Detection of a vibration-rotation emission line of hydrogen deuteride toward Orion Peak 1: excitation coupling of HD to H$_2$

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**ABSTRACT**

The 2.46 $\mu$m $v = 1 - 0$ R(5) line of deuterated molecular hydrogen, HD, has been detected in the Orion Peak 1 shock emission region, at a surface brightness of $(8.5 \pm 2.1) \times 10^{-9}$ Wm$^{-2}$sr$^{-1}$ over a 6 arcsec$^2$ area. Comparison of the column density of HD($v = 1, J = 6$) with the column density of HD($v = 0, J = 6$) previously observed from ISO and the H$_2$ level column densities toward the same region implies that the excitation of HD is similar to that of H$_2$ for these energy levels, despite much higher spontaneous transition rates for HD. We suggest that this rough equality is caused by the coupling of the HD levels to those of H$_2$, due to strong reactive collisions, HD + H $\leftrightarrow$ H$_2$ + D, in warm, partially dissociated gas. The deuterium abundance implied by the combined ISO and UKIRT measurements toward Orion Peak 1 is $[D]/[H] = (5.1 \pm 1.9) \times 10^{-6}$.

*Subject headings:* abundances - ISM: individual objects - Orion Peak 1: observations - infrared: ISM - lines and bands
1. Introduction

Hydrogen deuteride (HD) is the simplest and most abundant deuterated molecule. Its detection permits in principle a determination of the cosmic deuterium abundance, and thereby places constraints on the physical conditions during cosmic nucleosynthesis. Two pure rotational lines of HD have been detected by the Short (SWS) and Long (LWS) Wavelength Spectrometers on the Infrared Space Observatory (ISO). Wright et al. (1999) detected the 0-0 R(0) transition (i.e., $v = 0$, $J = 1 \rightarrow 0$) line at 112 $\mu$m toward the Orion Bar photodissociation region, and from an estimate of the H$_2$ column density and by assuming local thermodynamic equilibrium (LTE) for HD, they determined a deuterium abundance ratio, $[D]/[H] = (1.0 \pm 0.3) \times 10^{-5}$. Bertoldi et al. (1999; hereafter B1999) reported a detection of the 0-0 R(5) line at 19.43 $\mu$m toward Orion Peak 1, the brightest position of shocked H$_2$ line emission in the Orion OMC-1 outflow (Beckwith et al. 1978). They also derive upper limits to the fluxes of sixteen pure rotational and vibration-rotation lines toward the same position. Combining their HD detection with observations of H$_2$ lines by Rosenthal, Bertoldi & Drapatz (2000; hereafter R2000), they estimate $[D]/[H] = (7.6 \pm 2.9) \times 10^{-6}$. Their estimate takes into account the depletion of HD relative to H$_2$ that occurs in warm and partially dissociated gas, from which much of the line emission is thought to arise.

There are two major sources of uncertainty in the deuterium abundance estimates derived from the mid-IR HD and H$_2$ emission lines. One is the possibility of variations of $[HD]/[H_2]$ in warm, partially dissociated gas, where the exothermic chemical reaction HD + H $\rightarrow$ H$_2$ + D depletes HD relative to H$_2$ (Timmermann 1996, 1998; B1999). If the dissociation fractions of HD and H$_2$ differ and vary along the line of sight, the observations yield convolved averages over abundance and excitation gradients, from which a deuterium abundance cannot be derived directly.

The second major uncertainty is the derivation of an HD column density from the measurement of but a single excited level. In the absence of any constraint on the HD excitation, B1999 initially assume that the HD giving rise to the observed emission has the same excitation as the observed post-shock H$_2$. Using this assumption, which essentially presumes that both H$_2$ and HD are populated according to a LTE, they derive an HD column density $N(\text{HD})_{\text{LTE}} = (1.36 \pm 0.38) \times 10^{16}$cm$^{-2}$. B1999 then note that, unlike H$_2$ levels at comparable energy, HD(0,6) would not be expected to be populated according to LTE, mainly because HD has a faster radiative deexcitation than H$_2$, and the “critical density” for HD(0,6) exceeds that which is expected to exist in the emitting gas, $\sim 10^5 - 10^6$cm$^{-3}$. From extensive modelling of the HD level populations, B1999 derive a a factor of 1.5 (see section 3.4 of B1999) to account approximately for the sub-LTE excitation of HD(0,6) and adjust the total HD column upward.
This uncertainty in whether or not the HD level populations are in LTE, and hence whether the column density should be corrected for non-LTE, can only be resolved by measuring transitions from different HD levels. Here we report the detection at Peak 1 of the HD 1-0 R(5) line at 2.46 \( \mu \text{m} \). The upper level of this line is 7,747 K above ground (calculated from the vibrational constants of Herzberg 1950 and the rotational constants of Essenwanger & Gush 1984), compared to 2,636 K for the 0-0 R(5) line (B1999). Measurement of a second emission line of HD at Peak 1 allows a first determination of the HD excitation in shock-excited gas.

2. Observations

The observations were made at the United Kingdom Infrared Telescope (UKIRT) on the night of 1999 January 20 UT, using the facility infrared spectrometer, CGS4 (Mountan et al. 1990). The instrument contains a 256\( \times \)256 element InSb array. The echelle in CGS4 was used in twenty-second order with a 2-pixel wide (0.82 \('') \) slit to provide a spectral resolving power of \( \sim 18,500 \) and wavelength coverage of 0.017 \( \mu \text{m} \) near 2.46 \( \mu \text{m} \). The length of a pixel along the slit was 0.91 \('' \). The HD 1-0 R(5) line (2.458775 \( \mu \text{m} \), Rich, Jones & McKellar 1982) is located at the long wavelength end of the K window where the atmospheric transparency is generally poor; however, on Mauna Kea this HD line is well isolated from nearby strong telluric lines. The atmospheric model spectrum generator, ATRAN (Lord 1992) was used to determine this and it was confirmed by the observations. The \( \text{H}_2 \) 1-0 Q(5) line at 2.45476 \( \mu \text{m} \) also falls in the observed wavelength range, and is valuable for calibrating these observations with those done using ISO.

The observations towards Peak 1 were made with the slit of CGS4 oriented east-west and with row 84 of the array centered at \( \alpha(2000)= 5^h \ 35^m \ 13.7^s, \ \delta(2000)= -5^\circ \ 22^\prime \ 8.5^\prime\prime \). The position was achieved by offsetting from near-by visible stars and is accurate to better than 1arcsecond. This is the position for Peak 1 first identified by Beckwith et al (1978) and the ISO beam was centred on this position (B1999). Following each on-source exposure of 120 seconds the telescope was offset to a sky position 5 arcmin east of Peak 1. Sky and source frames were repeated until the total on-source exposure time was 40 minutes. Flat-field frames were also obtained. Individual exposures were flat-fielded and sky-subtracted, and the sky-subtracted pairs were despiked before being coadded. Wavelength calibration utilized telluric lines in the observed spectrum of the standard star (wavelengths are given in vacuo throughout this paper). The rms accuracy of this calibration is estimated to be 5 km s\(^{-1}\). The G4V star HR 2007 (\( K = 4.44, \ T_{\text{eff}} = 5740 \text{ K assumed} \)) was observed before and after the observations of Peak 1; its spectrum was used to correct for telluric features
in the atmosphere and to provide flux calibration. Weak stellar features were removed from the spectrum of HR 2007 before ratioing, using the solar spectrum (Livingston & Wallace 1991) as a template. No stellar features are closely coincident with the HD line wavelength. The seeing was poor during the observations and from the intensity profile of the calibration star along the slit it is estimated that $50 \pm 10\%$ of the flux from the star passed through the CGS4 slit. This 20\% uncertainty is included in the uncertainties in the line fluxes reported below. The statistical uncertainties associated with the HD line are less than this.

3. Results

3.1. Identification of the HD line

The spectrum of Peak 1 is shown in Fig. 1. The H$_2$ 1-0 Q(5) line, which dominates the spectrum, has a flux of $(1.06 \pm 0.21) \times 10^{-15}$ W m$^{-2}$, a full width at half maximum (FWHM) of $0.00041$ $\mu$m ($50 \pm 3$ km s$^{-1}$) and a full width at 10 percent of $0.0018$ $\mu$m (220 km s$^{-1}$). The broad line widths are due to the fact that the H$_2$ in this region is predominantly excited by shocks, as has long been established (e.g., Nadeau, Geballe, & Neugebauer 1982). The resolution of the spectrum is 16 km s$^{-1}$, and thus the deconvolved widths are only marginally less than the above values. The FWHM is in close agreement with that previously observed for the H$_2$ 1-0 S(1) line (Nadeau & Geballe 1979; Chrysostomou et al. 1997; Stolovy et al. 1998).

The much fainter HD 1-0 R(5) line is clearly detected; its centroid is $2.45922 \pm 0.00007$ $\mu$m (in vacuo). It is almost 1000 times fainter than the H$_2$ Q-branch line. The flux in the line is $(1.2 \pm 0.3) \times 10^{-18}$ W m$^{-2}$ where about half of the uncertainties are due to the systematic uncertainty in the flux calibration. Even in this small bright region, the surface brightness is a factor of 5 lower than the limits measured by ISO for other 1-0 band HD lines (B1999). The FWHM of the HD line, estimated from the locations of the line shoulders, is $68 \pm 15$ km s$^{-1}$ (the uncertainty is 1 $\sigma$), in bare agreement with the H$_2$ 1-0 Q(5) line width. No clear central peak is seen, unlike for the H$_2$ line, but this could be due to noise fluctuations.

To confirm the identification of the weak line as due to HD, we have checked the wavelength in two ways. First, from the laboratory wavelength of the HD line, the LSR velocity of Peak 1 (+8 $\pm$ 10 km s$^{-1}$, Chrysostomou et al. 1997) and the Doppler shift (+16 km s$^{-1}$) due to the earth’s orbital motion on the date of the observation, the peak of the HD line is calculated to occur at a laboratory vacuum wavelength of $2.45911 \pm 0.00009$ $\mu$m. This value is in good agreement with the measured line centroid, which we expect should be shifted only marginally ($\sim 0.0001$ $\mu$m) from the peak, as in the case of the H$_2$ line. Second, the shift
of the HD line between the laboratory and observed wavelengths, 0.00044 \(\mu m\), is the same
sign and nearly the same magnitude as the shift of the \(H_2\) line (0.00031 \(\mu m\)). The difference
of these shifts is less than the resolution of the spectrum. Moreover, while extensive line
lists reveal a few atomic and ionic lines (Ca I, Cu III, Prv, Sc I) with wavelengths within
0.0001 \(\mu m\) of the HD laboratory wavelength, none would be expected to have a spatial dis-
tribution roughly mimicking that of \(H_2\). To test this, we examined the eight rows adjacent
to the central eight brightest rows, both to the east and west along the CGS4 slit. The ratio
of the HD line to the \(H_2\) line is the same to within the estimated uncertainty of 30\%. These
tests demonstrate that the newly detected line indeed is the HD 1-0 R(5) transition.

3.2. Comparison with ISO: beam dilution

The \(H_2\) 1-0 Q(5) and HD 1-0 R(5) lines observed at UKIRT can be compared with
previous ISO observations centred on the same region (R2000). The CGS4 and ISO surface
brightnesses and beam sizes are summarised in Table 1. The ground-based observation yields
a surface brightness which is (2.1\(\pm\)0.4) times larger than the value measured with ISO.

The difference between the UKIRT and ISO measurements can be attributed to the
greatly different apertures of the two measurements. Whereas the ISO observation averaged
the emission over a large aperture centered on Peak 1, the CGS4 flux was determined from
the brightest eight adjacent rows in the Peak 1 spectrum, a solid angle of just 6 arcsec\(^2\). To
compare the observed flux from the HD 0-0 R(5) line observed by ISO and the HD 1-0 R(5)
line, we compensate for the different beam sizes using the difference in the \(H_2\) line fluxes as
a beam dilution factor. In using the difference in the \(H_2\) fluxes to correct the HD line, we
are assuming that the \(H_2\) and HD emissions have the same spatial distributions and that
the portions of Peak 1 sampled by CGS4 and by ISO have the same excitation. The rough
similarity the spatial distribution of HD and \(H_2\) line emissions along the slit was already
pointed out in Section 3.1. Rosenthal et al. (2000) attribute only \(\sim\)5\% of the emission
in the ISO beam to the PDR bordering the foreground Orion Nebula H\(\text{iii}\) region and it is
unlikely that the percentage has large variations within the ISO beam. Therefore one can
safely assume CGS4 slit samples \(H_2\) with the same excitation as the ISO beam.

The HD 0-0 R(5) flux measured with ISO was averaged over an even larger aperture of
380 arcsec\(^2\), so that there could be a modest difference in beam dilution factors between the
aperture in which the \(H_2\) 1-0 Q(5) line flux was derived and the HD 0-0 R(5). We ignore this
possibility, and for a comparison of the HD 0-0 R(5) and 1-0 R(5) line fluxes, we adopt a
beam dilution factor of 2.1, with a 20\% uncertainty. In other words, we decrease the UKIRT
HD line surface brightness by a factor of 2.1 for comparison with the ISO HD line.
3.3. HD column density and conditions in the post-shock gas

The HD 1-0 R(5) average brightness observed in the 6 arcsec$^2$ aperture can be converted to an average HD column density for the level from which this transition arises, $v = 1$, $J = 6$, through

$$N(v, J) = \frac{4\pi}{hc} \frac{\lambda I_{\text{obs}}}{A} 10^{0.4A_{\lambda}},$$

where $A$ is the Einstein-A coefficient (Table 2), and $A_{\lambda}$ is the line of sight extinction at the line wavelength, $\lambda$. Adopting the values in Table 1 and an extinction of 0.78 mag at 2.455 $\mu$m, which was derived by B1999 and R2000 (their Table 3) from the relative H$_2$ line intensities, the observed line flux yields

$$N_{\text{obs}}(1, 6) = (5.1 \pm 1.3) \times 10^{12} \text{ cm}^{-2}.$$  

To compare this with the HD $N(0, 6)$ column density derived by B1999, we correct the UKIRT column by $2.1 \pm 0.4$ as justified above, obtaining $N(1, 6) = (2.4 \pm 0.8) \times 10^{12} \text{ cm}^{-2}$, compared with $N(0, 6) = (3.0 \pm 1.1) \times 10^{14} \text{ cm}^{-2}$ found by B1999.

Figure 2 is an amended version of Fig. 6 from B1999, now including our new measurement. The figure includes a line which the HD level column densities follow if they have the same excitation as H$_2$. There is a good agreement of our new measurement with the prediction made by this line, which indicates that the relative excitation of the HD(0,6) and HD(1,6) levels is the same as that we find for H$_2$ levels at similar energies. This is rather surprising, since one might have expected that the population of these high HD levels would drop below those of equivalent H$_2$ levels, due to the faster radiative deexcitation rates of HD compared to H$_2$. The radiative transition probabilities of HD are much larger than those of H$_2$ because, unlike H$_2$, ro-vibrationally excited HD can decay through the emission of electromagnetic dipole radiation. The total radiative decay rate of the HD(1,6) level, e.g., is $5 \times 10^{-5} \text{s}^{-1}$, whereas that of H$_2$(1,4), which is at comparable excitation energy, is about 60 times smaller. With comparable collisional excitation rates, the level populations of H$_2$ and HD are expected to be quite different, unless the gas density is very high, $n > 10^7 \text{ cm}^{-3}$, which seems unlikely.

3.4. Coupling of the HD and H$_2$ excitations

Why does the HD excitation shown by the levels (0,6) and (1,6) appear to mimic the excitation of H$_2$ at similar level energies? We suggest that the cause may be excitation coupling.
between HD and H$_2$. In shock-heated, partially dissociated gas the exchange reaction

$$\text{HD} + \text{H} \leftrightarrow \text{H}_2 + \text{D} \quad (3)$$

occurs. If the reaction time for this is faster than the time for collisional and radiative equilibrium of HD energy levels to be established, the HD level populations will be coupled to that of H$_2$ through the reactive collisions. Because the abundance of HD is much smaller than that of H$_2$, the average H$_2$ level population would not be significantly affected.

The HD radiative decay time is roughly $2 \times 10^4$ seconds for the $v = 1$ levels. Vibrational relaxation of HD($v=1) \equiv$ HD$^*$ through non-reactive collisions ($3 \times 10^{12} n_{\text{H}}^{-1}$ sec and $3 \times 10^{11} n_{\text{H}}^{-1}$ sec at 1000 K and 2000 K, respectively) is slower than this at typical post-shock temperatures and densities. Thus it is just the radiative time that must be compared with the reaction times. There are two of the latter: the time that HD$^*$ is converted by the above forward reaction to H$_2$ and the time that HD$^*$ is formed from H$_2$ (through the reverse reaction). If these times are shorter, then the HD$^*$ abundance is driven by reactive collisions and both molecules show nearly the same vibrational excitation, with HD effectively becoming part of the H$_2$ level system.

The important reaction rates in eqn. (3) are those that form HD$^*$. Because only a small fraction of the H$_2$ is vibrationally excited, H$_2$(v=0)+D $\rightarrow$ HD$^*$+H is the fastest production channel of HD$^*$, even though per molecule H$_2$(v = 1) is more effective (Timmermann 1996; Rozenshtein et al. 1985). After employing the results of Gray & Balint-Kurti (1998) and Zhang & Miller (1989), we find a rate coefficient $k(2000K) = 1.24 \times 10^{-12}$ cm$^{-3}$s$^{-1}$ for D + H$_2$(v = J = 0) $\rightarrow$ HD$^*$ + H at 2000 K. Per unit volume, the “chemical excitation” rate of H$_2$ $\rightarrow$ HD$^*$ is then $k \ n(\text{H}_2) n(\text{D})$, compared with the HD$^*$ $\rightarrow$ HD radiative decay rate of $4 \times 10^{-5} \ n(\text{HD}^*) \ s^{-1}$. The formation of HD$^*$ is faster than its decay when

$$n(\text{H}_2) > 4 \times 10^7 \ \frac{n(\text{HD}) n(\text{HD}^*)}{n(\text{D}) n(\text{HD})} \ \text{cm}^{-3}. \quad (4)$$

For gas entering a partially dissociative C-type shock, the atomic hydrogen abundance grows as the gas heats. The deuterium fraction [D]/[HD] can be computed from detailed balance of the HD-H$_2$ exchange reaction. Equation (48) of Timmermann (1996) should read

$$r_{\text{HD}+\text{H}} = r_{\text{H}_2+\text{D}} \ \frac{Q(\text{H}_2) Q(\text{D})}{Q(\text{HD}) Q(\text{H})} \ e^{-\Delta E_0/kT}, \quad (5)$$

where $Q = Q_{\text{trans}} Q_{\text{vibr}} Q_{\text{rot}}$ is the total partition function. The H$_2$(v = 0)+D system lies $E_0/k=418$ K above that of HD(v = 0)+H, and the H$_2$(v = 1)+D system lies 1183 K above
that of HD($v = 1$)+H. For the HD($v = 0$)$\rightarrow$H$_2$($v = 0$) exchange reaction, detailed balance yields

$$\frac{[D]}{[HD]} = 2.3 \left(\frac{[H]}{[H_2]}\right) e^{-418K/T}. \quad (6)$$

Then eq. (4) becomes

$$n(H) > 2 \times 10^7 \frac{n(HD^*)}{n(HD)} e^{418K/T} \text{ cm}^{-3}. \quad (7)$$

In the portion of the post-shock region where the bulk of the observed $v = 1 - 0$ line emission occurs, the temperature is likely to be $\sim$2000 K. There the fraction of H$_2$ in the $v = 1$ state is $\sim$0.05 and that of HD would be similar if it were coupled to H$_2$. However, the temperature profile of the shocked gas is not well known. We therefore also estimate the excited fraction from the data of B1999 and R2000, who observed the H$_2$ level populations over the line of sight of shock-heated and cooling gas, which includes the entire range of temperatures. We obtain $N(H_2(v = 1))/N(H_2) \sim 0.001$. The relevant abundance fraction should lie between these two extremes. We adopt $n(HD^*)/n(HD) = 0.01$ in the region where much of the observed HD emission arises. The atomic hydrogen density above which the HD$^*$ abundance is dominated by H$_2$-HD reactive collisions is then $2 \times 10^5$ cm$^{-3}$. For comparison, at 2000 K the critical H density for LTE excitation of HD$^*$ is $1.5 \times 10^7$ cm$^{-3}$.

In Orion the density of atomic hydrogen in C-shocks is believed to be well in excess of $10^5$ cm$^{-3}$ in the front (Timmermann 1996; Timmermann 1998; B1999). Thus partially dissociative shocks appear to be able to couple HD strongly to H$_2$ over much of the warm shock layers. In regions with lower temperatures the exchange reactions are slower, but the HD$^*$ fraction is also lower, so that the critical density (eq.7) should not change much between 1000 K and 2000 K.

4. Deuterium abundance

We have found that the excitation of HD that is apparent through the HD(0,6) and HD(1,6) levels is very similar to the excitation observed (although averaged over a larger region) for H$_2$ at these level energies. Because of the lack of more information on the HD level distribution, especially for the lower energy states $v = 0$, $J = 0 - 5$, we assume that the HD and H$_2$ excitations are indeed similar. Under this assumption we can compute the HD partition sum to derive the total HD column density.

Since HD is somewhat depleted relative to H$_2$ in the warmest shock layers, the average excitation conditions of HD might be somewhat different from those of H$_2$. The lower HD
levels are predominantly populated by cooler gas that does not couple to H$_2$, but in this gas the low level populations may well follow LTE, so that HD and H$_2$ would show a similar excitation. Our assumption of identical excitation for HD and H$_2$ is therefore a reasonable one. Ideally, one would like to measure the level populations of the lower HD levels, but the corresponding infrared lines are only accessible from space with sufficient sensitivity. Upper limits derived from ISO measurements (see Fig. 2) yield constraints only within a factor ten from the adopted level populations.

Adopting the H$_2$ excitation measured by ISO, the total (warm) HD column density is that given by B1999 as $N(\text{HD})_{\text{LTE}} = (1.36 \pm 0.38) \times 10^{16}\text{cm}^{-2}$, compared with $N(\text{H}_2) = (2.21 \pm 0.24) \times 10^{21}\text{cm}^{-2}$. Accounting for a 40% depletion of HD relative to H$_2$ in warm, partially dissociated gas (see B1999 for a detailed justification of this factor), we derive a deuterium abundance $\left[\frac{\text{D}}{\text{H}}\right] = (5.1 \pm 1.9) \times 10^{-6}$. This value is lower than the $(7.6 \pm 2.9) \times 10^{-6}$ found by B1999, because they expected a lower excitation of HD relative to that seen for H$_2$.

The deuterium abundance we derive is the lowest value yet measured. Its typical range derived through deuterium absorption measurements in the local ISM is $(1 - 2) \times 10^{-5}$. Recent measurements by Jenkins et al. (1999) and Sonneborn et al. (2000) however show that the abundance of atomic deuterium does vary significantly along different lines of sight. Our low value is comparable to the low value derived from absorption measurements toward $\delta$ Ori A (Jenkins et al. 1999), which yielded $7.4_{-1.3}^{+1.9} \times 10^{-6}$.

5. Conclusion

We have detected an emission line of vibrationally excited HD toward Orion Peak 1. The two HD lines now detected from this region arise from widely different energy levels and their relative strengths surprisingly indicate a similar excitation as H$_2$, in spite of the considerably different spontaneous deexcitation rates of these isotopic molecular species. We propose that the similarity in excitation is due to the strong coupling of the HD and H$_2$ systems through reactive collisions and we have revised the deuterium abundance at Peak 1 in view of the higher than expected excitation of HD.

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the atomic line list data maintained by Peter van Hoof and hosted by the Department of Physics and Astronomy at the University of Kentucky (www.pa.uky.edu/peter/atomic). The authors are grateful to the referee for comments on the originally submitted manuscript and for highlighting recent work on HD reaction rates.

REFERENCES


Fig. 1.— Spectrum of a 0.82'' × 7.28'' (NS x EW) area of OMC-1 Peak 1 near 2.46 µm is shown in expanded form to reveal the HD line, and also compressed by a factor of fifty to the peak intensity of the H$_2$ 1-0 Q(5) line. The spectrum is a co-addition of the eight brightest rows of H$_2$ line emission. The H$_2$ and HD lines are indicated. The assumed continuum, used to calculate the flux in the HD line, is also shown. The line flux was estimated by fitting the continuum and integrating over a 0.0012 µm interval centered on the line.
Fig. 2.— Column densities of HD levels, divided by the level degeneracy, plotted against the level energy. The $v = 0$ column densities or upper limits are indicated by triangles, the $v = 1$ column densities by squares. All but the HD(1,6) column density are from the B1999 ISO measurements. The HD(1,6) column density is the value observed at UKIRT divided by 2.1 for comparison with the ISO measurements, to correct for the ISO beam dilution (see text). The solid line is a fit to the $\text{H}_2$ level populations (Rosenthal et al. 2000), normalised to the HD(0,6) column density.
Table 1. Line parameters for H$_2$ 1-0 Q(5) and HD 1-0 R(5) at OMC-1 Peak 1.

<table>
<thead>
<tr>
<th>Line</th>
<th>$I_{\text{obs}}$ (W m$^{-2}$sr$^{-1}$)</th>
<th>beam arcsec$^2$</th>
<th>$\lambda_{\text{obs}}$ (µm)</th>
<th>FWHM (µm)</th>
<th>$N(v, J)$ $^1$ (cm$^{-2}$)</th>
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<tbody>
<tr>
<td>H$_2$ 1-0 Q(5)</td>
<td>(7.6 ± 1.5) $\times$ 10$^{-6}$</td>
<td>5.97</td>
<td>2.4550</td>
<td>(4.1 ± 0.2) $\times$ 10$^{-4}$</td>
<td>(9.4 ± 1.6) $\times$ 10$^{17}$</td>
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<tr>
<td>HD 1-0 R(5)</td>
<td>(8.5 ± 2.1) $\times$ 10$^{-9}$</td>
<td>5.97</td>
<td>2.4592</td>
<td>(5.6 ± 1.2) $\times$ 10$^{-4}$</td>
<td>(5.1 ± 1.3) $\times$ 10$^{12}$</td>
</tr>
<tr>
<td>H$_2$ 1-0 Q(5)$^2$</td>
<td>(3.68 ± 0.18) $\times$ 10$^{-6}$</td>
<td>280</td>
<td>2.4548</td>
<td>1.6$\times$10$^{-3}$</td>
<td>(4.60 ± 0.22) $\times$ 10$^{17}$</td>
</tr>
<tr>
<td>HD 0-0 R(5)$^3$</td>
<td>(1.84 ± 0.4) $\times$ 10$^{-8}$</td>
<td>380</td>
<td>19.4035</td>
<td>8.7$\times$10$^{-3}$</td>
<td>(3.1 ± 1.1) $\times$ 10$^{14}$</td>
</tr>
</tbody>
</table>

$^1$Column density corrected for extinction (B1999)

$^2$From Rosenthal et al. (2000). The uncertainty in the 1-0 Q(5) line flux derives from a 5% flux calibration uncertainty (the line was detected with a signal to noise ratio of 176). The line FWHM is approximate, calculated from the reported spectral resolving power of 1000-2000.

$^3$From Bertoldi et al. (1999)
Table 2. HD and H\textsubscript{2} transition parameters.

<table>
<thead>
<tr>
<th>Line</th>
<th>energy\textsuperscript{1} (K)</th>
<th>$A$ \textsuperscript{2} (sec\textsuperscript{-1})</th>
<th>$g_J$ \textsuperscript{3}</th>
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<td>H\textsubscript{2} 1-0 Q(5)</td>
<td>8365</td>
<td>$2.55 \times 10^{-7}$</td>
<td>33</td>
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<td>HD 1-0 R(5)</td>
<td>7747</td>
<td>$5.29 \times 10^{-5}$</td>
<td>13</td>
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<tr>
<td>HD 0-0 R(5)</td>
<td>2636</td>
<td>$1.33 \times 10^{-5}$</td>
<td>13</td>
</tr>
</tbody>
</table>

\textsuperscript{1}HD energy level calculated from the vibrational constants of Herzberg (1950) and the rotational constants of Essenwanger & Gush (1984)

\textsuperscript{2}HD transition probabilities from Abgrall, Roueff & Viala (1982)

\textsuperscript{3}Degeneracy of the upper level. For the para-H\textsubscript{2} line the spin degeneracy, $g_s = 3$, and $g_J = g_s (2J + 1)$