Galactic Disk?

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Abstract

Analyses of spectra obtained with the FUSE satellite, together with spectra from the Copernicus and IMAPS instruments, reveal a very wide range in the observed deuterium/hydrogen (D/H) ratios for interstellar gas in the Galactic disk beyond the Local Bubble. For gas located beyond the Local Bubble but within several hundred parsecs, the observed D/H ratios differ by a factor of 4–5, which is difficult to explain solely on the basis of either: (i) small-scale spatial variations in stellar nuclear processes that convert deuterium to heavier elements; or (ii) the infall of deuterium-rich gas from the Galactic halo and the IGM. We argue instead that spatial variations in the depletion of deuterium onto dust grains can explain these local variations in the observed gas-phase D/H ratios. We present a deuterium depletion model that naturally explains the constant measured values of D/H inside the Local Bubble, the wide range of gas-phase D/H ratios observed in the intermediate regime ($\log N(H\ I)$ = 19.2–20.7), and the low gas-phase D/H ratios observed at larger hydrogen column densities. We test the deuterium depletion hypothesis by: (i) correlations of gas-phase D/H ratios with depletions of the refractory metals iron and silicon, and (ii) correlation with HD in heavily reddened lines of sight. Both of these tests are consistent with deuterium depletion from the gas phase in cold, not recently shocked, regions of the ISM, and high gas-phase D/H ratios in gas that has been shocked or otherwise heated recently. We argue that the total (gas plus dust) D/H ratio within 1 kpc of the Sun has a much larger value than D/H in the gas phase in the Local Bubble, indicating that over the lifetime of the Galaxy there has been a relative small decrease in the total D/H ratio from its primordial value.

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 now 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(H I) < 19.2, is essentially constant, (D/H)$_{\rm gas} = 15.6 \pm 0.4$ parts per million (ppm), where 0.4 ppm is the standard deviation of the mean (Wood et al. ApJ, 609, 838, 2004). 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 data (Spergel et al. ApJS, 148, 175, 2003) and the Cyburt et al. (Phys. Lett. B, 567, 227, 2003) nuclear reaction rates which place the primordial value of (D/H)$_{\rm prim} = 27.5^{+2.4}_{-1.9}$ ppm. **Recent observations with FUSE call this agreement into question.**

2 An emerging pattern for (D/H)$_{\rm gas}$ beyond the Local Bubble

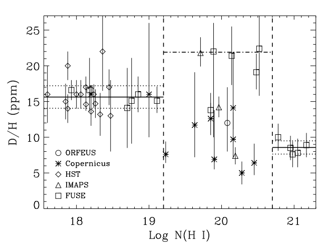

FIGURE 1: Gas phase D/H vs. H I column density

Figure 1 summarizes the published D/H measurements for lines of sight in our Galaxy now extending to beyond 1 kpc and to log N(H I) = 21.2. We call attention to an emerging pattern in the data:

For lines of sight (LOS) 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)$_{\rm gas}$ 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)$_{\rm gas}$ 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. For log N(H I) ≥ 20.5, the five FUSE data points are clumped at (D/H)$_{\rm gas} = 8.6 \pm 0.8$ ppm. The 3 lines of sight (1 IMAPS and 2 Copernicus) in the range log N(H I) = 20.2–20.5 are also very low. **Five lines of sight indicate a trend.**

All Galactic disk lines of sight observed so far have (D/H)$_{\rm gas}$ smaller than (D/H)$_{\rm prim} = 27.5^{+2.4}_{-1.9}$ ppm. Most Galactic lines of sight have (D/H)$_{\rm gas}$ values smaller than 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)$_{\rm gas}$ 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)$_{\rm gas}$ beyond the Local Bubble is difficult to explain given nuclear reaction rates, stellar evolution, and interstellar mixing timescales. Why should 5 lines of sight at large N(H I) 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)$_{\rm gas}$ over short (< 100 pc) distance scales? Why would the infalling gas be precisely placed in the local disk and then not well mixed at larger distances? 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 replaced by D, then D$_{\rm gas}$/H$_{\rm total}$ = 10 ppm and (D/H)$_{\rm gas}$ 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 0.083 eV. Therefore, it is energetically favorable for D atoms to displace H atoms in grains.
- In thermodynamic equilibrium (D/H)$_{\rm dust} \geq 5 \times 10^4$ for $T_{\rm gas} \leq 90$ 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.
- The time scale for deuterium depletion is a few million years in the cold neutral medium.
- Very large D/H ratios have been measured in interplanetary dust grains that were likely formed in the ISM. **This is an important "proof of concept" for deuterium depletion.**

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)$_{\rm gas}$ 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)$_{\rm gas}$. 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. These are two of the five lines of sight with large N(H I).

Regions that have recently been shocked will have high values of (D/H)$_{\rm gas}$ which should be close to the total value for D/H in the Local Disk, i.e., (D/H)$_{\rm LD}$. Note that (D/H)$_{\rm gas}$ 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)$_{\rm LBgas}$ is close to but somewhat lower than (D/H)$_{\rm LB}$.

Long lines of sight pass through many different shocked and nonshocked regions. **Since cold (not recently shocked) regions usually have much larger N(H I) than the warm, recently shocked gas, the average value of (D/H)$_{\rm gas}$ for lines of sight with large N(H I) should be systematically low.**

5 Evidence for Deuterium Depletion

If deuterium is depleted onto dust grains, then (D/H)$_{\rm gas}$ should be correlated with the depletion of metals that are depleted onto grains. We find good correlations using both iron and silicon, but here demonstrate the effect with iron using different data samples.

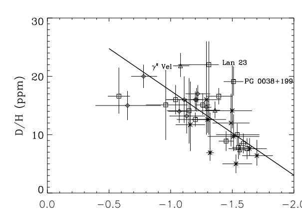

FIGURE 2: Gas phase D/H vs. the depletion of Fe using all 36 lines of sight. The solid line is a weighted least-squares fit to the data.

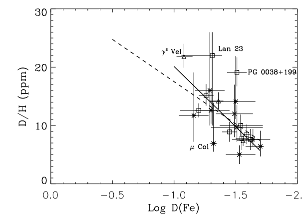

FIGURE 3: (D/H)$_{\rm gas}$ vs. Fe depletion for sightlines with log N(H I)≥ 19.0. Removal of the shorter lines of sight minimizes possible corrections for hydrogen partial ionization. The dashed lines is the fit in Figure 2.

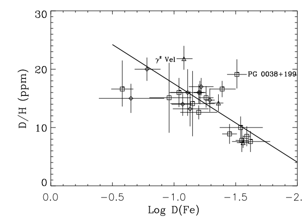

FIGURE 4: Gas phase D/H vs. the depletion of Fe using data only from STIS, GHRS, and FUSE. This plot deletes the more uncertain Copernicus data.

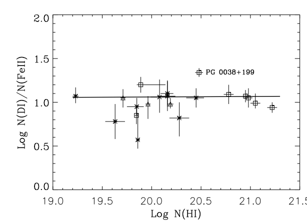

FIGURE 5: Gas phase N(D I)/N(Fe II) vs. the H I column density. In this plot N(H I) is used in only one axis to avoid spurious correlations. The dominant stages of ionization of D and Fe are clearly correlated.

6 Implications for Galactic Chemical Evolution (GCE) Models

(1) We propose that the most likely value of (D/H)$_{\rm LD}$ (total for gas and grains in the local disk) is $\geq 21.9 \pm 2.7$ ppm. This is the mean value of the four lines of sight with the highest (D/H)$_{\rm gas}$. Since even these lines of sight may have some deuterium in grains, (D/H)$_{\rm LD}$ is a lower limit.

(2) The primordial D/H estimated from analysis of the WMAP data is (D/H)$_{\rm prim}$ $= 27.5^{+2.4}_{-1.9}$ ppm. The corresponding astration factor is $(27.5^{+2.4}_{-1.9})/(21.9 \pm 2.7) \leq 1.25 \pm 0.17$, well below 1.5 predicted by GCE models.

(3) We conclude that GCE models should be modified to explain this very low astration factor and perhaps include higher rates of inflowing gas from the halo or IGM.

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