Deuterium abundances along three extended sightlines from *FUSE* observations: Preliminary Results

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Introduction

• Observations of the D/H ratio in the ISM provide important constraints on Galactic chemical evolution models as well as on Big Bang nucleosynthesis theory.

• Measurements of the D/H ratio show that D/H = $(1.56 \pm 0.04)\times10^{-5}$ inside the Local Bubble (log N(H I) $\leq$ 19.2) and D/H = $(0.87 \pm 0.08)\times10^{-5}$ for log N(H I) > 20.7. For 19.2 $\leq$ log N(H I) $\leq$ 20.7 there is a wide range of values.

• Measurements of the D/O ratio show that it behaves similarly to D/H. D/O = $(3.84 \pm 0.16)\times10^{-2}$ inside the Local Bubble and D/O = $(2.0 \pm 0.5)\times10^{-2}$ for log N(D I) > 15.5, with a wide range of values in the intermediate column densities.

• Measurements of the O/H ratio show that it does not vary as D/H and D/O. O/H = $(3.43 \pm 0.15)\times10^{-4}$ for low density sightlines ($n_H < 1.0$ cm^{-3}) and log N(H I) < 21.0.

• Currently, the behavior of the D/H and D/O ratios is not understood. Depletion of deuterium into dust grains is being investigated as a possibility to explain this behavior.

• The small number of sightlines with measured D/H and D/O ratios, for log N(D I) > 15.0, is a limitation to our understanding of the problem. In this work we present a preliminary study of the D/H, D/O, and O/H ratios for 3 sightlines with log N(D I) > 15.7.

FUSE Observations

Table 1 - Star Properties.

Target	Sp. Type	l (°)	b (°)	d (Kpc)	v_{sini} (km s^{-1})	log N(H I) (cm^{-2})	E_{B-V}
HD 41161	O8V	164.97	+12.89	1.25	300	20.98 ± 0.07	0.23
HD 53975	O7.5V	225.68	−2.32	1.5	147	21.10 ± 0.08	0.22
HD 177566	PAGB	355.55	−20.42	1.1	...	20.88 ± 0.09	0.07

Table 2 - FUSE Observations.

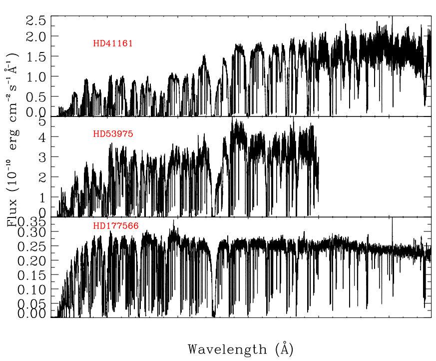
Target	Obs. ID	Date	Mode	Aperture	Time (s)
HD 41161	P1021001	20 Feb 01	HIST	LWRS	58
...	P1021002	25 Sep 03	HIST	MDRS	6520
HD 53975	P3032301	24 Feb 04	HIST	MDRS	482
HD 177566	P1017003	18 Sep 00	HIST	LWRS	7764

• HD 53975 was only observed with the SiC channels due to its brightness.

• All the data used in these analyses were calibrated with CalFUSE V3.

• The high v_{sini} of HD 41161 and HD 53975 allow us to determine which lines are of photospheric origin. For HD 177566 the separation between interstellar and stellar absorption is $v_{ISM-PH} \sim +120$ km s^{-1}.

Figure 1 - *FUSE* observations of the three targets.



Analysis Methodology

• *FUSE* observations of the three targets are presented in Figure 1. The column densities along the 3 lines of sight were determined by profile fitting (PF), curve of growth (COG) and apparent optical depth (AOD).

• With PF we use a single-Gaussian to describe the line spread function. We fit single absorption components to the molecular and atomic lines along the 3 sightlines.

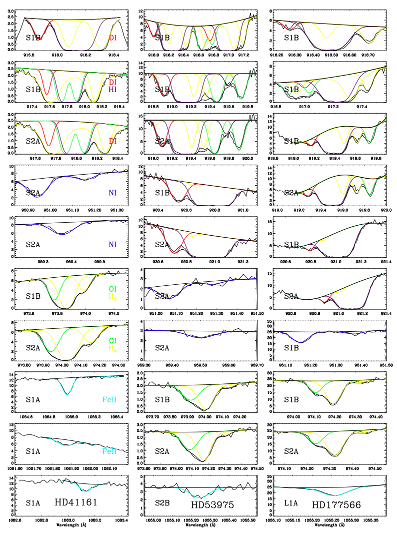
• With the COG method we fit a single component Gaussian curve-of-growth to the measured equivalent widths of all the non-blended transitions of species with more than 2 transitions in the *FUSE* bandpass.

• We use AOD to determine lower limits on N for species which only have saturated transitions in the *FUSE* bandpass and on weak lines as a consistency check on the PF and COG results.

• No stellar models are used to determine N.

• Figure 2 presents some examples of fits to the lines used in the analyses.

Figure 2 - Fits to some of the lines used in the analyses.



• In the fits presented in Figure 2 H I is represented by dark magenta, D I by red, N I by blue, O I by green, Fe II by cyan, and H$_2$ by yellow.

• H I is included in the fits (in a component separated from the other species), only to provide a continuum for the D I fit.

• We use N(H I) determined from *IUE* data for the three sightlines. N(H I) for HD 41161 is from Shull & Van Steenberg (1985, ApJ, 294), and from Diplas & Savage (1994, ApJ, 427) for HD 53975 and HD 177566.

• For HD 177566 strong and broad H I stellar lines fall near the position of the D I absorption, since $v_{ISM-PH} \sim +120$ km s^{-1}. These lines are very hard to model. The D I fits presented in Figure 2 show that we tried reproducing those stellar lines with a polynomial. Continuum placement in the vicinity of the D I lines is the major source of uncertainty in determining N(D I) for this sightline and is hard to quantify. N(D I) quoted in Table 3 does not take into account continuum placement uncertainties.

Results

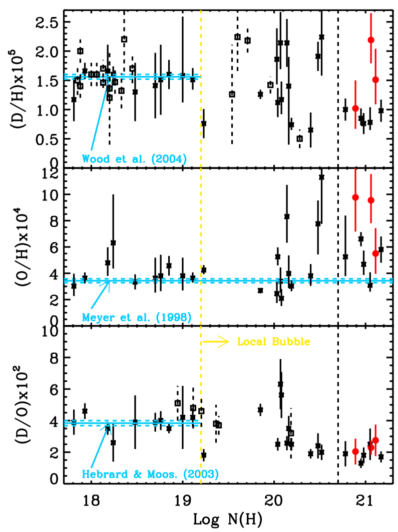
• Table 3 below presents the adopted column densities along the three sightlines studied here.

• The adopted values are a compromise between the results derived with the different methods described in the Analysis Methodology.

Table 3 - Interstellar column densities (Log) for HD 41161, HD 53975, and HD 177566, with 1σ error bars.

Species	HD 41161	HD 53975	HD 177566
H I	20.98 ± 0.07	21.10 ± 0.08	20.88 ± 0.09
D I	16.40 ± 0.06	16.29 ± 0.11	15.90 ± 0.15
N I	17.00 ± 0.06	16.84 ± 0.08	16.60 ± 0.08
O I	18.04 ± 0.06	17.85 ± 0.11	$17.59 \pm^{0.07}_{0.10}$
Fe II	14.98 ± 0.06	14.85 ± 0.05	14.68 ± 0.08
H_{20}	19.63 ± 0.05	18.90 ± 0.10	18.80 ± 0.10
H_{21}	19.76 ± 0.05	18.97 ± 0.10	18.70 ± 0.10
H_{22}	17.9:	18:	17.3:
H_{23}	17.3:	17.8:	16.6:
H_{24}	14.89 ± 0.05	14.20 ± 0.05	14.00 ± 0.10
H_{25}	14.33 ± 0.05	14.0	14.0
HD0	14.60 ± 0.10	14.0	14.0
H_{Total}	21.06 ± 0.06	21.11 ± 0.08	20.89 ± 0.09

Figure 3 - D/H, O/H, and D/O as a function of Log N(H).



• Figure 3 compares the ratios derived here (in red) with ratios from the literature.

• The data are from the compilation by Wood et al. (2004, ApJ, 609), Friedman et al. (2006, ApJ, in press), Hébrard et al. (2005, ApJ, 635) and Oliveira et al. (2006, ApJ, in press).

• Sightlines displayed with open squares in the top panel do not have N(O I) available. Sightlines displayed by open squares in the bottom panel do not have N(H) available. N(H) is estimated using N(O I) and the Meyer et al. (1998, ApJ, 493) O/H ratio.

Discussion

Table 4 - Ratios of several atomic species for HD 41161, HD 53975, and HD 177566.

Ratio	HD 41161	HD 53975	HD 177566
D I/H$\times10^5$	$2.19 \pm^{0.46}_{0.40}$	$1.51 \pm^{0.53}_{0.42}$	$1.02 \pm^{0.48}_{0.35}$
N I/H$\times10^5$	$8.71 \pm^{1.82}_{1.59}$	$5.37 \pm^{1.54}_{1.28}$	$5.13 \pm^{1.57}_{1.29}$
O I/H$\times10^4$	$9.55 \pm^{2.00}_{1.74}$	$5.50 \pm^{1.93}_{1.54}$	$5.01 \pm^{1.44}_{1.40}$
D I/O I$\times10^2$	$2.29 \pm^{0.48}_{0.42}$	$2.75 \pm^{1.12}_{0.87}$	$2.04 \pm^{0.91}_{0.73}$
O I/N I	$10.96 \pm^{2.30}_{2.00}$	$10.23 \pm^{3.60}_{2.86}$	$9.77 \pm^{2.61}_{2.60}$

Quoted errors are 1σ.

D/H

The D/H ratios for HD 41161 and HD 53975 do not seem to follow the trend of low D/H displayed in Figure 3 for Log N(H) > 20.7. The weighted mean of the previously published D/H ratios in Figure 3 with Log N(H) > 20.7 yields D/H$\times10^5$ = 0.87 ± 0.08, with χ^2_ν = 0.35 for 4 degrees of freedom. Considering in addition the three ratios derived here yields D/H$\times10^5$ = 0.93 ± 0.08 with χ^2_ν = 1.73 for 7 degrees of freedom, consistent with the weighted mean for the previously published D/H ratios. There is however a large increase in χ^2_ν. The probability that χ^2_ν > 1.7 for 7 degrees of freedom is <10%. The D/H ratios along the HD 41161 and HD 53975 sightlines might provide the first evidence that D/H is not low and constant in this N(H) range as previously thought. Further analysis will allow us to reduce $\sigma_{N(DI)}$ and derive tighter constraints on D/H for these two sightlines.

N/H

Meyer et al. (1997, ApJ, 490) have determined N/H = $(7.5 \pm 0.4)\times10^{-5}$ from a study of 7 sightlines with Log N(H) ranging from 20.18 to 21.15. The N/H ratios derived here are slightly low, but still within 1.5σ of the Meyer et al. value. These results seem to indicate that the high D/H ratios for HD 41161 and HD 53975 are not due to N(H I) being underestimated, as ionization corrections of N are thought to be negligible at these high N(H).

O/H

Several studies of the O/H ratio within ∼ 1 Kpc of the Sun (Meyer et al. 1998, ApJ, 493, André et al. 2003, ApJ, 591) have shown that this ratio is constant. Meyer et al. (1998, ApJ, 493) derived O/H = $(3.43 \pm 0.15)\times10^{-4}$. The O/H for HD 41161 is more than 3σ away from the Meyer et al. O/H value, while for HD 53975 and HD 177566 the values are within 1.4σ. In fact, only one out of seven O/H ratios in Figure 3 with Log N(H) > 20.7 is consistent within 1σ with the Meyer et al. value, and some are even super-solar. In effect, if only the *FUSE* O/H determinations were available one would be compelled to conclude that O/H is not constant. As this scatter in O/H has not been found in other studies the question of what causes it should be investigated.

D/O

Hébrard & Moos (2003) determined D/O = $(3.84 \pm 0.16)\times10^{-2}$ for the LB, and a considerably lower value outside. The D/O ratios derived here are all consistent within 1σ with the previously published D/O ratios for sightlines with Log N(H) > 20.7. This is however misleading since the low D/O ratios are probably due to the high oxygen abundance along these sightlines. For the 8 sightlines in Figure 3 in this N(H) regime we derive the weighted mean D/O$\times10^2$ = 2.04 ± 0.21 with χ^2_ν = 0.60 for 7 degrees of freedom.

O/N

The O/N ratios derived here are all inconsistent at the 2σ level with the ratio derived using the Meyer et al. (1997,1998) N/H and O/H ratios, O/N = (4.1 ± 0.3). For the HD 41161 sightline this is due to the high O/H ratio. For the HD 53975 and HD 177566 sightlines this is due to a combination of slightly high O/H ratios with slightly low N/H ratios.

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