The Mystery of the Deuterium Abundance in the Local Galactic Disk is Solved!

Jeffrey L. Linsky[1], Brian E. Wood[1]

[1] JILA, University of Colorado and NIST, Boulder, CO, 80309-0440, USA

Abstract

Analyses of spectra obtained with the FUSE satellite, together with earlier observations, reveal a very wide range in the deuterium/hydrogen (D/H) ratios for interstellar gas in the Galactic disk within 1 kpc of the Sun. This result is very difficult to explain on the basis of only nuclear processes in stars that convert D to ^{3}He and ^{4}He and the infall of D-rich gas from the Galactic halo and the IGM, because the observed D/H ratios differ greatly on < 100 pc spatial scales. We argue instead that spatial variations in the depletion of D onto dust grains can explain these local variations in the gas-phase D/H ratios. The D/H measurements appear to fall into three regimes depending on $N(HI)$. Our dynamic deuterium depletion model naturally explains the constant D/H measurements inside the Local Bubble ($\log N(HI) < 19.2$), the wide range of gas phase D/H ratios found in the intermediate regime ($\log N(HI) =$ 19.2–20.5), and the low gas phase D/H ratios at larger $N(HI)$. The anticorrelation of gas-phase D/H ratios with the fraction of cold H_2 provides evidence that D depletion on to grains is important in unshocked regions where H_2 can form, while all D will be in the gas phase where shocks have evaporated the grains and destroyed the H_2. We argue that the lines of sight with high gas-phase D/H ratios provide the most representative value for the total (gas plus dust) D/H ratio within 1 kpc of the Sun of 23 ± 4 ppm (parts per million). This result constrains Galactic chemical evolution models to have very small deuterium astration factors (1.2 ± 0.3) or higher inflow rates from the IGM.

1 Introduction

Observations of the D/H ratio in the Galactic disk ISM provide an important constraint on models of Galactic chemical evolution, as deuterium is thought to be formed only in the Big Bang and is converted to ^{3}He and ^{4}He in stars. Over time, supernovae and stellar winds pollute the ISM with deuterium-depleted but metal-rich gas. The disk is also enriched by the infall of deuterium-rich but metal-poor gas from the IGM and Galactic halo.

Because of its simple origin and evolution, D plays a key role in testing models of Galactic chemical evolution. Measurements of D/H have been obtained from the analysis of high resolution spectra of Lyman-α and higher Lyman lines observed by the Copernicus, IUE, HST/GHRS, HST/STIS, IMAPS, and now FUSE satellites. The Lyman lines show strong absorption by interstellar H I and D I (–81 km s^{-1} from the H I line).

There is agreement that the D/H ratio for interstellar gas within the Local Bubble, extending to $\sim$ 100 pc from the Sun or to $\log N(HI) < 19.2$, is essentially constant. In the most recent summary of HST and FUSE results for these short sightlines, Wood et al. (ApJ, in press) find that D/H = 15.6 ± 0.4 parts per million (ppm), where 0.4 ppm is the standard deviation of the mean. Recent Galactic chemical evolution models (e.g., Romano et al. MNRAS, 346, 295, 2003) have used similar values of D/H for comparison with their calculations. They compute an astration factor ~ 1.5 for the ratio of primordial to present day D/H in the solar neighborhood. This astration factor is consistent with the WMAP (Spergel et al. ApJS, 148, 175, 2003) and quasar data (Kirkman et al. ApJS, 149, 1, 2003) which place the primordial value of D/H = $27.8^{+4.4}_{-3.8}$ ppm. **Recent observations with FUSE call this agreement into question.**

2 An emerging pattern for D/H Beyond the Local Bubble

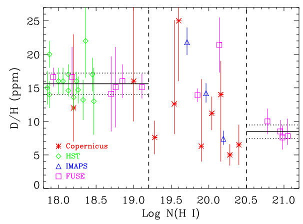

FIGURE 1: Gas phase D/H vs. H I column density

Figure 1 summarizes the available D/H measurements for lines of sight in our Galaxy now extending to beyond 1 kpc and $\log N(HI) = 21.1$. We call attention to an emerging pattern in the data:

For lines of sight extending beyond the Local Bubble, D/H has a wide range as seen toward white dwarfs, subdwarf OB stars, and main sequence OB stars. Beyond the Local Bubble D/H ranges from 5.0 ± 1.6 ppm for the θ Car LOS (Copernicus) to $21.8^{+2.2}_{-1.9}$ ppm observed for the γ^2 Vel LOS (IMAPS). This wide range in D/H values is seen in observations by the Copernicus, IMAPS, and FUSE satellites and is unlikely an instrumental effect.

For the longest lines of sight in the Galaxy studied so far, there is a pattern of D/H being a **factor of 2** below the Local Bubble value. This result is strengthened by the recent analysis (Wood et al. 2004) of lines of sight to the subdwarfs JL 9 and LSS 1274, located at about 590 pc. For $\log N_{HI} \geq 20.5$, the four FUSE data points are clumped at D/H = 8.5 ± 0.9 ppm. The 3 lines of sight (1 IMAPS and 2 Copernicus) in the range $\log N_{HI} =$ 20.2–20.5 are also very low. **Seven lines of sight indicate a trend.**

All Galactic disk lines of sight observed so far have D/H values smaller than D/H = $27.8^{+4.4}_{-3.8}$ ppm for quasar lines of sight (presumably close to primordial D/H). Most Galactic lines of sight have D/H values smaller than D/H = 22 ± 7 ppm reported by Sembach et al. (ApJS, 150, 387, 2004) for the PG 1259+593 (Complex C) line of sight. Complex C is a rapidly infalling cloud of gas with 0.1–0.4 $Z_\odot$ at 5–10 kpc distance.

What does this mean for Galactic chemical evolution? Previous studies have assumed two possible explanations for the large range of D/H values, but both explanations have problems and we argue for a different explanation.

Variable Astration: The observed factor of 4–5 range in D/H values beyond the Local Bubble is difficult to explain. Why should 7 lines of sight at large N_{HI} show the same low values of D/H over a wide range of Galactic longitude, while shorter lines of sight show large variations?

Variable Infall of primordial gas: Why should there be large variations in D/H over relatively short (< 100 pc) distance scales? Why would the infalling gas be precisely placed in the local disk and then not well mixed? Note that abundances in Complex C vary between 0.1 and 0.4 $Z_\odot$ over distance scales of 100 pc (Collins, Shull, and Giroux ApJ, 585, 336 (2003)).

3 Why Variable Depletion?

Draine (paper presented at the Carnegie Observatories symposium on "The origin and Evolution of the Elements") presented a detailed argument for D depletion on to grains:

- Consider dust grains containing 200 ppm of C relative to H (typical for the ISM). Solid C would likely be hydrogenated as PAHs with H/C = 0.25. So 50 ppm of H is in the grains.
- If 20% of the hydrogen in grains were D, then D_{gas}/H_{total} = 10 ppm and (D/H)$_{gas}$ would be reduced by 10 ppm. Could (D/H) in grains be 10^4 times higher than in the gas phase?
- The difference in binding energies of C-D vs C-H is 0.092 eV. The difference in binding energies of HD vs H_2 is 0.035 eV. Therefore, it is energetically favorable for impinging D atoms to displace H atoms in grains.
- In thermodynamic equilibrium (D/H)$_{dust}$ will exceed 10^4 for $T_{gas} \leq 70$ K. So grains will gradually deplete the ISM gas phase of D until a shock destroys the grains and returns the D to the ISM. A strong UV radiation field may do the same.

4 Our Hypothesis

We assume that the total D/H (gas and dust) is relatively constant in the Local Disk (within 1 kpc), but (D/H)$_{gas}$ varies because of time- and spatially-dependent D depletion.

Regions that have not been shocked in a long time will have low values of (D/H)$_{gas}$. The (J=0,1) rotational excitation temperature of H_2 toward JL 9 is 89 ± 6 K and toward LSS 1274 is 64 ± 5 K.

Regions that have recently been shocked will have high values of (D/H)$_{gas}$ which should be close to the total value for D/H in the Local Disk, i.e., (D/H)$_{LD}$. Note that (D/H)$_{gas}$ is high for the α Cru and γ^2 Vel lines of sight. These stars are in young star forming regions that were likely shocked recently.

The Local Bubble was recently shocked (1–2 million years ago), so (D/H)$_{LBgas}$ is close to but somewhat lower than (D/H)$_{LB}$.

Long lines of sight pass through many different shocked and nonshocked regions. If the cold (not recently shocked) regions have larger N_{HI}, then the average value of (D/H)$_{gas}$ for lines of sight with large N_{HI} should be systematically low.

5 Evidence for Variable Depletion

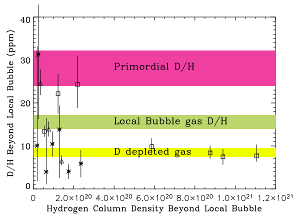

FIGURE 2: Gas phase D/H after subtraction for the Local Bubble component.

- Four lines of sight have high values of (D/H)$_{gas}$ beyond the LB: α Cru, Feige 110, γ^2 Vel, and PG 1259+593 (Complex C). Note that α Cru and γ^2 Vel are in regions with many young stars, so that much of the gas was likely shocked recently. Also γ^2 Vel is a WR+O star binary in a large H II region and near the Vela SNR.
- Many lines of sight with relatively and high N_{HI} have low values of (D/H)$_{gas}$ beyond the LB.
- H_2 is a good indicator of regions of low temperature where D depletion on grains could be important and shocks have not occured for some time. The fraction of H_2 is, $f(H_2) = \frac{2N(H_2)}{N(HI)+2N(H_2)}$.
- Low (D/H)$_{gas}$ correlates with high $f(H_2)$ and high (D/H)$_{gas}$ correlates with low $f(H_2)$ as predicted (see Fig. 3).
- But PG 0038+199 is an exception (prepublication data from Gerard Williger). Why? $T(H_2) = 141 \pm 8$ K, which is well above the usual value for the Galactic disk (see poster 61.19). So the gas and dust may be too hot in this line of sight for D depletion to work. PG 0038+199 is located near the edge of the disk.

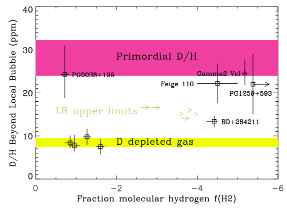

FIGURE 3: Anticorrelation of gas phase D/H with H_2 fraction for lines of sight beyond the Local Bubble.

6 Implications for Galactic Chemical Evolution

- The most likely value of (D/H)$_{LD}$ (total of the gas and grains) in the Local Disk is the highest credible value for (D/H)$_{gas}$. So (D/H)$_{LD} = 23 \pm 4$ ppm.
- If the quasar value of D/H is close to primordial, then the astration factor for the local disk is roughly $27.8^{+4.4}_{-3.8}/23 \pm 4 = 1.2 \pm 0.3$.
- If instead we use the primordial D/H estimated from analysis of the WMAP data (Spergel et al. ApJS, 148, 175 (2003)), then the astration factor would be even smaller, $25^{+3.0}_{-3.4}/23 \pm 4 = 1.1 \pm 0.25$.
- In either case present Galactic chemical evolution models would have to be modified to explain the very low astration factors or include higher rates of inflowing gas from the halo or IGM.

FUSE is a joint mission of NASA, the Canadian Space Agency, the French space agency CNES, the Johns Hopkins University, the University of Colorado at Boulder, and the University of California at Berkeley. We thank NASA and the JHU for their support.