ISO–LWS detection of the 112 µm HD $J=1\rightarrow0$ line toward the Orion Bar

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ABSTRACT

We report the first detection outside of the solar system of the lowest pure rotational $J=1\rightarrow0$ transition of the HD molecule at 112 \( \mu \)m. The detection was made toward the Orion Bar using the Fabry-Pérot of the Long Wavelength Spectrometer (LWS) on board the Infrared Space Observatory (ISO). The line appears in emission with an integrated flux of \((0.93\pm0.17)\times10^{-19}\) W cm\(^{-2}\) in the LWS beam, implying a beam–averaged column density in the \(v=0, J=1\) state of \((1.2\pm0.2)\times10^{17}\) cm\(^{-2}\). Assuming LTE excitation, the total HD column density is \((2.9\pm0.8)\times10^{17}\) cm\(^{-2}\) for temperatures between 85 and 300 K. Combined with the total warm H\(_2\) column density of \(\sim(1.5-3.0)\times10^{22}\) cm\(^{-2}\) derived from either the H\(_2\) pure rotational lines, C\(^{18}\)O observations or dust continuum emission, the implied HD abundance, HD/H\(_2\), ranges from \(0.7\times10^{-5}\) to \(2.6\times10^{-5}\), with a preferred value of \((2.0 \pm 0.6) \times 10^{-5}\). The corresponding deuterium abundance of \([\text{D}] / [\text{H}] = (1.0 \pm 0.3) \times 10^{-5}\) is compared with recent values derived from ultraviolet absorption line observations of atomic H\(\text{I}\) and D\(\text{I}\) in interstellar clouds in the solar neighborhood and in Orion.

*Subject headings:* ISM: abundances : molecules : individual : (Orion Bar) — infrared: ISM : lines and bands
1. Introduction

The deuterium abundance is one of the most sensitive probes of the baryon density in the early universe (Wilson & Rood 1994), since it is thought that all the deuterium was produced in the Big Bang, with no subsequent production via nuclear reactions in stars. Conversely, it is destroyed in stellar interiors, so that current measurements provide only a lower limit on the primordial deuterium abundance. Thus, an observed [D]/[H] ratio may also be used as a measure of galactic chemical evolution. However, previous ground and airplane based attempts to measure the [D]/[H] ratio in a variety of interstellar sources have met with several problems, such as the very low intrinsic strength of the D\(\text{I}\) 92 cm line (Heiles et al. 1993) or chemical fractionation and line saturation effects in molecules (Penzias et al. 1977). The most successful measurements so far have been through satellite ultraviolet absorption line observations of the Ly\(\alpha\) lines of atomic H\(\text{I}\) and D\(\text{I}\) through diffuse clouds along the line–of–sight toward several stars in the solar neighborhood (i.e. within \(\sim 90\) pc). These give [D]/[H]=1.6\(\times\)10\(^{-5}\) with a typical uncertainty of 15%, a value so far independent of the line–of–sight (e.g., Dring et al. 1997, Piskunov et al. 1997).

Hydrogen deuteride, HD, has also been detected in local diffuse molecular clouds through ultraviolet absorption line observations (e.g., Spitzer et al. 1973), but its abundance is low in these tenuous clouds because of rapid photodissociation of the molecule. In contrast, virtually all of the deuterium is expected to be contained within HD in dense, warm molecular clouds. Measurements of the \(v=0–0\) \(J=1\rightarrow0\) 112.072 \(\mu\)m line can potentially provide a direct and accurate determination of the HD abundance, and thereby also the deuterium abundance, in such clouds. A previous attempt to observe this line was made by Watson et al. (1985) toward the Orion KL region, but resulted only in an upper limit of \(1 \times 10^{-18}\) W cm\(^{-2}\). In this paper we report the first detection of the 112 \(\mu\)m HD \(J=1\rightarrow0\) line outside of the solar system.
The detection was made toward the Orion Bar, a warm Photon Dominated Region (PDR), and the line is observed to be in emission. PDRs have the advantage over other source types, such as embedded young stellar objects, in that they have a large amount of warm molecular gas at sufficiently high temperatures to excite the HD $J=1\rightarrow0$ 112 $\mu$m line. They do not have cold surrounding material which could absorb and cancel part of the emission. The main drawback is that HD is rapidly photodissociated at the edge of the PDR, so that its abundance does not become large until $A_V \approx 2 - 3$ mag into the cloud (e.g., Jansen et al. 1995a). The physical and chemical structure of the Orion Bar is, however, well understood from a variety of molecular line observations (e.g., Hogerheijde et al. 1995, Jansen et al. 1995b, van der Werf et al. 1996). It has a particularly high total H$_2$ column density due to its edge–on geometry, facilitating the detection of HD. Our successful observation provides a determination of the HD abundance, as well as a probe of the chemistry of molecular clouds. When compared with observations of molecular hydrogen, it also allows a constraint to be placed on the cosmologically important [D]/[H] ratio, the first such direct measurement in a dense molecular cloud without the complicating effects of chemical fractionation.

2. Observations and data reduction

The Orion Bar was observed during revolution 823 using the LWS04 Fabry–Pérot (FP) mode of the Long Wavelength Spectrometer (LWS, Clegg et al. 1996) on board the Infrared Space Observatory (ISO, Kessler et al. 1996). The rest frequency of the HD $J=1\rightarrow0$ line is 2,674,986.66±0.15 MHz (Evenson et al. 1988) corresponding to a vacuum wavelength of 112.072506±0.000007 $\mu$m. The observed coordinates were RA = 05$^h$ 35$^m$ 20.3$^s$ and DEC = $-05^\circ$ 25’ 20” (J2000), a position which closely corresponds to the peak column density of molecular gas (e.g., Burton et al. 1990; Parmar, Lacy & Achtermann 1991; Hogerheijde et
The observations consist of 120 separate LWS FP scans centered on the frequency of the HD $J=1\rightarrow0$ line, with 7 spectral elements on either side of the line. The data were taken with the LW2 detector in fast scanning mode, with 4 spectral samples per resolution element and 45.5 s per sample. The total on-target-time was 3913 s. The FWHM beam size at 122 $\mu$m, the central wavelength of detector LW2, in the spacecraft Y–Z directions is $78'' \times 75''$ with a systematic uncertainty of up to 20% (Swinyard et al. 1998). The resolving power is of order 9500 or $\sim 30$ km s$^{-1}$ (Clegg, Heske & Trams 1994), and the wavelength calibration accuracy is good to a third of a resolution element, or 10 km s$^{-1}$ (Trams et al. 1998). A full range 43–197 $\mu$m LWS01 grating spectrum, consisting of 5 scans with 0.7 s integration time per step and a spectral sampling interval of 2, was obtained during the same revolution for calibration purposes (fringes, continuum level).

Initial data reduction was carried out using the ISO–LWS Off Line Processing (OLP) software, version 7.0, up to the Auto Analysis Result stage. Further data processing, such as removal of bad data points, flat-fielding, sigma clipping and co-adding, was performed using software in the ISO Spectral Analysis Package, and the LWS and Short Wavelength Spectrometer (SWS) Interactive Analysis (IA) packages. Of particular note is the dark current subtraction and grating position correction. The relatively high flux of the Bar results in some straylight leakage through the misaligned Fabry–Pérot plates during the dark current measurements, meaning that they are not true dark currents. Therefore, the dark current was iteratively modified such that the resultant continuum flux was equal to that obtained in the LWS01 observation. Using the LWS IA tool FP\_PROC (Swinyard et al. 1998, Sidher et al., in preparation), the subsequent product was corrected for a grating positioning problem, which introduces a spurious slope in the spectrum. By adopting these procedures, our photometric accuracy is estimated to be 30% or better (Burgdorf et al.
3. Results

Figure 1 displays the resulting spectrum after co–addition of all FP scans. An emission line is clearly visible at $v_{\text{LSR}} \approx +13$ km s$^{-1}$, close to the expected $v_{\text{LSR}} \approx +10$ km s$^{-1}$ known for the Bar (e.g., Hogerheijde et al. 1995). The feature is unresolved, with an observed FWHM of $\sim 30$ km s$^{-1}$, i.e., near the resolving power of the LWS and implying an intrinsic FWHM less than this, again consistent with previous millimeter observations which show $\Delta V \approx 2$ km s$^{-1}$. The observed integrated line flux is $(7.3 \pm 1.3) \times 10^{-20}$ W cm$^{-2}$, obtained by fitting a Gaussian to the line profile, and a first order polynomial plus sinusoid due to fringing (see below) to the baseline. The uncertainty is statistical and represents the range of values obtained using different fitting procedures. When divided by the LW2 beam size, $1.08 \times 10^{-7}$ sr, the inferred surface brightness is $I = (6.76 \pm 1.20) \times 10^{-6}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$. As noted in the LWS Data Users Manual (Trams et al. 1998), the LWS OLP software corrects the data of detector LW2 by a factor of 0.68 for the effective aperture of the instrument, assuming that the source is point–like and located at the aperture centre. This is not the case for the Orion Bar, which is extended in both its gas and dust emission. The Data Users Manual gives a correction factor of 0.87/0.68 at 100–120 $\mu$m which must be applied to observed fluxes for extended sources. The resulting best estimate of the flux is $(9.3 \pm 1.7) \times 10^{-20}$ W cm$^{-2}$ and of the surface brightness is $(8.7 \pm 1.5) \times 10^{-6}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$. This corresponds to an antenna temperature of $\sim 0.22$ K in the LWS beam for $\Delta V \approx 2$ km s$^{-1}$.

The beam averaged column density in the HD $v=0$, $J=1$ state is obtained from $N_{0,1} = (4\pi I_{1\rightarrow 0})/(A_{1\rightarrow 0}h\nu_{1\rightarrow 0})$, where $I_{1\rightarrow 0}$ is the observed surface brightness. Using $A_{1\rightarrow 0} = 5.12 \times 10^{-8}$ s$^{-1}$ (Abgrall, Roueff & Viala 1982), $N_{0,1} = (1.20 \pm 0.21) \times 10^{17}$ cm$^{-2}$ is
found. The small $A$-value assures that the optically thin relation is valid.

Although we are confident that the observed feature is real and corresponds to the 112 $\mu$m $J=1\rightarrow0$ line of HD, there are a few noteworthy points to be made. First, it is well known that the LWS grating spectral responsivity calibration file at 112 $\mu$m has a spurious “absorption” feature resulting from HD absorption in the calibration source Uranus. However, this does not affect the FP spectrum, where the resolving power is a factor of $\sim 50$ greater than the grating. Across the width of our FP spectrum the calibration file is virtually flat. Second, a similarly sensitive HD 112 $\mu$m observation was made toward the Galactic Center, where no corresponding emission feature is seen (Wright et al., in preparation).

Another possible source of spurious emission is from leakage into the FP of adjacent spectral orders. The FP free spectral range at 112 $\mu$m is 1.12 $\mu$m, and the LWS Observer’s Manual (Clegg, Heske & Trams 1994) discusses possible contamination. The grating acts as an order sorter for the FP, and its resolving power was specifically set such that contamination is avoided. In any case, at submillimeter wavelengths the Orion Bar is very poor in lines compared with spectroscopically rich sources such as Orion–KL (Hogerheijde et al. 1995), and there are no other line-rich sources in the LWS beam. The only strong lines expected in the LWS wavelength range are the high–$J$ transitions from $^{12}$CO and $^{13}$CO. There is no such transition, nor any other common low–lying (i.e. $\leq 300$ K) molecular feature, known to be coincident with HD $J=1\rightarrow0$ within 0.01 $\mu$m, or to be a possible contaminant from adjacent spectral orders.

The LWS–FP data are also affected by fringing, in a similar way to LWS grating data of extended sources. However, the single high frequency fringing component apparent in the data has an essentially constant period of about 0.0095 cm$^{-1}$ (Sidher et al. in preparation), which makes it easier to correct. The effect appears to occur as a result of interference
within the instrument.

4. Analysis and Discussion

In the following, we will discuss the derivation of the column densities of HD and H$_2$ and compare the HD and deuterium abundances in the Orion Bar with those found in other regions.

4.1. The HD column density

Because of the limited sensitivity of the LWS detector SW2, observations of the 56.23 $\mu$m 0–0 $J$=2→1 R(1) line of HD were not feasible, so that no direct information on the excitation of the molecule is available. However, the HD excitation can be readily computed assuming LTE: $N$(HD) = $[N_{0,1}Q(T)/g_{0,1}] \exp(E_{0,1}/kT)$, where $g_{0,1}$ is the statistical weight of the $v=0$, $J=1$ level, and $Q(T)$ is the partition function. Hogerheijde et al. (1995) find gas kinetic temperatures in the Bar of 85±30 K from observations of a variety of molecules, whereas other analyses give values up to at least 300 K (Parmar et al. 1991, see §4.2). The corresponding total HD column densities range from (2.6±0.5)$\times10^{17}$ cm$^{-2}$ at 115–200 K to (3.1±0.6)$\times10^{17}$ cm$^{-2}$ at 85 and 300 K. Including the temperature range as an additional uncertainty, our best estimate of the total HD column density is (2.9±0.8)$\times10^{17}$ cm$^{-2}$. The estimated hydrogen densities of the Orion Bar, such as $10^4$ to $10^5$ cm$^{-3}$ for the so-called interclump medium, or $\geq 10^6$ cm$^{-3}$ for the high density clumps (e.g., Hogerheijde et al. 1995), are all above the critical density of the $J=1$ level. For the higher HD levels, the departures from LTE are small for these conditions.
4.2. The HD abundance

To derive the HD abundance with respect to H$_2$, the total H$_2$ column density, $N$(H$_2$), is needed in addition to $N$(HD). The most direct method is to use observations of the pure rotational lines of H$_2$ itself. Parmar, Lacy & Achtermann (1991) present data of the 17.0348 $\mu$m $0$–$0$ $J=3\rightarrow1$ S(1) and 12.2786 $\mu$m $0$–$0$ $J=4\rightarrow2$ S(2) lines of H$_2$ in a 10$''$ $\times$ 2$''$ slit at positions covering a 10$''$ $\times$ 16$''$ region in the Bar, and within our $\sim$ 76$''$ aperture. Our observed position is within a few arcseconds of their position 3, the point of peak emission, while their positions 1, 2, 4 and 5 fall well within our aperture. The averaged line fluxes for positions 1–5 (covering 10$''$ $\times$ 10$''$) give a mean excitation temperature $T_{ex}$ between levels $J=3$ and 4 of 482 K and a column density of 9.9$\times$10$^{20}$ cm$^{-2}$. However, this is unlikely to represent the total H$_2$ column density, since there is a strong temperature gradient throughout the PDR with a significant amount of cooler gas present, as indeed is shown in other molecular tracers.

Several methods may be used to determine the total amount of gas. First, the clumpy PDR models of Burton, Hollenbach & Tielens (1990, 1992) can be used to estimate the expected $T_{ex}$ between levels $J=2$ and 3. For the conditions appropriate to the interclump medium of the Orion Bar, where Burton et al. (1992) state that the bulk of the H$_2$ emission originates, $T_{ex}=180$–260 K. Using the observed column density in the $J=3$ level, we can then extrapolate to the $J=2$ level to determine its column density and thereby the total warm H$_2$ column density, assuming that the ortho–para ratio is in LTE (Sternberg & Neufeld 1999). For $T_{ex}=180$ K, $N$(H$_2$)=1.5$\times$10$^{22}$ cm$^{-2}$ is found, while for $T_{ex}=260$ K, $N$(H$_2$)=4.4$\times$10$^{21}$ cm$^{-2}$. We note that recent observations with the ISO–SWS at the same position in the Bar, including the 28.2188 $\mu$m $0$–$0$ $J=2\rightarrow0$ S(0) line, show that $T_{ex}$ between the $J=2$ and $J=3$ levels is 150–175 K, and that the total warm H$_2$ column density is $\sim$1.5$\times$10$^{22}$ cm$^{-2}$, with a statistical uncertainty of $\sim$10% (e.g. Rosenthal et al., in preparation).
Using \( N(H_2) = 1.5 \times 10^{22} \, \text{cm}^{-2} \), the HD abundance, \( N(\text{HD})/N(H_2) \) (denoted as HD/H\(_2\)), is \((2.0 \pm 0.6) \times 10^{-5}\). Our estimate of \( N(H_2) \) may be an underestimate since the H\(_2\) S(0) line may still be weighted toward warmer gas than the HD \( J=1 \rightarrow 0 \) line, given that their upper level energies are \( \sim 510 \) and 128 K above ground, respectively. This would lead to an overestimate of HD/H\(_2\). This may be counter-balanced by an intrinsic underestimate due to photodissociation of HD at the PDR edge and the fact that the LWS beam is significantly larger than the apertures used for the H\(_2\) observations (14" × 27" at 12 and 17 \( \mu\text{m} \) and 20" × 27" at 28 \( \mu\text{m} \) for ISO–SWS; see also below).

\( N(H_2) \) has also been estimated from observations of CO and its isotopic forms to be between 3 and \( 6.5 \times 10^{22} \, \text{cm}^{-2} \), varying with precise position, line and beam size (e.g., Graf et al. 1990, Hogerheijde et al. 1995, van der Werf et al. 1996). Using the molecular line maps and the C\(^{18}\)O 2→1 cut across the Bar by Hogerheijde et al. (1995), the beam dilution in the LWS aperture is estimated to be a factor of \( \sim 0.4 \sim 0.5 \) compared with their peak emission. This results in a LWS beam–averaged H\(_2\) column density of \( \sim 3 \times 10^{22} \, \text{cm}^{-2} \) if an \( H_2/C^{18}\text{O} \) ratio of \( 5 \times 10^6 \) is used. The corresponding HD/H\(_2\) is \((1.0 \pm 0.3) \times 10^{-5}\).

This value refers to HD with respect to the total amount of warm and cold H\(_2\). However, because the HD \( J=1 \) level lies at 128 K above ground it is only excited efficiently in gas with temperatures above \( \sim 30 \) K. In addition, HD is photodissociated at the edge of the PDR, so that the region over which H\(_2\) and HD are coexistent is less. These effects can be taken into account by comparison with detailed physical and chemical models of the Orion Bar, such as developed by Jansen et al. (1995a,b). The models show that HD becomes abundant 2 visual magnitudes deeper into the cloud than H\(_2\), and that the temperature stays above 30 K up to depths of 5–6 mag. These values need to be convolved with the edge–on geometry of the Bar as outlined by Jansen et al. (1995b). At the positions included in the LWS beam, the outer, warm layers are enhanced significantly, and it is estimated
that at least 50% of the total column density contains HD at sufficiently high temperatures. Thus, the relevant \( N(\text{H}_2) \) in the LWS beam for comparison with HD is \( \sim 1.5 \times 10^{22} \text{ cm}^{-2} \), consistent with that determined from the warm \( \text{H}_2 \) above. Similar values are obtained from \( ^{13}\text{CO} \ 6\rightarrow5 \) data from Lis (private communication) averaged over a 70″ beam and from the high-\( J \) \( ^{12}\text{CO} \) lines detected in our LWS01 spectrum. The corresponding HD abundance is again \( (2.0 \pm 0.6) \times 10^{-5} \).

Another method for determining the HD abundance is to utilise the dust continuum emission as a tracer of molecular hydrogen. Our LWS01 spectrum gives a dust temperature of 60 K and a 112 \( \mu \text{m} \) optical depth of 0.05, obtained from an optically thin fit to the data. Inserting these values into Eq. (4) of Watson et al. (1985), \( \text{HD}/\text{H}_2=(1.5 \pm 0.3) \times 10^{-5} \) is obtained. Alternatively, the 400 \( \mu \text{m} \) observations of Keene, Hildebrand & Whitcomb (1982) can be used along with Eq. (9) in Table 1 of Hildebrand (1983) to find \( N(\text{H}_2)=2.6 \times 10^{22} \text{ cm}^{-2} \) and \( \text{HD}/\text{H}_2=(1.1 \pm 0.3) \times 10^{-5} \), using a 400 \( \mu \text{m} \) optical depth of \( 4.4 \times 10^{-3} \). These methods assume thermal equilibrium between the gas and dust, however, and are uncertain by a factor of 2 due to uncertainty in the dust opacity. If the gas and dust are in thermal equilibrium at \( \sim 60 \) K, \( N(\text{HD}) \) increases to \( (4.6 \pm 0.8) \times 10^{17} \text{ cm}^{-2} \) and \( \text{HD}/\text{H}_2=(1.8 \pm 0.3) \times 10^{-5} \).

Although each of the above methods to derive the HD abundance have their own intrinsic uncertainties, our observations constrain the range of \( \text{HD}/\text{H}_2 \) in the Orion Bar to be between \( 0.7 \times 10^{-5} \) and \( 2.6 \times 10^{-5} \), not including the uncertainty due to the LWS photometric calibration and beam size. Our preferred value is \( (2.0 \pm 0.6) \times 10^{-5} \), the value obtained using the \( \text{H}_2 \) pure rotational lines or corrected CO isotopic emission as tracers of \( N(\text{H}_2) \).
4.2.1. Comparison with other determinations of the HD abundance

It is interesting to compare our result with those previously obtained toward other source types. The HD/H$_2$ ratios obtained from ultraviolet absorption line observations through diffuse clouds are typically $\sim 10^{-6}$ (e.g. Spitzer et al. 1973, Snow 1975, Wright & Morton 1979). Such low values are explained through preferential ultraviolet dissociation of HD, since HD does not self-shield. Although gas–phase HD formation is more rapid than that of H$_2$ due to the H$^+$ + D $\rightarrow$ D$^+$ + H and D$^+$ + H$_2$ $\rightarrow$ HD + H$^+$ reactions, the net effect is still a low HD/H$_2$ ratio. Future observations with the Far Ultraviolet Space Explorer (FUSE) will be able to extend these ultraviolet observations to thicker, translucent clouds in the solar neighborhood, where more of the deuterium is in HD. Recently, Bertoldi et al. (1999) measured the 19.4 $\mu$m HD 0–0 $J$=6$\rightarrow$5 R(5) line in the Orion shock using the ISO–SWS, and found an HD abundance of $(9.0 \pm 3.5) \times 10^{-6}$, corrected for non–LTE population. In partially dissociative shocks, the HD abundance may be reduced relative to H$_2$ by $\sim$40% due to the HD + H $\rightarrow$ H$_2$ + D reaction.

The HD abundance has also been determined for the giant planets using the SWS and LWS on board ISO to measure the 37.7 $\mu$m 0–0 $J$=3$\rightarrow$2 R(2) and 56.2 $\mu$m $J$=2$\rightarrow$1 R(1) lines, respectively. These yield (preliminary) values of $(2.6–5.8) \times 10^{-5}$ for Jupiter and $(3.0–8.0) \times 10^{-5}$ for Saturn (Lellouch 1999, and references therein). Our value is at the low end of these ranges, perhaps implying some Galactic evolution of the HD (and thereby D) abundance over the 5 billion year lifetime of our solar system.

4.3. The deuterium abundance

Our derived HD/H$_2$ ratios refer specifically to the regions of the PDR where deuterium is in molecular form. Thus, the amount of atomic deuterium can be neglected and
[D]/[H] ≈ 0.5 × HD/H₂. Our derived deuterium abundance ranges from 0.35 to 1.30 × 10⁻⁵, with a preferred value of (1.0 ± 0.3) × 10⁻⁵. This result is marginally outside the error estimate (~ 15%) of the value for the solar neighborhood of 1.6 × 10⁻⁵ (Piskunov et al. 1997). However, it is close to the value of (0.76 ± 0.29) × 10⁻⁵ found for the Orion shock by Bertoldi et al. (1999), and (0.74 ± 0.19) × 10⁻⁵, (0.65 ± 0.3) × 10⁻⁵ and (1.4 ± 0.5) × 10⁻⁵ for the lines-of-sight to the stars δ, ε and ι Orionis by Jenkins et al. (1999) and Laurent et al. (1979), respectively. Additional ultraviolet and far-infrared observations are needed to determine whether true variations in the deuterium abundance exist within Orion and between Orion and the local interstellar medium. Our value is however definitely below that of (3.9 ± 1.0) × 10⁻⁵ found through radio observations of the 21 cm H I and 92 cm D I hyperfine transitions in a region of reduced star formation activity in the outer Galaxy by Chengalur, Braun & Burton (1997). This provides some evidence of a Galactic deuterium abundance gradient, and is consistent with its destruction in stars. Better determinations of [D]/[H] in the Galactic Center will be important to further constrain the gradient across the Galaxy.

The successful detection of the HD 112 µm J=1→0 line by ISO in a reasonable integration time implies that the next generation of infrared airborne observatories, such as the Stratospheric Observatory for Far-Infrared Astronomy (SOFIA) and the Far-InfraRed and Submillimeter Space Telescope (FIRST), will be able to detect this line in a variety of sources, and possibly determine a [D]/[H] gradient across the Galaxy. At the high spectral resolution of the SOFIA and FIRST instruments, other sources such as dense molecular cloud cores may be more favorable for HD searches, because of their higher column densities compared with PDRs. The largest uncertainty in the [D]/[H] analysis remains the determination of the corresponding H₂ column density.

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Fig. 1.— The ISO–LWS Fabry–Pérot spectrum toward the Orion Bar of the HD 0–0 $J=1\rightarrow0$ 112.0725 μm line. The presented spectrum has not been corrected for the effective aperture of the instrument. The error bar represents the typical standard deviation in individual data points. The baseline has been corrected for fringing.
