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LOOKING FOR PURE ROTATIONAL H_2 EMISSION FROM PROTOPLANETARY DISKS

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ABSTRACT

We report on a limited search for pure rotational molecular hydrogen emission associated with young, pre–main-sequence stars. We looked for H_2 $v = 0$, $J = 3 \rightarrow 1$ and $4 \rightarrow 2$ emission in the mid-infrared using the Texas Echelon Cross Echelle Spectrograph at NASA's 3 m Infrared Telescope Facility. The high spectral and spatial resolutions of our observations lead to more stringent limits on narrow-line emission close to the source than previously achieved. One star, AB Aur, shows a possible (2 σ) H_2 detection, but further observations are required to make a confident statement. Our nondetections suggest that a significant fraction, perhaps all, of previously reported H_2 emission toward these objects could be extended on scales of 5″ or more.

Subject headings: circumstellar matter — infrared: stars — planetary systems: protoplanetary disks — stars: pre–main-sequence

1. INTRODUCTION

The formation of a circumstellar disk is recognized as a natural step in the process of star formation and a vital step toward forming planets. Currently, our knowledge of protoplanetary disk properties at anthropically interesting distances of 1–30 AU is relatively limited. The best spectroscopic constraints on disk temperature and density structure are dominated by material either within 0.5 AU of the central source (Najita et al. 1996; Carr, Mathieu, & Najita 2001) or at radii larger than 50 AU (Dutrey, Guilloteau, & Simon 1994). This radial sampling results from the tracers utilized to date: dust emission and scattering and CO rovibrational and rotational emission. Using H_2 rotational lines as tracers may allow the study of disks at radii of 1–50 AU.

Recent work by Thi et al. (1999, 2001a, 2001b) reports H_2 $v = 0$, $J = 2 \rightarrow 0$ and $3 \rightarrow 1$ emission from pre–main-sequence and main-sequence stars with circumstellar disks. From *Infrared Space Observatory* (*ISO*) data, these authors derive gas temperatures of 100–200 K and masses of up to 2×10^{-3} $M_{\odot}$. In the case of disks around main-sequence stars (Thi et al. 2001a), previously thought to be mostly gas free (Zuckerman, Forveille, & Kastner 1995), the presence of a substantial reservoir of H_2 alters ideas on the formation of giant planets (Lissauer 2001). Unfortunately, the large aperture and low spectral resolution of the observations leave open the question of whether the emission really comes from a disk.

Three mid-IR H_2 pure rotational lines are readily available from high, dry sites if observed at moderately high spectral resolution: $v = 0$, $J = 3 \rightarrow 1$ [i.e., $S(1)$] at 17 μm, $J = 4 \rightarrow 2$ [i.e., $S(2)$] at 12 μm, and $J = 6 \rightarrow 4$ [i.e., $S(4)$] at 8 μm. The high spectral and spatial resolutions possible with ground-based spectroscopy, together with large telescope apertures, can result in greater sensitivity to certain gas distributions than satellite observations. In particular, ground-based spectroscopy is well suited for detecting point sources with narrow-line emission, such as gas in Keplerian orbit at a radius of 1–50 AU from a solar mass star.

We report here on observations of a small sample of young stars taken with the Texas Echelon Cross Echelle Spectrograph (TEXES) in an effort to confirm the *ISO* detections and explore the feasibility of ground-based observations of H_2 from circumstellar disks.

2. OBSERVATIONS

We used TEXES (Lacy et al. 2002) at the NASA 3 m Infrared Telescope Facility (IRTF) to observe the H_2 $J = 3 \rightarrow 1$ transition ($\lambda = 17.0348$ μm, or $\tilde{\nu} = 587.032$ cm^{-1}) and the $J = 4 \rightarrow 2$ transition ($\lambda = 12.2786$ μm, or $\tilde{\nu} = 814.425$ cm^{-1}). All the observations were made with TEXES in high-resolution mode. Pertinent details regarding the observations may be found in Table 1. All sources were observed while using the IRTF offset guide camera as well as guiding on the dispersed continuum seen through the spectrograph.

The case of GG Tau deserves special comment since it has a weak continuum, is a strong case for *ISO* detection (Thi et al. 1999, 2001b), and has a unique geometry. The source is a quadruple system composed of a pair of binaries. GG Tau A is a 0″.25 binary with millimeter continuum emission (Guilloteau, Dutrey, & Simon 1999) and *Hubble Space Telescope* scattered-light observations (Silber et al. 2000) showing a circumbinary ring extending roughly from 180 to 260 AU (1″.29–1″.86). The ring is tipped at 37°, resulting in an ellipse on the sky with the major axis running essentially east-west. When we observed GG Tau A, we widened the slit to 3″ and rotated the instrument to orient the slit so that the major axis of the projected ellipse would lie along our slit. The weak continuum of GG Tau meant we could not guide on the continuum signal through the spectrograph. Therefore, we repeatedly checked our infrared boresight by observations of α Tau, a nearby bright infrared source. The maximum boresight offset found based on the α Tau observations was 0″.5, with a mean offset of 0″.2. By summing over ≈4″ along the slit, we can confidently state that we observed essentially all of the GG Tau A gap region.

Correction for atmospheric transmission was done using

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TABLE 1
Observation Information

Star	Line	Resolving Power ($R \equiv \lambda/\delta\lambda$)	Slit Width (arcsec)	Slit Length (arcsec)	Integration Time (s)
GG Tau	$J = 3 \rightarrow 1$	40,000	3.0	11.5[a]	7000
AB Aur	$J = 3 \rightarrow 1$	60,000	2.0	11.5	1800
	$J = 4 \rightarrow 2$	83,000	1.4	7.5	2600
HD 163296	$J = 3 \rightarrow 1$	60,000	2.0	11.5	2400
GW Ori	$J = 3 \rightarrow 1$	60,000	2.0	11.5[a]	1600
	$J = 4 \rightarrow 2$	83,000	1.4	7.5	3800
L1551 IRS5	$J = 3 \rightarrow 1$	60,000	2.0	11.5	2000
DG Tau	$J = 4 \rightarrow 2$	83,000	1.4	7.5	4800

[a] Slit was aligned east-west. Normally, the slit orientation is north-south.

bright infrared continuum objects, either stars or asteroids. Although most stars later than spectral type G show photospheric features at $R \geq 20{,}000$, we can locate features using the Kitt Peak Sunspot Atlas (Wallace, Livingston, & Bernath 1994) and the ATMOS3 photospheric atlas (Geller 1992), and we know that there are no features near the H_2 transitions. Asteroids have no features at our resolution. Both the $J = 3 \rightarrow 1$ and $4 \rightarrow 2$ lines are near telluric atmospheric lines, but the Doppler shift of the source, the Earth's motion, and the high spectral resolution available with TEXES helped to minimize atmospheric effects.

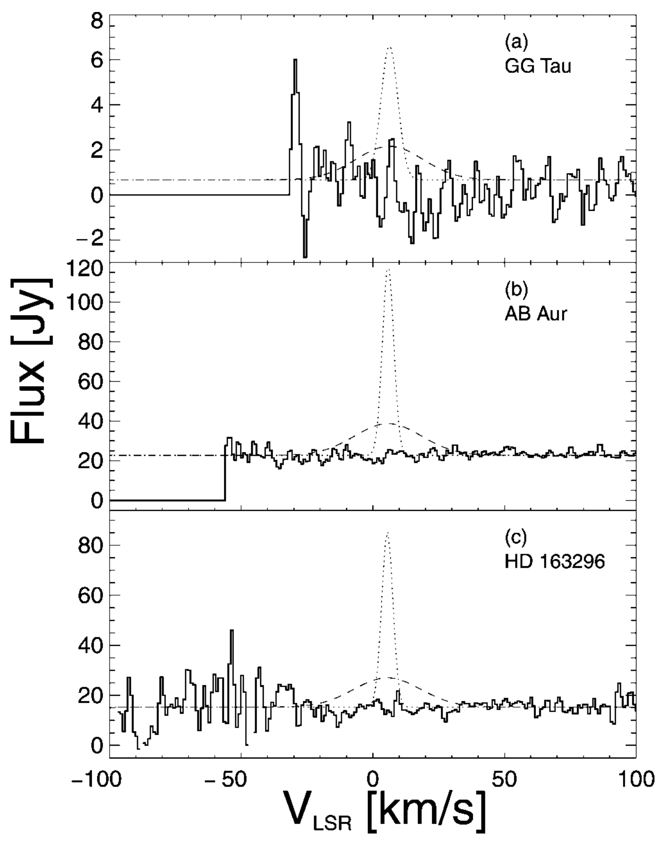

Fig. 1.—H_2 $J = 3 \rightarrow 1$ ($\lambda = 17.035$ μm) observations of the three sources observed by TEXES with reported *ISO* detections: (*a*) GG Tau, (*b*) AB Aur, and (*c*) HD 163296. In all cases, data (*histograms*) are overplotted with Gaussians that have integrated line flux equal to that reported in Thi et al. (2001b). The narrow Gaussian (*dotted lines*) matches our instrumental resolution: FWHM = 7.5 km s^{-1} for GG Tau and 5 km s^{-1} for AB Aur and HD 163296. The wide Gaussian (*dashed line*) has FWHM = 30 km s^{-1}. Gaussians are centered on the systemic velocity. At this wavelength, the spectral order is larger than the detector; regions of the spectrum set to 0 Jy are not sampled. Increased noise toward negative velocities is due to increasing telluric opacity.

Flux calibration was done using a blackbody and standard stars.

3. RESULTS

The data were reduced using the TEXES data pipeline (Lacy et al. 2002). We extracted spectra from the data with several strategies: optimal extraction of the point source to look for emission coincident with the continuum, sums over the nodded region to look for diffuse emission covering half the slit length, and selected sums along the slit to look for isolated emission offset from the point source. We saw no evidence for extended emission in any spectrum, although uniform emission on $\gtrsim 5''$ scales would not be recovered.

Figure 1 presents $J = 3 \rightarrow 1$ spectra for the three sources we observed that also have reported *ISO* detections: GG Tau, AB Aur, and HD 163296. To indicate the line flux reported by Thi et al. (2001b), we overplot Gaussians with an integrated line flux equal to the *ISO* measurements. Since *ISO* was unable to resolve the line profiles, we have simply assumed Gaussian FWHM values to match our resolution (5 or 7.5 km s^{-1}, depending on slit width) and 30 km s^{-1}, with the Gaussians centered at the systemic V_{LSR}. The figures clearly show a discrepancy between the reported line flux and our observations.

Of all our spectra, only the AB Aur 12 μm spectrum shows a possible detection (Fig. 2). A Gaussian fit to the AB Aur data finds a feature centered at the systemic velocity with FWHM $= 0.5$ km s^{-1} and a line flux of $2.0(\pm 1.0) \times 10^{-14}$ ergs s^{-1} cm^{-2}. There are no terrestrial lines and no photospheric absorption lines in the comparison star at this frequency that might artificially produce an emission feature. We discuss the implications of these data, particularly in light of the nondetection of the $J = 3 \rightarrow 1$ line, below.

Table 2 summarizes the results for all our observations. In all cases, we measure continuum levels comparable to past measurements, although the noise for GG Tau is such that many pixels must be combined to obtain a significant continuum measurement. We established line flux errors by summing over the number of pixels corresponding to the assumed line widths at all parts of the spectrum with comparable atmospheric transmission. We then use the line flux upper limit for the more conservative case of a 30 km s^{-1} FWHM line to calculate a maximum mass of H_2 assuming temperatures of 150 and 300 K. Note that these masses assume no extinction and do not include gas in equilibrium with optically thick dust.

4. DISCUSSION

We observed six sources with reasonable evidence for disks and report no convincing detection of H_2 pure rotational emission. Our nondetections have bearing on the interpretation of

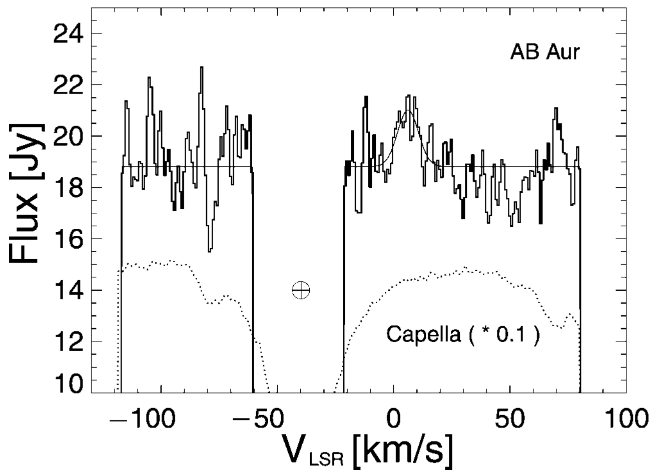

FIG. 2.—H_2 $J = 4 \rightarrow 2$ ($\lambda = 12.279$ μm) spectrum of AB Aur. One complete order (out of eight) is shown, but the region near -40 km s^{-1} where the terrestrial atmospheric transmission is less than 75% is set to zero. Data (*histogram*) are overplotted with a Gaussian fit. Resulting fit has FWHM = 10.5 km s^{-1} and centroid at the systemic velocity. Dotted line shows the spectrum of Capella (divided by 10), the atmospheric calibrator. Features in Capella near -80 and $+70$ km s^{-1} are photospheric OH absorption. Although we attempted to correct for the OH absorption before dividing AB Aur by Capella, some contamination may still be present.

previous *ISO* reports and on the distribution of gas and dust in these sources. In all cases where we set limits, those limits are subject to uncertainties in the assumed gas temperature and the assumed line widths. To provide an example of our sensitivity to these assumptions, we include two line widths and two gas temperatures in Table 2.

Three reported *ISO* detections of H_2 from circumstellar disks, out of three tested, are not seen with TEXES. For *ISO* to detect emission that we would miss, the emission could be either extended or spectrally broad. Given that the *ISO*/Short Wavelength Spectrometer aperture at 17 μm covered $14'' \times 27''$, compared with our effective aperture of $2'' \times 2''$ (280 AU × 280 AU at Taurus: $d = 140$ pc), and that *ISO* detected H_2 rotational lines from molecular clouds with even fairly modest incident UV fields (Li et al. 2002), the presence of extended emission is possible. Thi et al. (2001b) address this issue using ^{12}CO 3–2 emission and conclude that GG Tau shows no contaminating molecular material and that the bulk of molecular material for HD 163296 lies in the disk but that AB Aur may have a significant contribution from an extended envelope. For the case of broad lines, we believe we would have seen lines as broad as ≈50 km s^{-1} (see Fig. 1 and Table 2). Even for the case of GG Tau, we would have seen a line as broad as 30 km s^{-1} at the 2 σ level, given the best-fit line flux in Thi et al. (2001b), although the uncertainties are large enough that these observations may not be in conflict, especially for a broad line. Recent H_2 $v = 1 \rightarrow 0$, $J = 3 \rightarrow 1$ observations at 2 μm show line widths lower than 15 km s^{-1} for GG Tau (J. Bary 2002, in preparation), while CO rovibrational emission toward AB Aur is unresolved at 12 km s^{-1} (G. Blake 2002, in preparation). Although the relationship between these tracers and the pure rotational H_2 emission depends in detail upon the excitation mechanism, these observations show that our assumption of 30 km s^{-1} line widths when calculating mass upper limits is likely conservative. As a fiducial point, the projected Kepler ian velocity at a distance of 1 AU around GG Tau Aa ($M = 0.8$ $M_\odot$; White et al. 1999) and assuming any circumstellar disk has the same orientation as the more extended circumbinary ring (inclination $i = 37°$) would be $v = 16$ km s^{-1}. For AB Aur, taking $M = 2.4$ $M_\odot$ (van den Ancker, de Winter, & Tjin A Dije 1998) and inclination $i < 45°$ (Grady et al. 1999), the projected Keplerian velocity would be $v < 32$ km s^{-1}. Of course, emission lines broadened by Keplerian rotation will generally have widths broader than their characteristic Keplerian velocity.

Although TEXES is a relatively new instrument, we feel reasonably confident in our results. The successful detection of continuum emission from each source at levels consistent with past observations means we were pointed at the source and that our flux determinations are not dramatically in error. We have detected H_2 rotational emission in sources such as Uranus (L. Trafton 2000, private communication) and NGC 7027 (H. Dinerstein 2002, in preparation). The *ISO* detections are the result of special data processing and are near the sensitivity limit (Thi et al. 2001b). Because the *ISO* reports of molecular gas reservoirs around main-sequence stars such as β Pic (Thi et al. 2001a) have such important ramifications for our understanding of planetary formation, the current nondetections in pre–main-sequence disk sources strongly argue for follow-up observations of the main-sequence stars observed by *ISO*, all of which are reported to be "medium-confidence"

TABLE 2
RESULTS SUMMARY

	ISO RESULTS[a]		TEXES OBSERVATIONS					
					Line Flux[c] ($\times 10^{-14}$ ergs s^{-1} cm^{-2})		Mass[d] ($\times 10^{-5}$ $M_\odot$)	
SOURCE	F_ν (Jy)	$J = 3 \rightarrow 1$ Line Flux ($\times 10^{-14}$ ergs s^{-1}cm^{-2})	λ (μm)	F_ν[b] (Jy)	5 km s^{-1}	30 km s^{-1}	150 K	300 K
GG Tau	1.1	2.8 (0.8)	17	0.7 (1.4)	<1.6[e]	<3.9	<47	<3.0
AB Aur	24.4	30 (9)	17	22.7 (2.3)	<3.3	<7.2	<91	<5.9
	...	...	12	18.7 (1.3)	<4.0[f]	...	<1250[f]	<8.7[f]
HD 163296	16.9	22 (6)	17	15.3 (2.5)	<2.0	<5.1	<46	<3.0
L1551 IRS5	...	...	17	20.0 (1.7)	<1.4	<4.3	<51	<3.3
GW Ori	...	...	17	6.8 (2.0)	<1.6	<3.9	<330	<21.0
	...	...	12	6.1 (0.5)	<0.5	<2.2	<5300	<37.0
DG Tau	...	...	12	5.9 (0.5)	<0.6	<3.0	<880	<6.2

[a] From Thi et al. 2001b, with 1 σ errors given in parentheses.
[b] Errors given are 1 σ per pixel. Continuum level determined from more than 450 pixels where the atmospheric transmission is reasonably good.
[c] Upper limits are 3 σ assuming Gaussian FWHM of 5 and 30 km s^{-1}, except as noted.
[d] Mass upper limits assume 30 km s^{-1} FWHM Gaussian line profile, except as noted, and assume a temperature of 150 or 300 K.
[e] Assuming FWHM = 7.5 km s^{-1} due to three slits.
[f] Derived from fit to feature at systemic velocity plus 2 σ (see text). Fitted FWHM = 10.5 km s^{-1}.

detections. Follow-up observations are particularly needed for the well-studied source β Pic, where *Far Ultraviolet Spectroscopic Explorer* observations detect no H_2 absorption through the edge-on disk against a stellar O VI emission line (Lecavelier des Etangs et al. 2001) and where Na I emission shows a gas disk that seems to coexist with the well-known dust disk (Olofsson, Liseau, & Brandeker 2001; Heap et al. 2000)

In the disk sources we observed, the absence of H_2 emission certainly does not mean there is no warm H_2. Where the dust in the disk is optically thick, an emission line would result only if there is spatial and/or temperature separation between the dust and H_2, such as a gap in the dust disk or a hot layer above the optically thick disk (D'Alessio et al. 1998; Chiang & Goldreich 1997). Gaps are believed to be present in GG Tau and GW Ori (Guilloteau et al. 1999; Mathieu, Adams, & Latham 1991); for these sources, the mass upper limits constrain the gas within the gap. In general, our observations argue, albeit weakly, for little spatial separation or temperature differentiation between the bulk of the H_2 gas and dust.

As described in § 3, the 12 μm spectrum of AB Aur has a 2 σ bump at the correct velocity for the $J = 4 \rightarrow 2$ line and a reasonable width. When taken with the 3 σ upper limit on $J = 3 \rightarrow 1$ emission from this source, 3.3×10^{-14} ergs s^{-1} cm^{-2}, the $J = 4 \rightarrow 2$ line flux of $(2.0 \pm 1.0) \times 10^{-14}$ ergs s^{-1} cm^{-2} (-1 σ, $+1$ σ) implies $T_{gas} > 380$ K (275, 500 K), assuming no differential extinction. This is warmer than the 140 K seen in CO rovibrational lines (G. Blake 2002, in preparation). For simple thermal emission, we would expect the H_2 pure rotational lines to come from cooler regions than CO rovibrational emission, although 140 K gas would not collisionally excite rovibrational CO emission. The 3 σ upper limit on $J = 5 \rightarrow 3$ line flux as observed with *ISO*, 0.4×10^{-14} ergs s^{-1} cm^{-2} (Thi et al. 2001b), combined with the possible $J = 4 \rightarrow 2$ detection (-1 σ, $+1$ σ), suggest $T < 190$ K (220, 170 K). Given the errors and the resulting inconsistency, we consider the AB Aur spectrum to give an upper limit to the $J = 4 \rightarrow 2$ integrated line flux of 4.0×10^{-14} ergs s^{-1} cm^{-2}. As well as reobserving the $J = 3 \rightarrow 1$ and $4 \rightarrow 2$ lines, ground-based observations of the $J = 6 \rightarrow 4$ line at 8 μm, which should be quite strong if the gas is truly at 380 K, would help determine if the $J = 4 \rightarrow 2$ is actually as strong as it appears.

While the next infrared satellites will have exceptional mid-infrared sensitivity, they may not be able to detect low line-to-continuum ratio features such as may be present in the AB Aur 12 μm data. If AB Aur were observed at $R = 600$, the maximum resolution available with the *SIRTF* Infrared Spectrograph (Roellig et al. 1998), a signal-to-noise ratio (S/N) of $\approx$1000 would give a 3 σ detection of our derived line flux. The recommended mid-infrared imager/spectrograph for the *Next Generation Space Telescope* (*NGST*), with $R = 1500$ (Mather & Stockman 2000), would require a S/N of 450 for a 3 σ detection. Higher spectral resolution on *NGST*, still a design goal, would dramatically ease this type of observation.

Future ground-based observations with 8–10 m class telescopes and high-resolution spectrographs such as TEXES will improve on the sensitivity described here by an order of magnitude (a factor of 100 in time).

In conclusion, we have attempted to confirm reports of H_2 pure rotational emission from young circumstellar disks without success. Our observations generally set more stringent limits on gas within ~50 AU of the source and with widths of $\lesssim$50 km s^{-1} than those obtained with *ISO*. We have found possible (2 σ) emission from one source, AB Aur, although inconsistencies in derived gas temperatures lead us to consider the result as an upper limit. The absence of emission suggests the gas and dust have little segregation in temperature and/or spatial extent, although more observations are necessary. We have shown that ground-based, high-resolution spectroscopy is an effective way to search for narrow, pure rotational H_2 line emission such as that expected from circumstellar disks.

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