# FUSE OBSERVATIONS OF THE HD MOLECULE TOWARD HD 73882

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## ABSTRACT

The Lyman and Werner band systems of deuterated molecular hydrogen (HD) occur in the far UV range below 1200 Å. The high sensitivity of the *FUSE* mission can give access, at moderate resolution, to hot stars shining through translucent clouds, in the hope of observing molecular cores in which deuterium is essentially in the form of HD. Thus, the measurement of the HD/H<sub>2</sub> ratio may become a new powerful tool to evaluate the deuterium abundance, D/H, in the interstellar medium. We report here on the detection of HD toward the high extinction star HD 73882 ( $E_{\rm B-V} = 0.72$ ). A preliminary analysis is presented.

Subject headings: ISM: abundances — ISM: clouds — ISM: lines and bands — ISM: molecules — ultraviolet: ISM

### 1. INTRODUCTION.

It has long been recognized that the primordial abundance of deuterium represents the most sensitive probe of the baryonic density  $\Omega_{\rm b}$  of the Universe (see, e.g. Schramm & Turner 1998; Olive, Steigman & Walker 1999). Moreover, the abundance of deuterium at any epoch is a lower limit to its primordial abundance since deuterium is solely destroyed in stars of any mass. Therefore, D/H is also an efficient tracer of the universal star formation rate. However, the evolution of the deuterium abundance from zero to solar metallicity is still unclear.

Measurements of the atomic (D/H) ratio have been performed in different astrophysical sites, namely in moderate to high redshift quasar absorbers, in the presolar nebula and in the local interstellar medium (for reviews, see e.g. Ferlet & Lemoine 1996; Linsky 1998; Vidal-Madjar et al. 1998a; Lemoine et al. 1999). These studies indicate that D/H may vary within the local interstellar medium by a factor as high as ~ 2 over spatial scales of few tens of parsecs (Vidal-Madjar et al. 1998b; Jenkins et al. 1999; Sonneborn et al. 2000), while presolar and quasar absorbers D/H abundances are limited by the existing scatter in the results.

Deuterated molecules are another means of estimating the deuterium abundance. To date, over 20 single D-bearing species and two doubly deuterated molecules,  $D_2CO$  and  $ND_2H$ , have been observed at radio frequencies both in cold interstellar dark clouds and in warmer star forming regions (see e.g. Roueff et al. 2000). However, chemical fractionation takes place in cold regions and mantle desorption of grains are often invoked in star forming regions. Deriving accurate deuterium fractional abundances using these molecules is therefore very difficult.

Recently, the R(2) transition at 37.7  $\mu$ m of HD has been detected with ISO in giant planets (Feuchtgruber et al. 1999) and the pure rotational J=1 $\rightarrow$ 0 line at 112  $\mu$ m toward the Orion Bar (Wright et al. 1999). Bertoldi et al. (1999) have also detected the excited rotational line at  $19.43 \,\mu\text{m}$  of HD J=6 $\rightarrow$ 5 in Orion KL, a molecular outflow region. Although ISO thus opened the sky to HD emission, the derived column densities depend strongly on the modelling of HD excitation and on extinction corrections. With *Copernicus*,  $H_2$  and HD molecules were observed in absorption in the ultraviolet in diffuse interstellar clouds such as that toward  $\zeta$  Oph (Wright & Morton 1979). However, the low HD/H<sub>2</sub> value found (few  $\times 10^{-7}$  to few  $\times 10^{-6}$ ) reflects the mostly atomic nature of these diffuse clouds; to determine the D/H ratio from these data requires a detailed model of the formation and of the destruction of HD.

Because of its high throughput, the Far Ultraviolet Spectroscopic Explorer (FUSE; Moos et al. 2000) can give access to denser molecular clouds within which one might expect H and D to be essentially in their molecular form. If so, no chemical fractionation correction will be required and accurate deuterium abundances could result directly from the measurement of the HD/H<sub>2</sub> ratio. In Section 2, we present FUSE observations of HD in the translucent cloud in front of the star HD 73882, along with the data reduction and analysis. A companion paper by Snow et al. (2000) describes the H2 observations. A preliminary discussion is given in Section 3, while some conclusions are drawn in Section 4.

### 2. FUSE OBSERVATIONS OF HD 73882.

Twenty-seven years after *Copernicus*, *FUSE* was successfully launched on June 24, 1999 from Cape Canaveral.

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It has a sensitivity of about  $10^4$  times that of *Copernicus*, in the wavelength range from slightly below the Lyman limit (905 Å) to 1187 Å (Moos et al. 2000). The higher throughput comes about because of the use of a guider that can be used for fainter stars and of the use of an array detector instead of a scanning photomultiplier tube. Many absorption lines from different rotational states of H<sub>2</sub> and HD are available within that range.

The bright early type (O8.5V) star HD 73882 at about 925 pc has been the first target shining through a translucent cloud, with a reddening  $E_{\rm B-V}=0.72$  or  $A_{\rm v}=2.44$  (note that  $E_{\rm B-V}=0.38$  and  $A_{\rm v} \sim 1$  were the highest values observable by *Copernicus*), to be observed with *FUSE* in the time-tagged mode, for a total integration time of  $\simeq 7$  hours between 30 and 31 October 1999. At this time, the spectrograph was still unfocused, resulting in a spectral resolving power  $R=\lambda/\Delta\lambda\simeq 14000$ . Unfortunately, after a short time the two short-wavelength SiC channels became misaligned and failed to accumulate on the target. However, for our very reddened target, most of the information concerning HD is expected to lie above 1000 Å, in the LiF channels.

The spectra were extracted from the 11 sub-exposures with the version 1.6 of the pipeline, and the electronically induced detector bursts were subtracted by screening of the events with IDL tools. The processing includes data screening, thermal drift correction, geometric distortion correction, Doppler correction to heliocentric wavelengths, dead time correction (data loss due to overflow of photon events) and wavelength calibration, but not correction for astigmatism. In order to obtain the best resolution, the calibrated spectra were then manually coadded over small wavelength windows, using both exposure time and error weighting. The resulting signal to noise ratio is  $\simeq 20$  per resolution element in the continuum near the strongest available HD lines.

Fig. 1 shows the final recorded spectrum. Broad  $H_2$  bands are clearly seen (see also Snow et al. 2000), together with some CO bands and several other narrow interstellar features including atomic species such as CI, OI, NI, FeII and PII. One can note that the heavily saturated  $H_2$  lines reach a zero flux, indicating an extremely low level of scattered light in the *FUSE* instrument.

We have performed a preliminary analysis of these data by using a simultaneous profile fitting of all detected lines from any molecular and atomic species included in a recent updated compilation by Morton (private communication). In a first step, a single absorbing component was assumed (and found at a coherent radial velocity for all lines). It has to be noted that most of the lines are saturated so that the column densities are highly sensitive to the value of the intrinsic broadening parameter - b-value - which combines thermal and turbulent widening. Furthermore, the uncertainties in the instrumental line-spread function make it quite plausible that large amounts of cold absorbing gas might be "hidden". Nevertheless, the dominant J = 0 and J = 1 levels of the H<sub>2</sub> lines lie on the damped part of the curve of growth and the total  $H_2$  column density is almost independent of the assumed b-value and the velocity structure of the line of sight. We find  $\log_{10} N(H_2)_{tot} =$  $21.2 \pm 0.2$ , in agreement with Snow et al. (2000).

Absorption from R(0) lines of HD are also detected to-

ward HD 73882, four examples of which are presented 2, arbitrarily set to 0 km s<sup>-1</sup> radial velocity. in Fig. This is a  $\sim 5\sigma$  detection, as shown in the upper panel of Fig. 3, in which is plotted the  $\Delta \chi^2$  of the simultaneous fits of all detected HD lines (except the one blended with OVI near 1031.9 Å) as a function of the HD column density: when N(HD) decreases,  $\Delta \chi^2$  tends to nearly 25. The HD lines, as well as the CO and the high J level  $H_2$  ones, lie on the flat part of the curve of growth where N(HD) heavily depends upon the assumed effective *b*-value (note that this makes useless the use of equivalent widths). In that case, the assumption of a single absorbing component is indeed critical for deriving column densities. From the upper panel of Fig. 3, allowing, conservatively, for  $3\sigma$  variations (about 10 for  $\Delta\chi^2$ ), we find a huge range of values  $14.6 < \log_{10} N(\text{HD}) < 16.9$ , the lower end being even larger than most of the Copernicus measurements. From the present data alone, the saturation of the lines prevents a more precise determination. However, one sees that the best estimates  $(\Delta \chi^2 \sim 0)$  are found for  $\log_{10} N(\text{HD})$  around 16.1 (solid line in Fig. 2) which corresponds, according to the bottom panel of Fig. 3, to an effective *b*-value of about  $1 \text{ km s}^{-1}$ .

### 3. DISCUSSION.

Previous observations of molecules toward HD 73882 include CH, CH<sup>+</sup>, CN, C<sub>2</sub> and CO (Gredel, van Dishoeck & Black 1993, 1994). Although the molecular fraction 2  $N(\text{H}_2)/[N(H) + 2N(\text{H}_2)]$  is quite close to that found toward  $\zeta$  Oph (Snow et al. 2000), the CO/H<sub>2</sub> and CN/H<sub>2</sub> ratios, being very sensitive to the radiation field, differ greatly. These ratios are over 5 times larger for HD 73882 and closer to values found for other dark clouds such as TMC1. The extinction curve for HD 73882 is peculiar compared to "normal" diffuse cloud curves, with a steep far-UV rise and a weak bump at 2200 Å. Moreover, the value of  $R_v = A_v/E_{B-V}$  is 3.39, larger than the mean galactic value  $\simeq 3$  (Cardelli et al. 1989).

Ground based mm-wave <sup>12</sup>CO reveal three components in *emission* separated by 3 and 2.3 km s<sup>-1</sup> (i.e. 5.3 km s<sup>-1</sup> for the extreme ones, nearly as for <sup>13</sup>CO; Gredel, van Dishoeck & Black 1994), not resolved with *FUSE* spectra if indeed they are really intercepted by the HD 73882 line of sight. Snow et al. (2000) show that NaI has many components. However, all diatomic molecules seen in *absorption* show only one component, including the C<sub>2</sub> observations recorded at high spectral resolution (R=10<sup>5</sup>). These components agree in velocity. Therefore, several components might be present, but the possibility of a single molecular absorbing region on the HD 73882 line of sight is not excluded.

The present observation of this relatively high extinction target opens the possibility that, indeed, we are probing a cloud which could have reached the transition point where the reservoir of deuterium is primarily the HD molecule. We have modeled the photodissociation region with a density of 350 cm<sup>-3</sup>, as determined from the analysis of C<sub>2</sub> excitation (Gredel, van Dishoeck & Black 1993), a standard ultraviolet interstellar radiation field and a cosmic ionization rate  $\xi = 5 \times 10^{-17}$  s<sup>-1</sup>, considered as an average (Abgrall et al. 1992; Le Bourlot et al. 1993; Roueff & Nodé-Langlois 1998). The atomic-to-molecular transi-

tion is assumed to be represented by a semi-infinite, plane parallel slab with the radiation field impinging on one side only of the cloud. The mechanisms involved in the photodissociation of HD are very similar to those for  $H_2$ , but self-shielding is much more efficient for the abundant  $H_2$  than for HD. Similarly to  $H_2$ , HD is formed on grains. However, HD is also predominantly formed through the reaction  $H_2 + D^+ \rightarrow HD + H^+$ , whenever substantial H<sub>2</sub> is present.

The main results of this model are displayed in Fig. 4 which shows the evolution of the fractional abundances of atomic hydrogen and deuterium, and their associated molecular species, as a function of the extinction  $A_v$ . It is clear that the H to H<sub>2</sub> transition occurs at significantly lower extinction than the D to HD transition (note that the C to CO transition would take place at even higher extinction than HD). This reflects the smaller contribution of self-shielding in the photodissociation mechanism for HD. According to the extinction value for our target star, if there are not a large number of velocity components, we might be dealing with an absorbing region where HD is the primary reservoir of deuterium. It also shows that even if several components are detected in atomic lines, they may be present in the  $H_2$  lines, but not necessarily in the HD ones which are tracing a deeper region in the cloud.

### 4. CONCLUSION.

We have reported *FUSE* observations in the direction of the reddened star HD 73882. Several lines from the HD

molecule are detected, together with many from  $H_2$ . Under the assumption of a single absorbing molecular component, our best estimate for the  $HD/H_2$  column density ratio from a simultaneous profile fitting of all detected lines is of the order of  $10^{-5}$ . However, strictly speaking this is only an upper limit since the fit is very sensitive to the intrinsic width of the lines, most of them being saturated.

This preliminary evaluation toward such a reddened star opens the possibility of probing regions sufficiently deep into interstellar molecular clouds for HD to be the main reservoir of deuterium atoms. In such regions, the measurement of the  $HD/H_2$  ratio would thus become a new reliable and powerful tool for determining the interstellar D/H ratio in dense regions for which the simple relation  $(D/H) = 0.5 \times HD/H_2$  will apply. Recall that the possibility of multiple clouds for the present line of sight prevents claiming it is indeed the case. One may hope that a number of similar future FUSE observations will ultimately succeed, providing additional information on the structure of the observed sight-lines is available.

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FIG. 1.— *FUSE* spectrum of HD 73882 from 1030 to 1120 Å. Many atomic and molecular absorption lines are detected. Most of them are from molecular hydrogen (tick marks indicate those from J = 1 to J = 4). Lines from  $H_2(J = 0)$  at 1037, 1049, 1063, 1077, 1092 and 1108 Å and from  $H_2(J = 1)$  are strongly saturated. A CO band at 1088 Å is also indicated. The gap around 1085 Å is due to the gap in between the two micro-channel plates mounted in each LiF detectors.

FIG. 2.— Plots of four  $B^1 \Sigma_u^+ - X^1 \Sigma_g^+$  electronic transitions of HD detected in absorption toward HD 73882 at 1042.85, 1054.29, 1066.27 and 1105.91 Å, corresponding respectively to J=5 $\rightarrow$ 0, J=4 $\rightarrow$ 0, J=3 $\rightarrow$ 0 and J=0 $\rightarrow$ 0 (the J=2 $\rightarrow$ 0 and J=1 $\rightarrow$ 0 lines are hidden by strong H<sub>2</sub> lines). The actual *FUSE* wavelength absolute calibration being uncertain by few km s<sup>-1</sup>, the wavelength scale has been shifted and the HD lines aligned at the same radial velocity arbitrarily set to 0 km s<sup>-1</sup>. The solid line is the best fit obtained simultaneously for all detected HD lines and other identified absorptions. To underline the detection independently proven by the  $\chi^2$  variation (see text and Fig. ??), the bottom panel shows the composite solution covering the first three HD lines, thus enhancing the S/N ratio (the line at 1105.91 Å is blended with CI and has been excluded in the summation).

FIG. 3.— The upper panel is a plot of the  $\Delta \chi^2$  of the spectral fits as a function of the HD column density. The lower panel gives the best estimates of N(HD) as a function of the effective *b*-value. Small *b*-values are slightly favoured by the  $\Delta \chi^2$ .

FIG. 4.— Comparison of the relative evolution of H, D, H<sub>2</sub> and HD fractional abundances (relative to the proton density) with A<sub>v</sub>. We assume that a semi infinite plane-parallel cloud is exposed to an isotropic "standard" interstellar ultraviolet radiation field (scaling factor  $\chi$ =1). The cloud has a constant density  $n_{\rm H}$ =350 cm<sup>-3</sup>, deduced from C<sub>2</sub> observations toward HD 73882.  $\xi$  is the cosmic ionization rate. For HD 73882, A<sub>v</sub>=2.44. The small changes in the HD and D curves beyond A<sub>v</sub> ~5 are due to slight variations in temperature within the cloud which in turn induce slight chemical variations.







