WEAK H_2 EMISSION FROM DIFFUSE AND TRANSLUCENT CLOUDS

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ABSTRACT

We present the first results of a survey for the lowest pure-rotational lines of H_2 with the ISO-SWS in a number of well-studied low-density diffuse and translucent clouds. The data are compared with those of the high-density PDR IC 63, for which H_2 lines up to S(5) are detected, and of the "cool" PDR Cederblad 201. Searches for the S(0) line at 28.218 μm and the S(1) line at 17.035 μm have been performed for the diffuse cloud along the line of sight toward ζ Oph, the translucent clouds toward HD 94413 and HD 154368, the high-latitude cloud MBM 55D, as well as the translucent outskirts of the S 140 molecular cloud. The lines are not detected in diffuse clouds down to $\sim$0.3–0.5 Jy (2σ). They are weakly observed in the peripheral regions of S 140, where their intensities are more than an order of magnitude less than at the peak of the PDR. The observations are compared with available physical models based on optical absorption and/or millimeter emission line data, and, in the case of ζ Oph, with H_2 observations in the ultraviolet. The models include both collisional excitation and ultraviolet pumping. The data form tests of the temperature structure and heating mechanisms of these clouds.

Key words: diffuse clouds; translucent clouds; photon-dominated regions (PDRs); molecules: H_2

1. INTRODUCTION

Early results from the *Short Wavelength Spectrometer* (SWS) on board the *Infrared Space Observatory* (ISO) have shown that the pure rotational lines of H_2 are readily detected in photon-dominated regions (PDRs) (Timmermann et al. 1996, Bertoldi 1997, see review by Draine in this volume). These observations refer to molecular clouds with densities $n > 10^4$ cm^{-3}, exposed to intense ultraviolet radiation from nearby bright stars with an enhancement factor $I_{\rm UV} \geq 100$ relative to the average interstellar background starlight (e.g., Draine 1978). Much less attention has been paid to the weakly illuminated clouds of lower density, which may contain a large fraction of the molecular gas in galaxies. This dilute molecular gas may fill much of the volume occupied by self-gravitating giant molecular clouds and includes the diffuse and translucent clouds that are not gravitationally bound. A good understanding of the physical conditions in the diffuse molecular gas is needed to determine their role in global star-forming activity and galactic evolution (e.g., McKee 1989, Li et al. 1997). The pure rotational lines of H_2 accessible with the ISO-SWS form an important new diagnostic tool of these regions.

We present here the first results of a deep survey of the H_2 J=2→0 S(0) and J=3→1 S(1) pure-rotational lines at 28.218 and 17.035 μm with the ISO-SWS in diffuse, translucent and high-latitude clouds. These clouds have densities n=n(H) + n(H_2) of 100–3000 cm^{-3} and are exposed to $I_{\rm UV} \leq 10$ (van Dishoeck et al. 1991). For comparison, results for the well-studied dense PDR IC 63 with n=5×10^4 cm^{-3} and $I_{\rm UV}$=650 are shown as well, together with those for the reflection nebula Cederblad 201 exposed to radiation with a lower color temperature (Kemper et al. 1999). The H_2 J=2 and 3 levels lie high in energy at 510 K and 1015 K respectively, and are thus excellent tracers of the warm $T \geq 100$ K gas component.

The objects are chosen to be well constrained by a wide variety of other observations. Specifically, the line-of-sight toward the bright O9.5 star ζ Oph is observed, for which a wealth of complementary optical absorption line data exist, including H_2 observations in the ultraviolet (e.g., Spitzer et al. 1974). Other objects include translucent and high-latitude clouds from the sample of Gredel et al. (1993, 1994) chosen to be free from contaminating emission of other clouds along the line of sight. Finally, H_2 has been observed along a cut through the outskirts of the molecular cloud S 140, for which complementary submillimeter data on CO isotopes and [C I] are available (Li 1997). The data will be compared with the available models for these regions.

2. OBSERVATIONS AND REDUCTION

The observations were performed with the SWS grating mode SWS02. The spectral resolving power and aperture for extended sources are 1500 and $20'' \times 27''$ at the S(0) line, and 1800 and $14'' \times 27''$ at the S(1) line, respectively. Typical integration times range

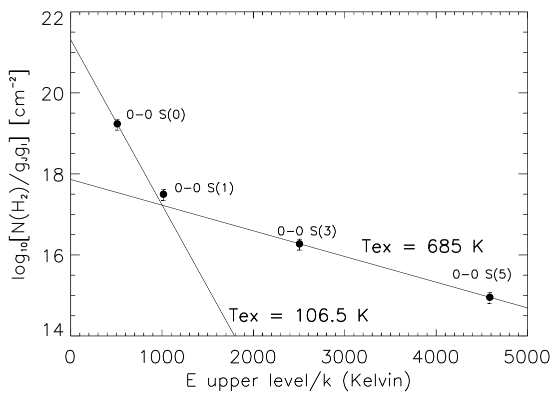

Figure 1. The H_2 excitation diagram toward IC 63 as derived from the ISO-SWS observations.

from 100 s per line for IC 63 to 2000 s per line for the diffuse clouds. These are among the deepest integrations performed with the SWS. Special software designed by Valentijn & Thi (1999) has been used to handle glitches and dark current fluctuations, together with the standard Interactive Analysis Package. The flux uncertainty is of the order of 30% for strong lines. The quality of the data varies from orbit to orbit due to the effects of "cosmic weather".

3. THE DENSE PDR IC 63

IC 63 is a small comet-shaped reflection nebula with $A_V \simeq 7$ mag situated at a distance of ~230 pc. It is exposed to far ultraviolet radiation ($I_{UV} \approx 650$) from the B0.5 star γ Cas located at a distance of 1.3 pc from the cloud. The observed molecular lines in the (sub)millimeter are narrow, $\Delta V \approx 1$ km s^{-1}, indicating the absence of shocks. The size of the cloud as mapped in ^{12}CO 3→2 is $40'' \times 20''$ or 0.04×0.02 pc. The fact that it is isolated and nearby makes it one of the simplest, best-characterized PDRs.

IC 63 has been studied intensively by Jansen et al. (1994, 1996), who observed a large variety of molecular lines to constrain the physical and chemical structure. One- and two-dimensional PDR models have been constructed by Jansen et al. (1995). The density is $\sim 5 \times 10^4$ cm^{-3} and the temperature is found to decrease from ~ 200 K at the edge to ~ 10 K in the center. This temperature profile reproduces well the ^{13}CO 6→5 data for this cloud. Using the IUE satellite, Witt et al. (1989) observed the ultraviolet fluorescence of H_2 and more recently, Luhman et al. (1997) detected three near-IR ro-vibrational H_2 emission lines. These lines are well fitted by the H_2 excitation model which takes ultraviolet pumping and collisional processes into account.

Pure rotational H_2 lines up to S(5) are detected with the ISO-SWS toward the peak of the CO map at RA (1950)=$0^h55^m58^s$, DEC(1950)=$60^o37'7''$. Although the density and radiation field are similar to those of the S 140 PDR observed by Timmermann et al. (1996), the lines in IC 63 are typically a factor of 10 weaker, 0.5–1.5 Jy (Thi et al. 1997). This suggests that geometrical and beam-filling effects play a role. The corresponding H_2 excitation diagram is shown in Figure 1. Because the S(2) line was not observed, no constraints on the ortho/para ratio can be obtained (Sternberg & Neufeld 1999).

The intensities of the four observed lines can be fit by two components of thermalized emission at temperatures of 106 and 685 K. The intensity of the S(1) line has nearly equal contributions from the two components. The inferred column density of warm H_2 at 106 K is 5.9×10^{21} cm^{-2}, while that of the hot component at 685 K is 1.2×10^{19} cm^{-2}. The total column of H_2 agrees well with the estimate of Jansen et al. (1994), $(5 \pm 2) \times 10^{21}$ cm^{-2}, although a temperature rather lower than 100 K was inferred in that analysis. The excitation temperatures characterizing levels J=0 to 2 and $J = 3$ to 7 are similar to those found in diffuse molecular clouds through ultraviolet absorption line observations (Spitzer & Jenkins 1975).

The results show that a very small column density of hot H_2 ($T \geq 500$ K) is sufficient to produce the observed intensities of the higher lines. The hot temperature is a factor of three higher than the maximum kinetic temperature of ~200 K at the edge given by the (2D) PDR models. It is comparable, however, to the temperatures of 500–600 K inferred from high-J H_2 lines for other dense PDRs (Timmermann et al. 1996, Bertoldi 1997). The PDR models of Jansen et al. (1995), which fit the H_2 ultraviolet and near-infrared observations, give fluxes in the pure rotational lines which are up to an order of magnitude too low compared with observations. Thus, even for this simple PDR the physical structure is not yet fully understood. Possible solutions for this discrepancy include an enhanced H_2 formation rate at high temperatures and/or a higher photoelectric heating efficiency (Bertoldi 1997).

4. THE 'COOL' PDR CEDERBLAD 201

Weak H_2 S(1) and S(3) emission at the level of 0.5–1.0 Jy has been detected toward the reflection nebula Cederblad 201 by Kemper et al. (1999). This cloud is illuminated by the B9.5 star BD+69^{o}1231 and is an example of a PDR around a cooler star (Spaans et al. 1994). The inferred density is $n \approx 5000$ cm^{-3}, and the intensity of the radiation is enhanced by a factor of 200. Because the radiation field lacks ultraviolet photons with short enough wavelengths to pump H_2, only collisions play a role in this source. The 1-D and 3-D models by Kemper et al. (1999), which include a detailed treatment of the heating and cooling, again fall short of the observed fluxes of the pure rotational lines. Since the density and ultraviolet radiation are too low in this source for heating due to H_2 collisional de-excitation to be important, it suggests that the discrepancy lies in other parameters controlling the heating. The absence of [O I] 63 μm emission indicates that shocks with velocities greater than 7 km s^{-1} do not play a role.

Table 1. H_2 line fluxes toward diffuse and translucent clouds[a]

Source	Observing time (s)		Flux (Jy)	
	H_2 S(1)	H_2 S(0)	H_2 S(1)	H_2 S(0)
HD 94413	800	1800	<0.4	< 0.4
HD 149757N	n.a.	2000	n.a.	0.5
HD 149757	600	1200	0.4	< 0.3
HD 149757-OFF	600	1600	< 0.3	< 0.3
HD 154368	600	1400	< 0.5	< 0.4
MBM 55D	n.a.	2000	n.a.	< 0.3

[a] Upper limits are 2σ.

5. DIFFUSE AND TRANSLUCENT CLOUDS

The diffuse and translucent clouds were selected from the sample of Gredel et al. (1993, 1994) (see Table 1), and have been studied extensively by optical absorption and millimeter emission lines. MBM 55D is a high-latitude cloud, first detected by Magnani, Blitz & Mundy (1985). The objects were chosen to be isolated and well characterized, and to have a simple CO emission line profile with no evidence for other molecular clouds along the line of sight. For the well-known cloud toward ζ Oph (HD 149757), both the direction toward the star, as well as a position 30′ north have been observed. At the latter position, the CO 1–0 emission is two times stronger than at the position of the star (Liszt 1997). The OFF position was chosen as the location of lowest IR background intensity adjacent to ζ Oph that could be observed without an additional pointing of the spacecraft. The estimated densities range from 100–3000 cm^{-3} and the incident radiation field from $I_{\rm UV}$ $\approx$0.5 for MBM 55D to $I_{\rm UV}$ $\approx$1–2 for the other clouds.

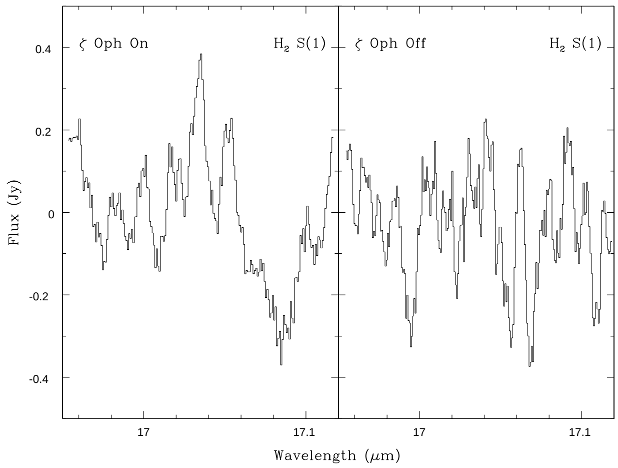

Figure 2. Examples of ISO-SWS spectra toward the diffuse cloud ζ Oph.

Examples of spectra are presented in Figure 2 and the results are summarized in Table 1. In general, the H_2 S(0) and S(1) lines are not detected down to 0.3 Jy (2σ). The only possible exception is ζ Oph which shows a marginal 2 σ detection of the S(1) line with a flux of $\sim$ 0.4 Jy on source. Assuming that the emission fills the beam, this implies an intensity of 4×10^{-6} erg s^{-1} cm^{-2} sr^{-1} and a J=3 column density a factor of $\sim$10 higher than derived from the ultraviolet observations toward the star (Spitzer et al. 1974).

Table 2. Excitation temperatures and column densities of H_2 in peripheral regions of S 140[a]

22h17m24.5s			22h19m32.5s			22h20m36s		
-30″	0	+30″	-30″	0	+30″	-30″	0	+30″
I (10^{-5} erg s^{-1} cm^{-2} sr^{-1})								
0.6[b]	0.9	1.1	1.3	1.0	1.0	0.2	1.0	0.8
0.6[b]	2.3	1.3	0.9	1.0	1.4	0.6	0.8	0.3
$T_{\rm ex}$ (K)								
106	131	110	100	105	114	133	101	89
N (10^{21} cm^{-2})								
1.0	0.6	1.4	2.6	1.5	1.1	1.3	1.9	2.9

[a] All data are taken at DEC(1950)=+63°23′15.4″.
[b] The top entry at each position refers to the S(0) line, the lower entry to the S(1) line

Diffuse cloud models such as developed by van Dishoeck & Black (1986) predict typical S(0) and S(1) fluxes of 0.03–0.1 and 0.01–0.07 Jy, respectively. Most of the J=2 and 3 population is due to ultraviolet pumping, since the densities in these clouds, $n\approx150$ cm^{-3}, are below the critical densities for collisional excitation of the H_2 lines at $T\approx100$ K. Higher fluxes would require larger values of $I_{\rm UV}$. However, this would be in conflict with the detection of only weak ultraviolet absorption out of vibrationally excited levels of H_2, which indicates that the incident radiation field cannot be larger than $I_{\rm UV}$=1–2 for ζ Oph (Federman et al. 1995).

If the S(1) line were real, there may be two possible explanations for this discrepancy. First, the J=2 and 3 column densities derived from the ultraviolet absorption line observations may have been underestimated due to saturation effects. The absorption lines from these levels lie on the flat and damped part of the curve of growth, and the derived column densities are very sensitive to the adopted line profiles. The velocity structure toward ζ Oph is known to be complicated, consisting of at least two components with narrow widths (Langer et al. 1987, Kopp et al. 1996).

The second possibility is that unresolved small-scale structure in the ISO-SWS beam is responsible for the H_2 emission, but does not contribute to the ultraviolet absorption, which arises in a very narrow pencil beam line of sight. Spaans (1995) and Joulain et al. (1998) have shown that the dissipation of turbulence can result in enhanced formation of molecules such as CH^+ and excitation of H_2. CH^+ is readily detected toward ζ Oph in optical absorption lines, so that the difference is unlikely to be due to line-of-sight effects. The possible S(1) intensity toward ζ Oph is within a factor of two of the value predicted by Joulain et al. (1998) for a cloud with n = 30 cm^{-3}. At densities typical of the ζ Oph cloud, $n\approx150$ cm^{-3}, the model intensity should be reduced significantly, however. The turbulent models of Joulain et al. do not take ultraviolet pumping into account, which will enhance the populations of the higher J levels.

The lack of detections in the other sources implies that H_2 emission at this level is not a common phenomenon, and that H_2 lines from cold translucent clouds such as MBM 55D and HD 94413 are weak. The HD 154368 cloud is thought to be similar in density to the ζ Oph cloud and to have a factor of 2–3 larger total column density (Snow et al. 1996). The absence of H_2 emission toward this cloud makes the possible detection toward ζ Oph more questionable.

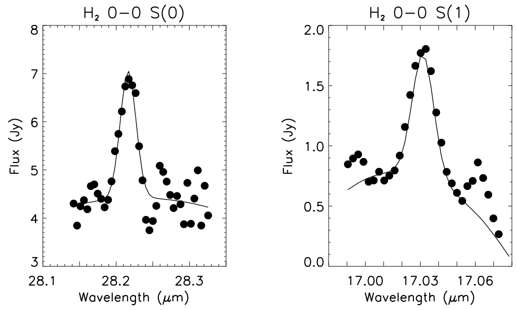

Figure 3. Examples of ISO-SWS H_2 S(0) and S(1) spectra in the outskirts of S 140. The spectra refer to RA(1950)=$22^h\,17^m\,24.5^s$, DEC(1950)=$+63^o\,23'\,15''$.

6. PERIPHERAL REGIONS OF S 140

The PDR S 140 ($d \approx 910$ pc) has been studied extensively by ISO (e.g., Timmermann et al. 1996), but these observations have focused on the brightest emission at the interface. The peripheral regions, studied here at $\sim 20'$ offset from the interface, are more representative of general GMC material. Typical conditions are A_V = 5–15 mag, I_{UV} = 40–100 and n = 500–3000 cm^{-3} derived from submillimeter lines and far-infrared continuum (Li 1997). Table 2 summarizes the results obtained at 9 positions in a cut across the cloud and Figure 3 shows examples of spectra. The lines are weak (~ 1 Jy) and indicate a column density of warm gas of (1–3) 10^{21} cm^{-2} at an excitation temperature of ~ 100 K. Only PDR models with I_{UV} = 60–100 and $n \geq 3000$ cm^{-3}, i.e., the upper range of parameters deduced from other diagnostics, can match the data.

7. CONCLUSION

We have presented the most sensitive ISO-SWS searches for the H_2 S(0) and S(1) lines from diffuse and translucent clouds down to 0.1 – 0.2 Jy rms. The lines are generally not detected until the density reaches $n \approx 3000$ cm^{-3} and the radiation field $I_{UV} \geq$ 50. Where detected, the observed lines are stronger than computed in detailed PDR models which take collisional excitation in warm gas and UV pumping into account. This suggests that the photoelectric heating efficiencies and the H_2 formation rate at high temperatures need to be re-examined. The detection of H_2 emission from cool PDRs indicates that the discrepancy is unlikely to be due to an underestimate of the heating due to collisional de-excitation of vibrationally-excited H_2.

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