H_2 EMISSION FROM DISKS AROUND HERBIG Ae AND T TAURI STARS

W.F. Thi[1], E.F. van Dishoeck[1], G.A. Blake[2], G.J. van Zadelhoff[1], M.R. Hogerheijde[1], V. Mannings[2,10], A.I. Sargent[2], E.E. Becklin[3], J. Horn[3], B. Zuckerman[3], D. Koerner[4], L.G. Mundy[5], L.B.F.M. Waters[6], P.R. Wesselius[7], M.E. van den Ancker[6], A. Natta[8], C. Waelkens[9], & K. Malfait[9]

[1] Leiden Observatory, P.O. Box 9513, 2300 RA Leiden, The Netherlands
[2] California Institute of Technology, Pasadena, CA 91125, USA
[3] Dept. of Astronomy, University of California, Los Angeles, CA 90095, USA
[4] Dept. of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA
[5] Astronomy Program, University of Maryland, College Park, MD 20742, USA
[6] Astronomical Institute, University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
[7] SRON, P.O. Box 800, 9700 AV Groningen, The Netherlands
[8] Osservatorio Astrofisico di Arcetri, I-50125 Firenze, Italy
[9] Instituut voor Sterrenkunde, K.U. Leuven, Celestijnenlaan 200B, 3001 Heverlee, Belgium
[10] Jet Propulsion Laboratory 169-506, Pasadena, CA 91109, USA

ABSTRACT

We present the initial results of a deep ISO-SWS survey for the low J pure rotational emission lines of H_2 toward a number of Herbig Ae and T Tauri stars. The objects are selected to be as isolated as possible from molecular clouds, with a spectral energy distribution characteristic of a circumstellar disk. For most of them the presence of a disk has been established directly by millimeter interferometry. The S(1) line is detected in most sources with a peak flux of 0.3–1 Jy. The S(0) line is definitely seen in 2 objects: GG Tau and HD 163296. The observations suggest the presence of "warm" gas at $T_{\rm kin} \approx 100$ K with a mass of a few % of the total gas + dust mass, derived assuming a gas-to-dust ratio of 100:1. The S(1) peak flux does not show a strong correlation with spectral type of the central star or continuum flux at 1.3 millimeter. Possible origins for the warm gas seen in H_2 are discussed, and comparisons with model calculations are made.

Key words: molecular hydrogen; Herbig Ae stars; T Tauri stars; circumstellar disks.

1. INTRODUCTION

Surveys of their infrared and millimeter continuum emission have shown that a large fraction of low-mass T Tauri stars are surrounded by $\sim 10^{-3} - 10^{-1}$ $M_\odot$ of gas and dust, most likely in the form of a disk (see Beckwith & Sargent 1996 for a review). The study of this material in disks is important, because it serves as the reservoir from which potential planetary systems are formed. Direct imaging of lines and continuum with millimeter interferometers indicate that the disks have typical sizes of $\sim$ 100–400 AU, comparable to that of our own primitive solar system (e.g., Koerner & Sargent 1995, Dutrey et al. 1996, Mundy et al. 1999). Disks have also been confirmed and imaged around intermediate mass Herbig Ae stars (Mannings & Sargent 1997).

Observations of H_2 with the *Short Wavelength Spectrometer* (SWS) on board the *Infrared Space Observatory* (ISO) can contribute to several important questions in the study of disks, including their radial and vertical temperature structure and the gas survival timescales. The radial temperature structure of the disks is usually constrained by modeling of their spectral energy distributions assuming a thin flat disk geometry (e.g., Adams, Lada & Shu 1987) or a flaring disk (e.g., Kenyon & Hartmann 1987). The dust in such models is heated by radiation from the central star and by the release of energy due to accretion. Recent calculations of the temperature structure by different groups show substantial differences, however (e.g., Bell et al. 1997, Men'shchikov & Henning 1997, D'Alessio et al. 1998). Specifically, flared disks may have a surface layer with temperatures in excess of 100 K out to ~100 AU (Chiang & Goldreich 1997). The H_2 J=2→0 S(0) 28.218 μm and $J = 3 \rightarrow 1$ S(1) 17.035 μm lines originate from energy levels at 510 K and 1015 K above ground, respectively. They are thus excellent tracers of the "warm" ($T \approx$100 K) component of disks, especially in the interesting inner part where giant gaseous planets may form.

The H_2 observations also provide constraints on the gas-to-dust ratio in disks. ^{12}CO and/or ^{13}CO observations often indicate gas masses that are up to two orders of magnitude lower than those inferred from the continuum emission (e.g., Dutrey et al. 1996). Explanations for this discrepancy include the possi-

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ble freeze-out of molecules in the cold outer part of the disk at >10 AU, an inadequate description of the radiative transfer in the very optically thick ^{12}CO line, or a gas dissipation time scale that is shorter than that of the dust (Zuckerman et al. 1995). H_2 has the advantage that it is the dominant molecule and that it does not deplete onto grains. Moreover, the lines are optically thin so that the radiative transfer is simple. A disadvantage is that the lines are only sensitive to warm gas and cannot probe the bulk of the (cold) circumstellar material.

Many pre-main sequence stars are binaries or even higher multiple systems (e.g., Simon et al. 1995). The tidal interaction in a binary system may affect the disk structure and evolution, such as clearing of the material in the inner part. Gaps in disks can also result if giant planets have formed. The presence of gaps or holes in disks facilitates the detection of any residual gas, since the lines are no longer obscured by optically thick dust continuum (e.g., Najita et al. 1996).

We present here the first results of a deep survey for the H_2 S(0) and S(1) lines with the ISO-SWS toward a sample of T Tauri and Herbig Ae stars. The data are used to constrain the temperature and mass of warm gas in the disks. An initial account for a few objects has been presented by van Dishoeck et al. (1998).

2. OBSERVATIONS AND REDUCTION

The H_2 S(0) line at 28.218 μm and the S(1) line at 17.035 μm were observed with SWS grating mode AOT02. Typical integration times were 600–1000 s per line, in which the 12 detectors were scanned several times over the 28.05–28.40 and 16.96–17.11 μm ranges around the lines. The S(3) 9.66 μm and S(5) 6.91 μm lines were measured in parallel with the S(0) and S(1) lines, respectively, at virtually no extra time. The spectral resolution for point sources is 2000 at 28 μm and 2400 at 17 μm. The SWS apertures are $20'' \times 27''$ at S(0), $14'' \times 27''$ at S(1), and $14'' \times 20''$ at S(3) and S(5).

The expected peak flux levels of the H_2 lines are close to the sensitivity limit of the instrument, and the raw data show a high level of noise due to the effects of cosmic rays on the detectors. In order to extract the H_2 lines, special software designed to handle weak signals was used for the data reduction in combination with the standard Interactive Analysis Package. The details and justification of the methods used in the software are described elsewhere (Valentijn & Thi 1999). The flux calibration uncertainty is ~30%. The quality of the reduced data is the best that could be obtained at the time of submission of this paper.

3. OBJECTS

The sources in our sample have been selected primarily from the nearby Taurus-Auriga ($d \approx 140$ pc) and Ophiuchus ($d \approx 160$ pc) low-mass star-forming regions. The spectral energy distributions of the objects from infrared to millimeter wavelengths are dominated by emission from the disks rather than surrounding envelope material. Imaging of the gas and dust with the Owens Valley Millimeter Array (OVRO) has been performed for most objects and reveals disk-like structures on arcsec scales with evidence for Keplerian rotation of the gas. The strong millimeter emission of our selected sources implies disk masses of at least 10^{-2} $M_\odot$.

In total, 16 sources in Taurus-Auriga and 5 sources in Ophiuchus have been observed in the ISO programs by Blake et al. and van Dishoeck et al. We present here only the results for sources in Taurus-Auriga with a mid-infrared continuum of only a few Jy, since these data do not suffer from fringing. In addition, data on the Herbig Ae star HD 163296 and on two isolated young stars, 49 Cet and HD 135344, from the program by Becklin et al. are added to the sample (Zuckerman et al. 1995). The selected objects cover a wide range of spectral types from M0-A0, and their estimated ages range from <1 to 10 Myr. The results of the full data set will be presented elsewhere.

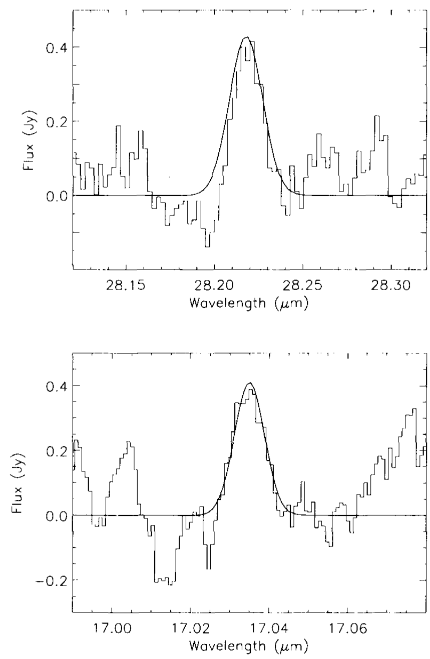

Figure 1. The pure-rotational H_2 S(0) (upper panel) and S(1) (lower panel) lines toward GG Tau with the continuum subtracted.

In order to avoid confusion with low surface brightness extended H_2 emission, the objects were chosen to be as isolated as possible from any remaining cloud material. Single dish CO 3–2 and/or 2–1 data obtained with the Caltech Submillimeter Observatory (CSO) and the James Clerk Maxwell Telescope (JCMT) generally show a double-peaked line profile with an antenna temperature of ~ 0.5 K on source, but no emission $30''$ off source. The presence of warm gas is in many cases confirmed by detections of the ^{12}CO 6–5 line with the CSO. Near-infrared Keck-images in the (1,0) S(1) line have been obtained for some objects, as well as deep ISO integrations on the S(1) line at a few off-source positions.

4. RESULTS

Table 1 summarizes the results of our observations. The H_2 S(1) line is detected toward all Herbig Ae stars and a few T Tauri stars with a typical strength of 0.3–1 Jy. The S(0) line is seen toward at least two sources: HD 163296 and GG Tau. Figure 1 shows the observed spectra toward GG Tau. Two sets of observations have been carried out for this object in revolutions 668 and 834. The lines are visible in both cases and the results agree within the error bars. The data toward HD 163296 have been presented in van Dishoeck et al. (1998). These sources have the strongest single dish 1.3 mm continuum flux of our sample and the largest disk surface area. The S(3) and S(5) lines are not detected down to ~0.1 Jy rms.

In the optically thin limit, the observed line fluxes are directly related to the populations in the H_2 J=2 and 3 levels. Although the J=3 level has a factor of 40 lower population in LTE than the J=2 level in gas with a temperature around 100 K, the spontaneous transition probability of the S(1) line, $A_{31} = 4.8 \times 10^{-10}$ s^{-1}, is much larger than that for the S(0) transition, $A_{20} = 2.9 \times 10^{-11}$ s^{-1}. In addition, the spectral resolution at 17 μm is somewhat higher than that at 28 μm, so that the line/continuum ratio is larger. Both of these factors explain why the S(1) line is more easily detected than the S(0) line. The inferred beam-averaged excitation temperatures are 106±10 K for GG Tau and 120±20 K for HD 163296. The limits on the S(3) lines for these sources imply temperatures less than 400 K and 300 K, respectively, assuming no correction for differential extinction.

Since the ISO beam is much larger than the sizes of the disks, it is important to check whether any of the observed H_2 emission can arise from surrounding cloud material. H_2 lines up to S(9) are readily detected toward embedded Herbig Ae stars with the ISO-SWS (e.g., van den Ancker et al. 1998a). In these cases, the emission is dominated by the interaction of the young star with its surrounding envelope through shocks and PDRs. The typical H_2 excitation temperatures for these regions are $T_{\rm rot}$=500–700 K, much larger than the values found for our sources.

Deep searches for the H_2 S(0) and S(1) lines toward diffuse and translucent clouds have been performed by Thi et al. (this volume). The lines are not detected down to 0.3 Jy (2σ) in gas with densities of a few hundred to a few thousand cm^{-3} exposed to the normal interstellar radiation field. The single dish CO line intensities at offset positions from our sources are generally lower than those observed for diffuse clouds ($\sim$ 1 K). For example, the ^{12}CO 1-0 emission around GG Tau is less than 32 mK (Strutskie et al. 1993). In addition, a deep Keck image does not show any H_2 emission in the (1,0) S(1) line down to ~20 μJy per pixel, indicating the absence of shocks faster than $\sim$ 20 km s^{-1}. For HD 135344, a deep ISO integration on the S(1) line 1′ south does not reveal any feature at the level of 0.3 Jy (2σ rms). Thus, we are confident that in these cases the bulk of the H_2 emission originates from the disks rather than interstellar material in the ISO beam. However, for a few sources some residual cloud emission may contribute. In particular, the H_2 S(1) line has also been detected with a flux of 0.3 Jy 1′ south of LkCa15.

Assuming no continuum extinction and LTE excitation, typical values for the beam-averaged warm H_2 column densities are $\sim 10^{21}$ cm^{-2} for $T \approx 100 - 120$ K. The corresponding masses of warm H_2 are typically 0.003–0.007 $M_\odot$. These values assume that the ortho/para H_2 ratio is in LTE.

5. DISCUSSION

Although the H_2 S(0) line has only been detected in sources with the strongest 1.3 millimeter continuum flux, the data in Table 1 data show no strong correlation between the H_2 S(1) flux and the 1.3 millimeter continuum. In addition, comparison of the S(1) fluxes obtained for the Herbig Ae and T Tauri stars indicates that there are no significant differences between the two categories, suggesting that spectral type does not play a large role. The age estimates of the observed objects are uncertain, but no obvious trend of evolutionary phase and H_2 emission is seen. However, the errors in the observed fluxes are large and the dynamic range small, which may mask any relations.

For GG Tau, the inferred warm H_2 mass of ~0.007 $M_\odot$ is about 4% of the total gas + dust mass of 0.17 $M_\odot$ derived from millimeter continuum observations assuming a gas-to-dust ratio of 100. (Dutrey et al. 1994). The amount of warm gas is higher than that found from disk models based on the CO emission or continuum SED of this object, which sample the cold component of the disk (Dutrey et al. 1996). For HD 163296, a similar fraction of warm gas is obtained.

Where does the H_2 emission originate? The first possibility is that the H_2 lines come from the inner part ($\leq$ 10 AU) of the disk, heated by accretion. However, a large fraction of this warm gas may be hidden by the optically thick dust continuum. Moreover, gas heated by accretion shocks due to infalling material at the disk surface would be warm enough to emit strongly in the S(3) line and the 2 μm vibration-rotation lines.

A second explanation is provided by flaring disk models, in which the surface layer of the disk is heated by radiation from the central star out to 100 AU (e.g. Chiang & Goldreich 1997). These disk models have a non-isothermal vertical temperature profile. The warm gas is located in the upper part of the disk so that the emission arising from this region is not absorbed by cooler layers before reaching the Earth. An H_2 excitation calculation has been performed using the density and temperature structure of the standard model by Chiang & Goldreich (1997) and assuming gas:dust=100:1 in mass with $T_{\rm gas} = T_{\rm dust}$. Typical S(0) and S(1) fluxes from a single face-on surface layer are 0.05 and 0.5 Jy, respectively. The S(1) flux is comparable to the observed values. However, the flux may be reduced by the optical depth in the continuum and line. Specifically, emission from the opposite warm layer may be affected by the passage through cooler, absorbing parts of the disk. The inferred masses are thus a lower limit to the total "warm" gas mass and a detailed radiative transfer model including the viewing angle of the disk and possible velocity shifts between the warm and cold gas is needed to provide more reliable values.

Table 1. Peak H_2 line fluxes observed toward Herbig Ae and T Tauri stars

Name	Spectral Type	d (pc)	Gas Radius (AU)	$f_{1.3mm}$[a] (mJy)	H_2 S(0) (Jy)	H_2 S(1) (Jy)	Ref.
HD 163296	A1 Ve	122^{+17}_{-13} (b)	310×160	441–780	0.8	1.3	1
HD 31648	A3ep+sh	131^{+24}_{-18} (b)	240×150	360	<0.5	0.5	1
CQ Tau	A1-F5 IVe	100^{+25}_{-17} (b)	120×120	221 ±40	<0.4	0.5	1
HD 36112	A5 IVe	200^{+60}_{-40} (b)	245×245	72	<0.5	0.45	1
GG Tau	K7-M0 (binary)	140	800	593	0.4	0.4	2
GM Aur	K7	140	500	170-253	<0.3	<0.3	3
LkCa15	T_{eff}=4000K	140		167	<0.4	<0.3	4
DR Tau	K7	140		159	<0.3	≃0.5	5
GO Tau	M0	140		83	<0.4	≃0.3	5
49 Cet	A3V	70			<0.4	<0.4	6,7
HD 135344	F4IVe	100		142	<0.5	≃ 0.4	6,7

[a] Single-dish 1.3 mm continuum flux
References: [1]Mannings & Sargent 1997, [2]Dutrey et al. 1996, [3]Dutrey et al. 1998, [4]Osterloh & Beckwith 1995, [5]Beckwith et al. 1990, [6]Zuckerman et al. 1995, [7]Sylvester et al. 1996.
[b] From Hipparcos data by van den Ancker et al. (1998b)

Finally, the fact that up to 80% of young stars are double may facilitate the detection of the H_2 lines. The dynamical interactions in a binary can result in a situation in which each star has an associated disk which lies within a circumbinary disk with a cleared inner region (e.g., Artymowicz & Lubow 1994, Jensen et al. 1996). For the GG Tau double binary system, this is precisely the case (Roddier et al. 1996, Dutrey et al. 1996, Ghez et al. 1997). The presence of an inner cavity may allow the H_2 line emission from the stellar warm accretion disks to escape unattenuated. In addition, the ultraviolet radiation from the star-disk boundary layers may reach the circumbinary disk and heat a layer up to $\sim$ 100 K, similar to the case of circumstellar envelopes described by Spaans et al. (1996).

In summary, this work demonstrates that H_2 pure rotational lines can be detected from disks around pre-main sequence stars and that they provide complementary information to submillimeter observations of CO and other molecules. The H_2 observations are particularly sensitive to small amounts of warm gas in disks. Future observations at higher spectral and spatial resolution accompanied by more sophisticated modeling should be able to clarify the origin of the H_2 emission from T Tauri and Herbig Ae stars.

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