inside of the LIC that have been observed by FUSE. These DI/HI ratios are obtained from analyses of the higher members of the Lyman series, although in several cases the N(H I) values are from the analysis of HST or EUVE spectra.

Table 1.3 summarizes the measured OI/HI and DI/OI ratios for lines of sight entirely within the LB. As the most abundant element after hydrogen and helium, oxygen is a good measure of the total metal abundance. Since the ionization potentials of neutral oxygen and hydrogen are nearly the same and the two neutrals are closely coupled by change exchange reactions, the column density ratio, N(O I)/N(H I), should accurately measure the OI/HI ratio in the gas phase. Some oxygen in warm clouds will be locked up in grains, however, and the total O/H ratio will therefore be somewhat larger than OI/HI in the gas phase. The N(D I)/N(O I) ratio, equaling DI/OI in the gas phase, is especially useful because the column densities of D I and O I differ by only a factor of 30, rather than a factor of 10^5 in the case of DI/HI, so that one can measure optically thin D I and O I lines in FUSE spectra. Table 1.3 lists measured line ratios in FUSE spectra of seven white dwarfs located within the LB. Also listed in the table are ratios for the Capella line of sight and mean values for 33 lines of sight inside of the LB measured from HST spectra (GHRS or STIS). The HST ratios have larger errors bars than the FUSE ratios, because N(O I) is measured using the optically thick 1302 Å line. The recently measured solar value of OI/HI by Allende Prieto et al. (2001) is also given in the table.

Consideration of these results lead me to the following conclusions:

Table 1.3. *Measurements of OI/HI and DI/OI inside the Local Bubble.*

OI/HI (10^{-4})	DI/OI (10^{-2})	Instr. Used	Targets	Location	Reference
4.6 ± 0.7	3.5 ± 0.3	FUSE	WD1634-573 (DO)	37 pc	Wood et al. (2002b)
3.8::	4.0 ± 0.6	FUSE	WD2211-495 (DA)	53 pc	Hébrard et al. (2002)
3.6 ± 0.4	4.6 ± 0.5	FUSE	HZ43A (DA)	68 pc	Kruk et al. (2002)
4.6 ± 0.7	3.5 ± 0.4	FUSE	G191-B2B (DA1)	69 pc	Lemoine et al. (2002)
3.6:	$3.9^{+0.6}_{-0.5}$	FUSE	WD0621-376 (DA)	78 pc	Lehner et al. (2003)
$3.63^{+0.77}_{-0.67}$	$4.17^{+1.2}_{-1.0}$	FUSE	GD 246 (WD)	79 pc	Oliveira et al. (2003)
	$5.13^{+2.20}_{-1.69}$	FUSE	WD2331-475 (DA)	82 pc	Oliveira et al. (2003)
$6.0^{+6.1}_{-3.0}$	$2.65^{+2.7}_{-1.3}$	HST	Capella (GIII)	12 pc	Wood et al. (2002c)
$2.5^{+1.9}_{-1.1}$	$6.0^{+4.7}_{-2.6}$	HST	33 stars	< 100 pc	Redfield (2003)
4.90 ± 0.56		Opt	Sun		Allende Prieto et al. (2001)

(1) There are no significant variations in DI/HI observed for lines of sight inside of the LB.
(2) We adopt the value D/H = 15 ± 2 ppm as representative for the LB.
(3) There is no evidence for significant variations in OI/HI or DI/OI inside of the LB. The scatter is consistent with measurement errors.
(4) Inside the LB OI/HI = $(4.0 \pm 0.4) \times 10^{-4}$ and DI/OI = $(4.1 \pm 0.4) \times 10^{-2}$.
(5) DI/OI is more accurately measured than OI/HI.

1.3 D/H, D/O, and O/H outside of the Local Bubble

As one proceeds beyond the LB, a very different picture emerges. Table 1.4 summarizes the published measurements of DI/HI obtained from analyses of far ultraviolet spectra obtained with the FUSE and Copernicus satellites and with IMAPS and ORFEUS for lines of sight to more distant white dwarfs, OB stars, a Wolf-Rayet star and a hot subdwarf. Although the cited errors are larger than for the sightlines within the LB, the range of DI/HI ratios is very large with some values well below the LB ratio and some above. All of the measured DI/HI ratios lie below the mean values for lines of sight to four or five QSOs cited by O'Meara et al. (2001) and very recently by Kirkman et al. (2003). Figure 1 plots the D/H values obtained for sightlines inside and outside of the LB and toward QSOs.

Are the D/H values obtained for sightlines outside of the LB accurate, or are systematic errors, perhaps associated with the very saturated H Lyman lines, responsible for the large scatter in D/H. To address this question, I consider the DI/OI ratio, which is generally considered to be a good proxy for D/H. Table 1.5 summarizes the published DI/OI ratios for lines of sight extending beyond the LB obtained from the analysis of FUSE, Copernicus, and IMAPS data. These results show a wide range of DI/OI values like the direct measurments of the DI/HI ratio. Could the wide range in the DI/OI ratios be due to a wide range in the OI/HI ratios? Meyer, Jura, and Cardelli (1998) measured OI/HI using HST observations of the weak intersystem O I 1356 Å line for sightlines extending out to 1.5 kpc. (See Moos et al. 2002 for a correction to the oscillator strength of this line.) He found very little variation in OI/HI in this sample of sightlines. The OI/HI ratios measured from FUSE, Copernicus,

Table 1.4. *Measurements of DI/HI beyond the Local Bubble.*

DI/HI (ppm)	Instrument Used	Targets	Location	Reference
13.9 ± 1.0	FUSE	BD+28°4211 (sdO)	104 pc	Sonneborn et al. (2002)
5.0 ± 1.6	Copernicus	θ Car (B0V)	135 pc	Allen et al. (1992)
21.4 ± 4.1	FUSE	Feige 110 (WD)	180 pc	Friedman et al. (2002)
13 ± 2.5	Copernicus	γ Cas (B0IV)	188 pc	Ferlet et al. (1980)
7.6 ± 2.5	Copernicus	λ Sco (B2IV)	216 pc	York et al. (1983)
21.8 ± 2.0	IMAPS	γ^2 Vel (WC)	258 pc	Sonneborn et al. (2000)
12 ± 4	ORFEUS	BD +39 3226	270 pc	Bluhm et al. (2000)
14.2 ± 1.5	IMAPS	ζ Pup (O5I)	430 pc	Sonneborn et al. (2000)
$7.4^{+1.2}_{-0.9}$	IMAPS	δ Ori A (O9II)	500 pc	Jenkins et al. (1999)
$8.5^{+3.4}_{-2.4}$	FUSE	HD 195965 (B1Ib)	800 pc	Hoopes et al. (2003)
$7.8^{+5.2}_{-2.5}$	FUSE	HD 191877 (B0V)	2.2 kpc	Hoopes et al. (2003)
30 ± 4	Keck	4 QSOs		O'Meara et al. (2001)
$27.8^{+4.4}_{-3.8}$	Keck	5 QSOs		Kirkman et al. (2003)
20 ± 4		Protosolar	here	Geiss et al. (2002)

Table 1.5. *Measurements of OI/HI and DI/OI beyond the Local Bubble.*

OI/HI (10^{-4})	DI/OI (10^{-2})	D/H Inst.	Targets	Location	Reference
2.4 ± 0.3	5.9 ± 0.7	FUSE	BD+28°4211	104 pc	Sonneborn et al. (2002)
	$4.57^{+2.22}_{-1.63}$	FUSE	HZ21	115 pc	Oliveira et al. (2003)
	$3.24^{+3.27}_{-2.06}$	FUSE	Lan23	122 pc	Oliveira et al. (2003)
3.9 ± 0.8	$5.5^{+0.8}_{-0.7}$	FUSE	Feige 110	180 pc	Friedman et al. (2002)
3.67 ± 0.62	3.5 ± 0.9	Coper	γ Cas	188 pc	Ferlet, Meyer
2.82 ± 0.46	2.62 ± 0.71	IMAPS	δ Ori A	500 pc	Jenkins, Meyer
$6.61^{+1.03}_{-1.11}$	$1.29^{+0.51}_{-0.37}$	FUSE	HD 195965	800 pc	Hoopes et al. (2003)
$3.09^{+1.98}_{-0.98}$	$2.51^{+2.14}_{-0.86}$	FUSE	HD 191877	2.2 kpc	Hoopes et al. (2003)
3.43 ± 0.15		HST	13 OB stars	< 1.5 kpc	Meyer et al. (1998)
4.90 ± 0.56		Opt	Sun		Allende Prieto et al. (2001)

and IMAPS data listed in Table 1.5 are more widely scattered, but are consistent with the Meyer et al. (1998) mean ratio.

These results suggest an emerging picture of D/O, O/H, and D/H in the Galaxy:

- Unlike the observed constant value inside of the LB, the gas phase measurements of DI/OI outside of the LB show very credible variations with a range $(1.3\text{–}5.9)\times10^{-2}$. This range is more than a factor of 4!
- By contrast, the HST gas phase observations of OI/HI beyond the LB show very little variation with a mean value $(3.43 \pm 0.15) \times 10^{-4}$. Measurements of OI/HI based on data from FUSE and other satellites show some scatter but are consistent with the HST result.
- If we adopt the HST value for OI/HI in the gas phase, then the DI/OI ratios imply that DI/HI lies in the range 4.3–20.2 ppm. Since some of the oxygen is condensed on to grains, the inferred D/H ratios will be somewhat higher. Moos et al. (2002) estimate that 25% of the oxygen in the LB could reside in grains, and Jenkins (2003) provides additional support for this estimate. If this rough estimate is representative of the region within 1–2 kps of the Sun, then the inferred range in D/H rises to 5.5–26.0 ppm, which is similar to the directly measured range in D/H of 5.0–21.8 ppm (Table 1.4). Thus the two methods of determining D/H are consistent, implying that no large systematic errors are present.
- The question of whether the Sun is metal rich compared with the ISM has been raised many times. If we adopt the Meyer et al. (1998) value for OI/HI in the ISM gas phase and the most recent (and lowest) value for the solar O/H ratio (Allende Prieto et al. 2001), then the Sun is oxygen rich by the factor 490 ppm/343 ppm = 1.43 (0.16 dex). If, on the other hand, we assume that 25% of oxygen is condensed on to grains, then the ratio becomes 490/457 = 1.07 (0.03 dex). Thus the Sun either has the present interstellar abundance of oxygen, or, if there is minimal depletion of oxygen in the ISM, the Sun is slightly oxygen rich.
- The extent to which primordial deuterium has been burned by nuclear reactions in stars to form heavier elements is often called the astration factor, $A = (D/H)_{primordial}/(D/H)_{ISM}$. If we assume that the most recent value of D/H for 5 quasars with low metal abundances is close to the primordial value, then in the LB we have $A = (D/H)_{primordial}/(D/H)_{LB} = (27.8 \pm 4.1)/(15 \pm 2) = 1.85 \pm 0.37$.
- Beyond the LB and extending out to 1–2 kpc, the astration factors appear to have a wide range of values from 1.3 to 5.6. This very large range in the astration factor over a small portion of our Galaxy challenges contemporary Galactic chemical evolution models as I will describe below.
- Since deuterium is destroyed and oxygen created over time, one might expect that the O/H and D/H ratios are inversely correlated. In fact there is as yet little evidence of any correlation (Moos et al. 2002). Why? Could there be something missing in the Galactic chemical evolution models?

1.4 Can the D/O measurements be reconciled with Galactic chemical evolution?

1.4.1 Are the deuterium and oxygen abundances anticorrelated?

If galactic chemical evolution occurs in a closed box in which the original gas is nearly primordial and evolution proceeds without the input of extragalactic material, then one expects D/H to decrease monotonically with time and O/H to increase. In this simplest of chemical evolution models, one would expect to see an anticorrelation of D/H and O/H when one samples different parcels of gas with different chemical histories. This scenario is rather simple, but it does suggest that we search for an anticorrelation of D and O in he FUSE data. Moos et al. (2002) did this by plotting O/H vs D/H and D/O vs D/H for the nine sightlines for which good measurements were available. They concluded that there was no

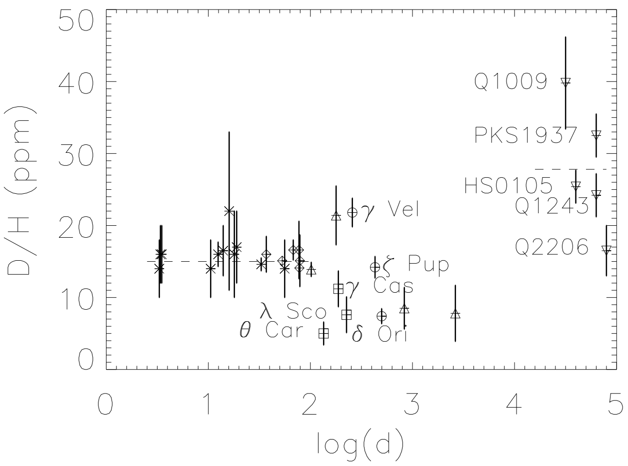

Fig. 1.1. A summary of D/H measurements obtained with HST (asterisks), FUSE inside the LB (diamonds), FUSE outside of the LB (triangles), Copernicus (squares), and Keck (upside down triangles) with distance d in units of parsecs. The quasar lines of sight studied with Keck are not plotted at their correct distances. The dashed lines refer to the mean D/H ratios inside the LB and for the five QSO lines of sight.

significant anticorrelation, although there is a hint of decreasing D/O with increasing O/H. Steigman (2003) also says that there is a hint of an anticorrelation between D/O and O/H. Observations of more sightlines is needed to verify or refute this hint.

1.4.2 Galactic chemical evolution out of the box

Geiss, Gloeckler, and Charbonnel (2002) have developed an empirical approach to explaining the present abundances of D/H, O/H, N/H, and ^{3}He/H in the LIC that has interesting implications. They start with the abundances of the protosolar nebula measured in the most primitive material in the solar system, specifically D/H = 20 ± 4 ppm and O/H = 545 ± 107 ppm. They also assume that at the beginning of the Galaxy, D/H = 30 ± 4 ppm and O/H = 0, and that the rate of Galactic chemical evolution is constant with time. Then extrapolating the primordial abundances forward 4.6 Gyr to the present, they predict that in the closed box approximation D/H = 12 ppm and O/H = 710 ppm. Since D/H is too low, O/H too high, and the other ratios are also inconsistent with the LIC values, they look for an alternative solution. The input of less evolved gas from outside of the Galaxy would increase D/H and lower O/H, leading to better agreement with the LIC values. Geiss et al. (2002) assumed that the gas falling into the Galaxy in the region of the Sun during the last 4.6 Gyr was similar in composition to the LMC with D/H = 27 ppm and O/H = 160 ppm (30% of the protosolar nebular value). The abundances of D/H, O/H, N/H, and ^{3}He/H are consistent with LIC values if the total gas includes a mixture of 30–44% infalling material with the chemical composition of the LMC.

This purely empirical model demonstrates the need for infalling gas to explain the abundances of deuterium and oxygen in the local region of our Galaxy. The observations of large variations in D/O over distance scales of several hundred parsecs would suggest spatially and perhaps time dependent differences in the infall rate and long mixing timescales.

Recent theoretical models of chemical evolution in the Galaxy provide different scenarios for the input of relatively unprocessed material into the Galaxy. For example, Chiappini, Renda, and Matteucci (2002) compute a "two-infall" model to explain the halo and thin disk. Their model explains the D/H, ^{3}He/H, and ^{4}He/H ratios near the Sun. They find that the value of D/H is very sensitive to both the infall rate and the star formation rate. Their predicted astration rate is ≈ 1.5 in the solar neighborhood and increases gradually to ≈ 5 in the thin disk at 2 kpc from Galactic Center. These astration rates cover the range of astration that we already see within a few hundred pc of the Sun. This suggests that the spatial variations in the infall and stellar formation rates are much larger than assumed in the Chiappini et al. (2002) models, and that the time scales for mixing are very long.

1.4.3 Have we ignored something important?

Before I complete this summary of deuterium as a tool for measuring chemical inhomogeneity in our Galaxy, let us consider whether there could be a systematic error in the way that we measure the D/H ratio. There are four important questions to answer:

(1) Could the deuterium abundances be very inaccurate? I do not think so because the D/H ratios measured directly from the Lyman lines and indirectly through the DI/OI ratio are in substantial agreement. Also the D/H measurements obtained with HST and FUSE toward many different types of stars by different authors using different analysis software are in excellent agreement for sightlines inside of the LB bubble. There is no reason for expecting that a major systematic error should begin just as we consider sightlines outside of the LB.

(2) Could the deuterium absorption lines actually be blueshifted stellar hydrogen? In the Copernicus observations of OB stars, one occasionally sees transient extra absorption near the location of the deuterium lines (-81 km s^{-1} from the hydrogen line), presumably produced by transient absorption in the stellar wind. The FUSE onservations, on the other hand, are mostly of white dwarfs and hot subdwarfs that do not show low velocity wind features. Thus there is no reason to presume that the deuterium lines are not genuine.

(3) Could a significant amount of deuterium be tied up in molecules? In the FUSE observations of white dwarfs very few H_2 lines and no HD lines are observed. In particular, Jenkins et al. (1999) detected no HD lines toward δ Ori A, a line of sight with low D/H. Thus N(H_2)/N(HI) $\ll 1$ and N(HD)/N(HI) is very much smaller.

(4) Could a significant amount of deuterium be tied up in grains as originally suggested by Jura (1982)? Even in the warm ISM, grains are cold and the binding energy of deuterium to carbon or metals on the surface of grains is slightly larger than for hydrogen. A serious calculation of this process is needed to address this question. Draine (2003) calculates that extreme D-enrichment of carbonaceous grains is possible in the absence of grain destruction processes.

1.5 Conclusions

Accurate measurements of interstellar deuterium abundances along lines of sight extending out to several hundred parsecs by FUSE and other instruments is making D/H a useful tool for understanding Galactic chemical evolution. I believe that the new D/H measurements directly from the Lyman line absorption and indirectly from the D/O ratio are credible and for the most part may not have systematic errors. We find that the gas inside the Local Bubble is chemically homogeneous, but that large variations in D/H beyond the Local Bubble are real and challenge present concepts of chemical evolution. A new set of models is needed that will include spatially dependent infall of relatively unprocessed material and the timescales for mixing should be investigated.

1.6 Acknowledgements

I would like to thank the FUSE Science Team for providing the beautiful data upon which much of this paper is based. I also thank Seth Redfield and Brian Wood for helpful discussions on this topic. This work is supported by NASA through grants to the Johns Hopkins University and to the University of Colorado.

References

Allen, M. M., Jenkins, E. B., & Snow, T. P., 1992, ApJS, 83, 261
Allende Prieto, C., Lambert, D. L., & Asplund, M., 2001, ApJ, 556, L63
Bluhm, H., Marggraf, O., de Boer, K. S., Richter, P., & Heber, U., 2000, A&A, 352, 287
Chiappini, C., Renda, A., & Matteucci, F., 2002, A&A, 395, 789
Draine, B. T., 2003, in *Carnegie Observatories Astrophysics Series, Vol. 4: Origin and Evolution of the Elements*, ed. A. McWilliam & M. Rauch (Cambridge: Cambridge Univ. Press), 000
Ferlet, R., York, D. G., Vidal-Madjar, A., & Laurent, C., 1980, ApJ, 242, 578
Friedman, S. D. et al. 2002, ApJS, 140, 37
Frisch, P. C., Grodnicki, L., & Welty, D. E., 2002, ApJ, 574, 834
Geiss, J., Gloeckler, G., & Charbonnel, C., 2002 ApJ, 578, 862
Hébrard, G. et al. 2002, Planetary and Space Science, 50, 1169
Hoopes, C. G., Sembach, K. R., Hébrard, G., Moos, H. W., & Knauth, D. C., 2003, ApJ, 586, 1094
Jenkins, E. B., 2003, in *Carnegie Observatories Astrophysics Series, Vol. 4: Origin and Evolution of the Elements*, ed. A. McWilliam & M. Rauch (Cambridge: Cambridge Univ. Press), 000
Jenkins, E. B., Tripp, T. M., Wozniak, P. R., Sofia, U. J., & Sonneborn, G., 1999, ApJ, 520, 182
Jura, M., 1982, in *Advances in Ultraviolet Astronomy*, ed. Y. Kondo, (NASA CP-2238), 54
Kirkman, D., Tytler, D., Suzuki, N., O'Meara, J. M., & Lubin, D., 2003, astro-ph/0302006
Kruk, J. W. et al., 2002, ApJS, 140, 19
Lallement, R. & Bertin, P., 1992, A&A, 266, 479
Lehner, N., Jenkins, E. B., Gry, C., Moos, H. W., Chayer, P., & Lacour, S., 2003, submitted to ApJ
Lemoine, M., et al., 2002, ApJS, 140, 67
Linsky, J. L., 1998, Space Science Reviews, 84, 285
Linsky, J. L., 2003, Space Science Reviews, in press
Meyer, D. M., Jura, M., & Cardelli, J. A., 1998, ApJ, 493, 222
Moos, H. W., et al., 2002, ApJS, 140, 3
Oliveira, C. M., Hébrard, G., Howk, J. C., Kruk, J. W., Chayer, P., & Moos, H. W., 2003, ApJ, 587, 2350
O'Meara, J. M., Tytler, D., Kirkman, D., Suzuki, N., Prochaska, J. X., Lubin, D., Wolfe, A. M., 2001, ApJ, 552, 718
Redfield, S. & Linsky, J. L., 2000, ApJ, 534, 825
Redfield, S. 2003, PhD thesis, University of Colorado
Sfeir, D. M., Lallement, R., Crifo, F., & Welsh, B. Y., 1999, A&A, 346, 785
Sonneborn, G., Tripp, T. M., Ferlet, R., Jenkins, E. B., Sofia, U. J., Vidal-Madjar, A., and Wozniak, P. R. 2000, ApJ, 545, 277
Sonneborn, G., et al., 2002, ApJS, 140, 51
Steigman, G., 2003, ApJ, 586, 1120
Welty, D. E., Morton, D. C., & Hobbs, L. M., 1996, ApJS, 106, 533
Wood, B. E., Müller, H. R., Zank, G. P., Linsky, J. L., 2002a, ApJ, 574, 412
Wood, B. E., Linsky, J. L., Hébrard, G., Vidal-Madjar, A., Lemoine, M., Moos, H. W., Sembach, K. R., & Jenkins, E. B., 2002b, ApJS, 140, 91
Wood, B. E., Redfield, S., Linsky, J. L., & Sahu, M. S., 2002c, ApJ, 581, 1168
York, D. G., 1983, ApJ, 264, 172