H$_2$ Mid-IR Pure Rotational Emission from Young Stars: The TEXES/IRTF Survey

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Abstract. We describe the TEXES survey for mid-IR H$_2$ pure rotational emission from young stars and report early successes. H$_2$ emission is a potential tracer of warm gas in circumstellar disks. Three pure rotational lines are available from the ground: the $J = 3 \Rightarrow 1$, $J = 4 \Rightarrow 2$, and $J = 6 \Rightarrow 4$, transitions at 17.035 $\mu$m, 12.279 $\mu$m, and 8.025 $\mu$m, respectively. Using TEXES at the NASA IRTF 3m, we are midway through a survey of roughly 30 pre-main-sequence stars. To date, detected lines are all resolved, generally with FWHM $< 10$ km/s. Preliminary analysis suggests the gas temperatures are between 400 and 800 K. From the work so far, we conclude that high spectral and spatial resolution are critical to the investigation of H$_2$ in disks.

1 Introduction

With the excitement caused by the detection of extra-solar planets [1], there has been growing emphasis on the study of circumstellar disks as the birthplace of diverse planetary systems. While great progress has been made in the study of circumstellar dust at both near-infrared (e.g. [2]) and millimeter wavelengths (e.g. [3]). The observations generally do not provide information at disk radii comparable to the orbits of planets in our own solar system. Furthermore, knowledge of the gas is critical to understanding the formation of Jovian planets.

Circumstellar gas studies are also making tremendous progress. Most of the work involves CO rotational lines [4] or ro-vibrational lines [5], although hot H$_2$O ro-vibrational transitions are another tool [6]. While the rotational lines are dominated by gas at large radii ($\sim 100$ AU), the ro-vibrational lines are able to probe regions out to $\sim 1$ AU.

An alternative method of looking at circumstellar gas is to study H$_2$ directly. H$_2$ is the most abundant molecule, does not freeze onto dust grains, and has electronic transitions in the UV [7], ro-vibrational transitions in the near-infrared [8], and rotational transitions in the mid-infrared. The mid-infrared lines come from low lying rotational states that are easily thermalized, are almost completely unaffected by extinction, and are optically thin. With sufficient spectral resolution, it may be possible to invert the H$_2$ line profile and derive...
the gas temperature in the disk as a function of radius. Unfortunately, the mid-infrared lines are weak, as they arise from quadrupole transitions. Three low energy rotational lines of H$_2$ are available from ground-based telescopes: the J = 3 $\Rightarrow$ 1 at 17.035 $\mu$m (also called the 0-0 S(1) line); the J = 4 $\Rightarrow$ 2 at 12.279 $\mu$m (the 0-0 S(2) line); and the J = 6 $\Rightarrow$ 4 at 8.0251 $\mu$m (the 0-0 S(4) line).

Thi et al. [9,10] used the Infrared Space Observatory (ISO) to survey young stars for circumstellar H$_2$. Their results suggested the gas was cold, T $\sim$ 100-200 K, and that significant reservoirs of H$_2$ persisted even around main sequence stars with no apparent CO. Richter et al. [11], using ground-based observations of the J = 3 $\Rightarrow$ 1 transition, showed ISO could not have been detecting disk gas.

In order to test the usefulness of H$_2$ as a probe of disk gas, we began the survey of young stars described here to examine the frequency of disk H$_2$ emission. In the following sections, we will describe the survey (Section 2), some early general results (Section 3), and finish with a short discussion of our preliminary results along with guidelines for future attempts to utilize the mid-IR H$_2$ emission lines (Section 4). More detailed discussions of the survey are in preparation for future publication.

2 Observations and the Survey Strategy

Our H$_2$ survey is made possible by the high spectral and spatial resolution provided by TEXES, the Texas Echelon-cross-Echelle Spectrograph [12]. TEXES is a mid-infrared, cross-dispersed spectrograph with resolving power $\sim$80,000 at 12.3 $\mu$m. On a 3 meter telescope such as NASA’s Infrared Telescope Facility (IRTF), TEXES provides the sensitivity to match or surpass ISO for observations of unresolved sources with narrow lines. The high spectral resolution not only provides optimal sensitivity to narrow lines, but also helps to separate atmospheric features from those of astronomical interest. This is particularly important for observing H$_2$ lines (Fig 1). In addition, the spatial resolution with TEXES approaches the diffraction-limit (0.85" at 12.3 $\mu$m on a 3 meter telescope) giving us access to spatial clues for understanding the emission.

Based on our previous work [11], we expected to reach line flux limits comparable to or better than those obtained with ISO in roughly one hour. This realization, along with the non-detection of H$_2$ in ISO sources, prompted our survey of roughly 30 young stars. Since no one knows the characteristic temperature of circumstellar H$_2$ emission, we concentrate on J = 3 $\Rightarrow$ 1 and J = 4 $\Rightarrow$ 2. The ratio of these two lines is sensitive to gas temperatures in the range 200-600 K. Figure 2 shows that 10 M$_\oplus$ of H$_2$ gas can readily be detected at a distance of 140 pc for the case of gas in equilibrium with a radiatively heated dust surface layer composed of small grains [13]. For all sources where we detect line emission, we will also observe J = 6 $\Rightarrow$ 4. The third line provides additional leverage on the gas temperature, up to $\sim$1000 K, as well as a glimpse at the ortho:para ratio for H$_2$. Finally, while the observations of the two primary lines are sensitive to the amount of water in our own atmosphere, the J = 6 $\Rightarrow$ 4 line observations are relatively unaffected by terrestrial water vapor (Fig 1).
We currently concentrate on sources with relatively strong mid-infrared continuum fluxes to allow guiding through TEXES. We use the IRTF visible camera for source acquisition and offset guiding whenever possible, but long integrations on weak mid-infrared sources raise concerns about the pointing and tracking efficiency. Unfortunately, requiring a strong mid-infrared continuum biases the survey toward the brightest sources and diminishes its general applicability. Consequently, our survey targets include more higher mass Herbig Ae stars and fewer weak-lined T Tauri stars and debris disks than desired. A larger telescope or an internal guider would improve our survey.

In making our observations, we concentrate on detecting material within $\sim 200$ AU of the central source. Typical instrumental setups are given in Table 1. To remove background emission, we nod the telescope so the object is always on the slit. This renders us insensitive to emission on scales larger than $\sim 5''$. We oriented the slit north-south for all observations.

3 Results

Roughly a third of the 21 stars observed so far show evidence of H$_2$ emission at one or more settings. No clear, symmetric, double-peaked line profiles indicative of disk emission have been seen. While almost all the detected lines are clearly resolved, most lines are relatively narrow with a typical FWHM $\approx 10$ km/s and
Fig. 2. An estimate of the line flux from the three mid-infrared rotational lines of H$_2$ available from the ground assuming the gas is the same temperature as a hot disk surface layer composed of small grains [13]. At each radial step, we calculate the line flux from a gas mass of 10 M$_\odot$ at a distance of 140 pc. In one hour, TEXES observations on the IRTF can reach 3$\sigma$ detection limits $< 10^{-14}$ erg/s/cm$^2$.

| Setting | R $\equiv$ $\lambda/\Delta\lambda$ | Slit Width | Slit Length |
|---------|-------------------------------|------------|------------|
| J = 3 $\Rightarrow$ 1 | 60,000 | 2$''$ | 10.5$''$ |
| J = 4 $\Rightarrow$ 2 | 90,000 | 1.4$''$ | 7.5$''$ |
| J = 6 $\Rightarrow$ 4 | 90,000 | 1.4$''$ | 7.5$''$ |

Table 1. Typical TEXES Observing Parameters
Fig. 3. Portions of the spectra recorded at 17 and 12 $\mu$m from sources with clear $J = 4 \Rightarrow 2$ detections. We show normalized spectra offset for clarity with wavelength scale as observed. Both panels include a telluric transmission spectrum, although the offset is different because of the low transmission at 17 $\mu$m. Gaps in the spectral coverage result from the spectral order being larger than the detector.

the line emission comes from roughly 0.5$''$ south of the mid-infrared continuum source.

4 Discussion

By taking the measured line fluxes, we can use the line ratios to determine an $H_2$ temperature and mass. For the case of T Tau, as will be described in a future paper, we determine a gas temperature of $\sim$400-800 K and a mass of $\sim$5-10 M$_{\odot}$. Errors in the flux determinations at the three wavelength settings will have a large effect on the final temperature and mass determinations. We have tried to account for these effects in the ranges given.

Given the narrow line widths we see and the centrally-peaked nature of the line profiles, it is unlikely our first detections come from disk material close to the central star or gas shock-excited and associated with a bipolar outflow. The material close to the star in a Keplerian disk provides the greatest velocity extent. If the inner regions produce no emission, the intrinsic line shape, when convolved with the instrumental profile, would more closely match a single centrally-peaked profile. Line-of-sight effects – a disk inclined to the line of sight or a shock traveling perpendicular to the line of sight – could also result in narrow line widths. Disks with their rotation axes within roughly 20 degrees of the line of
sight will show a single centrally-peaked profile. Naturally, higher signal-to-noise observations would help in the study of the line profiles.

As mentioned above, flux determinations through our spectrograph slit are a concern since calibration errors result in large allowed temperature and mass ranges. Ideally, the line strength would be fixed to the mid-IR continuum which can be accurately determined from imaging. Unfortunately, even this method can introduce errors if the source varies in the mid-infrared, such as the T Tau system [14]. Based on our experiences, future efforts for studying H$_2$ disk emission should be very careful about establishing good fluxes.

Finally, we note that the TEXES spectra show the importance of both high spatial and spectral resolution. The spatial offset between continuum and line emission, such as seen in the T Tau system, requires spatial resolution $\sim 1''$. Since the equivalent widths of the emission detected so far is less than $< 5$ km/s, instruments with R $< 10,000$ will require very high signal-to-noise ratios in order to detect the lines and will be have a limited ability to examine the velocity structure in what appears to be the small fraction of sources with broad lines.

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