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DETECTION OF H_2 PURE ROTATIONAL LINE EMISSION FROM THE GG TAURI BINARY SYSTEM[1]

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ABSTRACT

We present the first detection of the low-lying pure rotational emission lines of H_2 from circumstellar disks around T Tauri stars, using the Short Wavelength Spectrometer on the *Infrared Space Observatory*. These lines provide a direct measure of the total amount of warm molecular gas in disks. The $J = 2 \rightarrow 0$ $S(0)$ line at 28.218 μm and the $J = 3 \rightarrow 1$ $S(1)$ line at 17.035 μm have been observed toward the double binary system GG Tau. Together with limits on the $J = 5 \rightarrow 3$ $S(3)$ and $J = 7 \rightarrow 5$ $S(5)$ lines, the data suggest the presence of gas at $T_{\rm kin} \approx 110 \pm 10$ K with a mass of $(3.6 \pm 2.0) \times 10^{-3}\ M_\odot$ ($\pm 3\ \sigma$). This amounts to ~3% of the total gas + dust mass of the circumbinary disk as imaged by millimeter interferometry, but it is larger than the estimated mass of the circumstellar disk(s). Possible origins for the warm gas seen in H_2 are discussed in terms of photon and wind-shock heating mechanisms of the circumbinary material, and comparisons with model calculations are made.

Subject headings: circumstellar matter — infrared: ISM: lines and bands — ISM: molecules — molecular processes — stars: individual (GG Tauri) — stars: formation

1. INTRODUCTION

T Tauri stars are considered to resemble our Sun at an age of a few million years. Studies of their surrounding gas and dust can therefore provide important clues on the early evolution of the solar nebula. It is well established through surveys at infrared and millimeter wavelengths that most T Tauri stars have circumstellar disks with masses of $\sim 10^{-3}$–$10^{-1}\ M_\odot$ and sizes of ~100–400 AU (see overviews by Beckwith & Sargent 1996; Dutrey et al. 1996; Mundy et al. 2000). In addition to serving as a conduit for mass accretion onto the young star, the disks also provide a reservoir of gas and dust for the formation of potential planetary systems (Shu et al. 1993). Theories of disk evolution depend strongly on the radial and vertical temperature structure of the disks (e.g., Hartmann et al. 1998), but these parameters are still poorly constrained by the available observations.

We report here the results of a deep survey for the lowest two pure rotational lines of H_2, the $J = 2 \rightarrow 0$ $S(0)$ line at 28.218 μm and the $J = 3 \rightarrow 1$ $S(1)$ transition at 17.035 μm, using the Short Wavelength Spectrometer (SWS) on board the *Infrared Space Observatory* (*ISO*). In emission, the H_2 lines originate from levels at 509.9 K and 1015.1 K above ground and are thus excellent tracers of the "warm" ($T \gtrsim 80$ K) gas in disks, especially in the interesting inner part where Jovian planets may form. H_2 has the advantage that it dominates the mass budget and that it does not deplete onto grains, contrary to CO. Moreover, the lines are optically thin up to very high column densities owing to the small Einstein A coefficients for electric quadrupole transitions, so that the modeling of the radiative transfer is simple.

Here we present H_2 pure rotational line observations of the GG Tau system, which is situated at the edge of the Taurus-Auriga cloud complex at a distance of approximately 140 pc (Kenyon, Dobrzycka, & Hartmann 1994). GG Tau consists of two close binary pairs separated by 10″, or 1400 AU. The main binary GG Tau A has a separation of ~35 AU (Ghez, White, & Simon 1997) and is composed of a K7 and a M0.5 star (White et al. 1999), both classified as emission-line or "classical" T Tauri stars by Herbig & Bell (1988) with an estimated accretion rate of $2 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1}$ (Hartmann et al. 1998). The GG Tau B binary is comprised of an M5 and M7 star separated by ~200 AU. The age of the GG Tau system is estimated to be ~1.5 Myr by White et al. (1999), using the evolutionary models of Baraffe et al. (1998) and assuming the four stars to be coeval.

High spatial resolution images taken in the near infrared show that each of the stars in the GG Tau A system has associated circumstellar material within a radius of less than 10 AU (Roddier et al. 1996). These stars are located within a cavity of radius ~200 AU cleared by the dynamical interaction of the binary (Ghez et al. 1997), and a circumbinary disk extending up to ~800 AU as imaged at millimeter wavelengths (Dutrey, Guillotaeu, & Simon 1994; Guilloteau et al. 1999). The circumbinary disk mass of $\sim 0.12\ M_\odot$, deduced from the strong millimeter dust continuum and assuming a gas-to-dust ratio of 100 : 1, is one of the largest observed to date (Guilloteau et al. 1999). However, observations of ^{13}CO and C^{18}O indicate gas masses that are up to a factor of 100 lower (Dutrey et al. 1994). Explanations for this discrepancy include the possible freeze-out of CO in the cold outer part of the disk and/or a gas dissipation timescale that is shorter than that of the dust (Zuckerman, Foreveille, & Kastner 1995). The H_2 observations presented here allow a direct measurement of the amount of warm gas in the disk.

The H_2 data for GG Tau form part of a survey of a larger number of T Tauri and Herbig Ae stars with the *ISO*-SWS by Thi et al. (1999a, 1999c). An initial account of the results has been given in van Dishoeck et al. (1998).

2. OBSERVATIONS AND DATA REDUCTION

The low-lying pure-rotational H_2 $J = 2 \rightarrow 0$ $S(0)$ line at 28.218 μm and the $J = 3 \rightarrow 1$ $S(1)$ line at 17.035 μm were observed with the *ISO*-SWS in the AOT02 mode (de Graauw

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TABLE 1

OBSERVATIONS

Revolution	Transition	Rest Wavelength (μm)	Integrated Flux (ergs s^{-1} cm^{-2})
668	H_2 0–0 $S(0)$	28.218	2.5×10^{-14}
834	H_2 0–0 $S(0)$	28.218	2.3×10^{-14}
668	H_2 0–0 $S(1)$	17.035	2.8×10^{-14}
834	H_2 0–0 $S(1)$	17.035	2.9×10^{-14}
668	H_2 0–0 $S(3)$	9.66492	$<5.4 \times 10^{-15}$
668	H_2 0–0 $S(5)$	6.90952	$<7.1 \times 10^{-15}$

et al. 1996). The observations were centered in the direction of GG Tau A at R.A.(2000) = $04^h32^m30^s$, decl. (2000) = $17^\circ31'42''$. 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 $J = 5 \rightarrow 3$ $S(3)$ 9.66 μm and $J = 7 \rightarrow 5$ $S(5)$ 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 (150 km s^{-1}) at 28 μm, 2400 (125 km s^{-1}) at 17 μm, 2280 (130 km s^{-1}) at 9.7 μm and 1550 (195 km s^{-1}) at 6.9 μm. The SWS apertures are $20'' \times 27''$ at $S(0)$, $14'' \times 27''$ at $S(1)$, and $14'' \times 20''$ at the $S(3)$ and $S(5)$ lines. Two independent sets of observations have been carried out in orbital revolutions 668 and 834. The expected peak fluxes of the H_2 lines are close to the sensitivity limit of the instrument, and the raw data show a high level of noise induced by charged-particle impacts 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 by Valentijn & Thi (1999). Because the mid-infrared continuum emission from GG Tau is weak, less than 1 Jy at less than 17 μm and ~3 Jy at 28 μm, the data do not suffer from fringing effects caused by an inadequate responsivity function correction.

3. RESULTS

The H_2 $S(0)$ and $S(1)$ lines are detected in both sets of observations (see Table 1), and the differences in fluxes between the two sets are ~10%. This is well within the estimated total error of ~30%, which is mostly due to uncertainties in the flux calibration. The $S(3)$ and $S(5)$ lines are not detected down to a limit of ~$(5–7) \times 10^{-15}$ ergs s^{-1} cm^{-2} (3 σ). The spectra of the H_2 $S(0)$ and $S(1)$ lines are displayed in Figure 1 for revolution 668. Since the turbulent and rotational velocities in disks are only a few km s^{-1}, respectively, both lines are unresolved. After subtraction of the continuum, the lines are fitted by Gaussians with widths fixed by the instrumental resolution and the line fluxes are computed from -3 times to $+3$ times HWHM.

In the optically thin limit, the observed line fluxes are directly related to the populations in the H_2 $J = 2$ and 3 levels. The derived kinetic temperature assuming local thermodynamic equilibrium (LTE) is 110 ± 10 K, where the error bar reflects the 30% uncertainty in the fluxes. Although the $J = 3$ level has a factor of 40 lower population than the $J = 2$ level in gas with a temperature near 100 K, the radiative transition probability of the $S(1)$ line, $A_{31} = 4.8 \times 10^{-10}$ s^{-1}, is much larger than that of 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, and the line-to-continuum ratio is correspondingly larger. Both of these factors explain why the $S(1)$ line is detectable as well. The limits on the $S(3)$ and $S(5)$ lines imply temperatures less than ~260 and ~450 K, respectively, neglecting any correction for differential extinction.

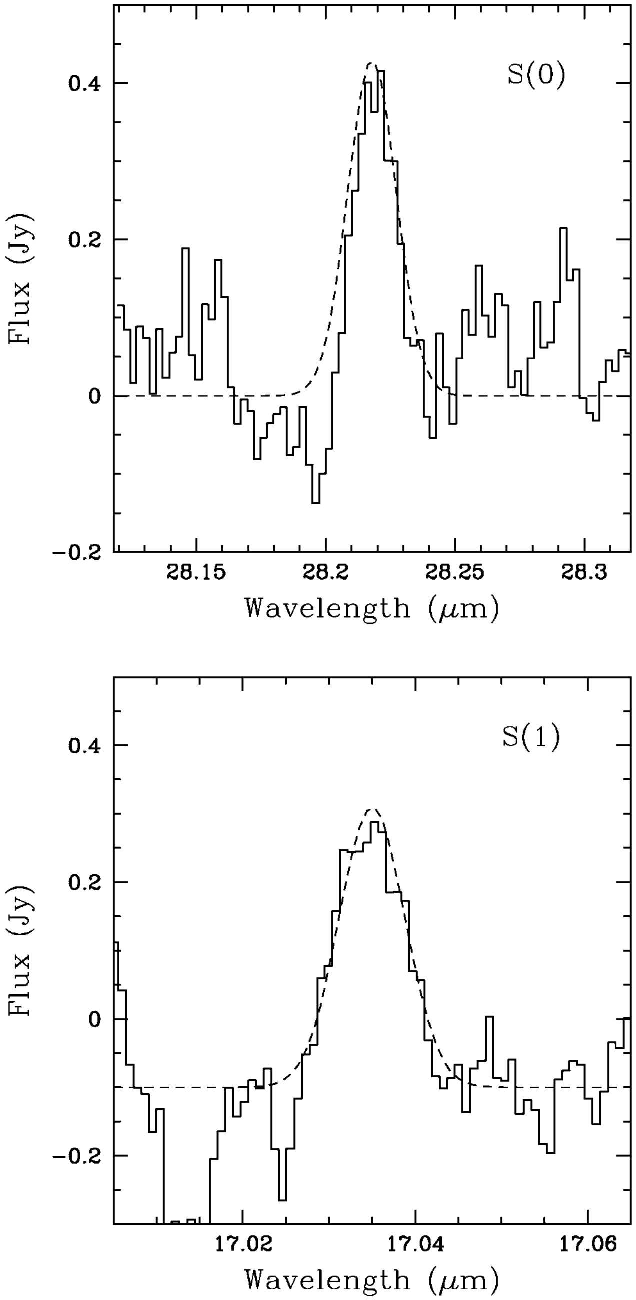

FIG. 1.—H_2 $J = 2 \rightarrow 0$ $S(0)$ (*top*) and $S(1)$ $J = 3 \rightarrow 1$ (*bottom*) emission toward GG Tau obtained with the *ISO*-SWS after subtraction of the continuum. The solid lines indicate Gaussian fits to the data with a width fixed at the instrumental resolution.

Since the *ISO* beam is much larger than the size of the circumbinary disk, it is important to check whether any of the observed H_2 emission may arise from residual extended envelope or 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. 1998). In these cases, the emission is dominated by the interaction of the young star with its surrounding envelope through shocks and ultraviolet photons. The typical H_2 excitation temperatures for these regions are T_{exc} = 500–700 K, much larger than the value found for GG Tau. Deep

ISO searches for the H_2 $S(0)$ and $S(1)$ lines toward diffuse and translucent clouds have been performed by Thi et al. (1999b). The lines are not detected down to 2×10^{-14} ergs s^{-1} cm^{-2} ($2\ \sigma$) in gas with densities of a few hundred to a few thousand cm^{-3} exposed to the normal interstellar radiation field. The ^{12}CO 1–0 emission around GG Tau is less than 50 mK ($3\ \sigma$) (Skrutskie et al. 1993), more than an order of magnitude lower than found for diffuse clouds such as that toward ζ Oph. The corresponding mass in the SWS beam is estimated to be less than a few $\times 10^{-4}$ $M_\odot$, significantly lower than the mass derived from the H_2 lines (see below).

Keck images of GG Tau in K' continuum and H_2 emission in the $v = 1 \rightarrow 0$ and $v = 2 \rightarrow 1$ $S(1)$ lines at 2.1250 and 2.2486 μm were obtained on 1998 November 3 and 6 using the facility Near Infrared Camera (NIRC) and the appropriate filters. No H_2 emission down to ∼20 μJy ($2\ \sigma$) was detected in a 1ʺ.5–6ʺ (i.e., 200–800 AU) radius around the stars, nor outside this region. This translates to a limit on the intensity of $\sim 3 \times 10^{-6}$ ergs s^{-1} cm^{-2} sr^{-1}. Altogether, we are confident that the bulk of the H_2 emission toward GG Tau originates from the disk(s) rather than interstellar material in the *ISO* beam.

Assuming no continuum extinction and LTE excitation, the corresponding mass of warm gas is computed via the relation

$$M_{\rm warm\,gas} = 1.76 \times 10^{-20} \frac{F_{ul} d^2}{(h\nu_{ul}/4\pi) A_{ul} x_J(T)}\ M_\odot,$$

where F_{ul} is the integrated flux in ergs s^{-1} cm^{-2}, d is the distance of GG Tau in pc (taken to be 140 pc), ν_{ul} is the frequency of the transition in Hz, and $x_J(T)$ is the fractional population in the upper rotational level J_u. The derived amount of warm gas is $(3.6 \pm 2.0) \times 10^{-3}$ $M_\odot$ ($3\ \sigma$), including the 30% uncertainty in the fluxes. The derivation assumes that the ortho/para H_2 ratio is ∼1.8, the LTE value at 110 K. If the emission were affected by 30 mag of visual extinction, the derived excitation temperature would increase to 121 K and the mass to 4.0×10^{-3} $M_\odot$.

4. DISCUSSION

The inferred warm H_2 mass of $\sim 3.6 \times 10^{-3}$ $M_\odot$ is about 3% of the total gas + dust mass of 0.12 $M_\odot$ derived from millimeter continuum observations of the circumbinary disk assuming a gas-to-dust ratio of 100 : 1 and a gas + dust absorption coefficient of 0.01 cm^2 g^{-1} at 2.6 mm (Guilloteau et al. 1999). The temperature is much higher than that derived from the continuum spectral energy distribution and optically thick CO emission, which give a temperature of only 34 K at the inner edge of the circumbinary disk at 180 AU.

Where does the warm H_2 emission originate and what is the heating mechanism? The bulk of the circumbinary disk is too cold to account for emission by gas at 100 K. Moreover, the disk is optically thick in the mid-infrared continuum. The H_2 emission must therefore arise either from the circumstellar disk(s), or from the surface layers and inner edges of the circumbinary disk. Two kinds of heating mechanisms may be at work: heating by absorption of part of the stellar and accretion luminosity, and heating by dynamical processes including shocks and turbulent decay. These possibilities are discussed in turn below.

Several radiative processes must be examined. The first possibility is that the H_2 lines arise from material within 10–20 AU around the individual stars, where the gas and dust are heated by the ultraviolet radiation from the YSOs. In general, a large fraction of this warm gas in the inner circumstellar disk(s) may be hidden by the optically thick continuum of colder surrounding dust, especially if the disks are observed nearly edge on. However, GG Tau presents a special case, since the dynamical interaction of the binary has cleared the inner part of the circumbinary disk. The near-infrared observations of Roddier et al. (1996) suggest that at least some of the radiation from the inner disks can escape through holes in the circumbinary disk combined with favorable orientations of the material. The masses of the inner circumstellar disks are estimated to be only $\sim 10^{-4}$ $M_\odot$ each, however, based on the millimeter continuum data (Guilloteau et al. 1999). It therefore does not appear that there is sufficient mass in the inner disks to explain the warm H_2 emission.

Consider next the case of the more extended circumbinary disk. If this disk is flared, as is expected if hydrostatic equilibrium is approached, there exists a surface layer that is heated by radiation from the central star(s) to temperatures near 100 K out to radii of ∼100 AU (e.g., Chiang & Goldreich 1997, 1999). These disk models have a nonisothermal vertical temperature profile, and the warm gas is located in the near-surface regions of the disk. Thus, the emission arising from the heated material 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 of Chiang & Goldreich (1997), assuming a gas-to-dust mass ratio of 100 : 1 with $T_{\rm gas} = T_{\rm dust}$. Typical $S(0)$ and $S(1)$ fluxes from a single face-on surface layer are 7×10^{-16} and 2×10^{-15} ergs s^{-1} cm^{-2}, respectively. These values depend sensitively on the adopted continuum opacities at mid-infrared wavelengths and the geometry, resulting in uncertainties of factors of 2–3. Even taking these factors into account, however, the model fluxes are a factor of 5–10 lower than the observed values. Moreover, the model $S(0)/S(1)$ ratio of 0.4 is lower than the observed ratio of 1.0 ± 0.5, and the model $S(3)/S(1)$ ratio of 0.4 is higher than the observed ratio of less than 0.2. A more detailed radiative transfer simulation including the disk inclination angle of ∼35°–43° (Roddier et al. 1996; Guilloteau et al. 1999) and possible velocity shifts between the warm and cold gas is needed to provide a more accurate assessment of this model, but it is beyond the scope of this Letter.

A third radiative mechanism may be provided by ultraviolet radiation from the star-inner disk boundary layer(s) which can irradiate the inner edge of the circumbinary disk (or any residual gas in the cavity) and heat it to ∼100–200 K. This situation has been described for circumstellar envelopes by Spaans et al. (1995). The intensity of the ultraviolet radiation from a 10,000 K boundary layer with a luminosity of $0.3L_{\rm bol}$ is estimated to be up to a factor of 600 larger than the average interstellar radiation field at a distance of ∼180 AU. If the density at the boundary is assumed to be a few times 10^6 cm^{-3}, the computed H_2 fluxes are $\sim 3 \times 10^{-15}$ and $\sim 2 \times 10^{-15}$ ergs s^{-1} cm^{-2} for the $S(0)$ and $S(1)$ lines, respectively, an order of magnitude lower than observed. Similar discrepancies between models and H_2 observations are found for dense interstellar clouds exposed to ultraviolet radiation (e.g., Draine & Bertoldi 1999), indicating that the heating mechanisms are not fully understood. The $S(0)/S(1)$ ratio of ∼1.5 and $S(3)/S(1)$ ratio of less than 10^{-3} in these models are consistent with the data within the errors, however. Further modeling of the radiative heating of the surface layer and inner edge of the circumbinary disk is needed to investigate whether a combination of these radiative mechanisms can reproduce the observations.

An alternative class of heating mechanisms involves shocks caused by infalling material at the inner disk surface(s) or by the interaction between an outflowing supersonic wind and the surfaces of the circumstellar or circumbinary disk(s) (Hartmann & Raymond 1989). Evidence for such winds comes from optical observations of atomic and ionic lines, from which Hartigan, Edwards, & Ghandour (1995) derive a mass-loss rate of $7.9 \times 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$ for GG Tau. Since the masses of the inner circumstellar disk(s) are too low to explain the H_2 emission, only the interaction of the wind with the circumbinary disk at ~180 AU needs to be considered. The problem with these models is that shocks are expected to warm the surface layers to sufficiently high temperatures to emit strongly in the $S(5)$ and $S(3)$ lines and the 2 μm vibration-rotation lines. Consider as an example the wind-disk models of Hartmann & Raymond (1989). For typical wind velocities of 200 km s^{-1}, the estimated shock velocities along the disk surface range from 20–40 km s^{-1} at distances of 50–200 AU. Comparison with the J- and C-shock models of Burton, Hollenbach, & Tielens (1992) and Kaufman & Neufeld (1996) shows that in virtually all models the flux in the $S(3)$ line is predicted to be larger than that in the $S(1)$ line, in contrast with the observations. Using the $S(3)/S(1)$ ratio as a constraint, at most 30% of the $S(1)$ emission could be contributed by shocks. The lack of detected $H_2\ v = 1 \rightarrow 0\ S(1)$ emission also indicates the absence of shocks faster than ~20 km s^{-1}. Thus, the H_2 $S(3)$ and 2 μm upper limits suggest that heating by shocks is unlikely to be the major contributor to the line emission. Most likely, a combination of heating by ultraviolet photons and dynamical processes is responsible for the warm molecular gas.

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 the warm gas in the disks. With current instrumentation, masses of warm H_2 can be detected that are only a small fraction of the total gas + dust mass in circumstellar disks. The line ratios provide important constraints on the heating mechanisms. In order for the H_2 emission to escape, however, the emission must arise either from the disk surface layers or requires the presence of gaps or holes in the disks. In the case of GG Tau, the binary nature of this system has cleared a large inner cavity in the circumbinary disk, which may have facilitated the detection of the lines. Future observations at higher spectral and spatial resolution such as provided by mid-infrared spectrometers on ground-based telescopes and aboard platforms such as the *Stratospheric Observatory for Infrared Astronomy* (*SOFIA*) and the *Next Generation Space Telescope* (*NGST*), accompanied by more sophisticated modeling, should be able to clarify the origin of the H_2 emission from disks around T Tauri and Herbig Ae stars and allow much more sensitive searches.

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