A search for $\text{H}_2$ around pre-main-sequence stars

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ABSTRACT

We present the results of a search for pure rotational molecular hydrogen emission from two pre-main-sequence stars, AB Aur and CQ Tau. Observations were made using MICHELLE, the mid-IR echelle spectrometer at the UK Infrared Telescope. We found some evidence for emission in the $J = 4 \rightarrow 2$ line in AB Aur, but no $J = 3 \rightarrow 1$ line from either star. We derive upper limits on line flux which are significantly smaller than previous line flux estimates based on ISO observations. This suggests that the emission detected by ISO is extended on scales of at least 6 arcsec, and does not come from the disk as previously thought.

Key words: circumstellar matter.

1 INTRODUCTION

Circumstellar disks play a vital part in both star and planet formation, and if we are to understand these processes then it seems we must understand the composition and physics of disks first. The discovery that disks can survive well into the main sequence lifetime of a star (after planet formation ended in our own system) has opened up an exciting window on the planet formation process (Zuckerman 2001).

This means that we can directly probe the environment of planet formation, even though planets themselves may be undetectable.

The dominant constituent of the disks around pre-main-sequence stars is H$_2$. However, observing emission from H$_2$ which represents the bulk of the warm ($\sim$200K) gas in the disks is not straightforward. Near-infrared (Bary et al. 2002), UV emission (Valenti et al. 2001) or absorption observations (Roberge et al. 2001) trace only the hottest gas or are dependent on the line of sight through the circumstellar disk. Mid-infrared observations of the pure rotational emission lines of H$_2$ trace the bulk of the warm gas, but are difficult from ground-based sites, due to telluric absorption and the high mid-infrared background emission. Thus, many previous studies of the gas component of such disks has relied on observations of tracer molecules, particularly CO (Mannings & Sargent 2002; Duvert et al. 2000). While these observations have been successful in tracing the velocity structure in disks, it seems that CO is a poor indicator of the total gas content. This is because CO can be destroyed by UV photons or frozen onto dust grains, leading to a severe underestimate of the total amount of gas. Most estimates of disk mass are based on sub-mm observations of the dust continuum (Beckwith et al. 1990; Sylvester et al. 2001), but these rely on assumptions about the composition and size distribution of the dust grains, and also on the gas/dust mass ratio. More importantly, we know that the dust and gas do not evolve in the same way – disks around main-sequence stars are composed mainly of dust, while disks around pre-main-sequence stars are composed mainly of gas. It is important to be able to measure gas properties independently from the dust properties using direct observations of H$_2$.

Recently, the Infrared Space Observatory (ISO) has been used to search for H$_2$ pure-rotational emission lines from pre-main-sequence stars, and also young main-sequence stars which are known to have dust disks. Thi et al. (2001) report detections of the H$_2$ $J = 3 \rightarrow 1$ transition ($\lambda = 17.035$ $\mu$m) and H$_2$ $J = 2 \rightarrow 0$ transition ($\lambda = 28.221$ $\mu$m). H$_2$ masses derived from these observations imply large masses of H$_2$ in the disks around main-sequence targets (Thi et al. 2001), reversing the previous belief that dust is the main component. However, as the ISO beam is large ($14 \times 27$ arcsec) compared with the disks and the observations have moderate spectral resolution ($R \sim 2000$), these results cannot distinguish circumstellar disk emission from that of a foreground cloud or extended source.

Follow up observations of both the pure rotational emission lines and H$_2$ in absorption have provided strong evidence that the warm H$_2$ is extended in sources selected from the ISO studies. Using the echelle spectrometer, TEXES, Richter et al. (2002) obtained observations of six sources, three of which have reported ISO H$_2$ detections (Thi et al. 2001b): HD163296, AB Aur and GG Tau. They obtained upper limits on the line fluxes from five sources, with a possible 2 sigma detection of the H$_2$ $J = 3 \rightarrow 1$ S(0) line in AB Aur and conclude that the majority of the H$_2$...
emission detection by ISO is extended on scales of 5 arcsec or more. The far-UV spectrum of Beta Pictoris presented by [Lecavelier des Etangs et al. (2003)] shows a complete absence of H$_2$ absorption lines, contrary to expectations if large quantities of H$_2$ are present within the edge-on dust disk.

We present the results of our attempts to confirm the ISO results using MICHELLE, the mid-infrared echelle spectrometer on the ground-based United Kingdom Infrared Telescope (UKIRT). We targeted two pre-main-sequence stars, CQ Tau (distance 100 pc) and AB Aur (distance 142 pc), both of which have good ISO detections and one of which (AB Aur) was also observed by [Richter et al. (2002)]. In both cases, the dust disk is expected to be unresolved spatially by MICHELLE.

2 OBSERVATIONS AND DATA REDUCTION

Mid-IR echelle spectroscopy of AB Aur and CQ Tau was carried out on 2001 December 29 and 30 using MICHELLE ([Glasse et al. 1997]) on UKIRT. AB Aur and CQ Tau were observed in the H$_2$ J = 3 → 1 transition (λ = 17.035 μm), providing direct comparison with the ISO observations. AB Aur was also observed in the H$_2$ J = 4 → 2 transition (λ = 12.279 μm). The H$_2$ J = 2 → 0 transition (λ = 28.221 μm) was used in the ISO observations, but is not readily accessible from the ground due to the structure of the atmospheric transmission at 28 μm. Details of the observations are shown in Table 1.

MICHELLE is a mid-IR imager and spectrometer which uses a 320×240-pixel Si:As array and operates between 8 and 25 microns. For these observations the echelle grating was used, to provide maximum sensitivity to the H$_2$ lines which are expected to be unresolved. AB Aur was observed with a 2-pixel slit width; CQ Tau with a 4-pixel slit width. The resolving power was R = 15 200 at 12 μm and R = 18 600 (R = 9 300) at 17 μm for a two (four) pixel wide slit; as a result the H$_2$ lines are well separated from the bright sky lines. A single order from the grating is selected using blocking filters. The pixel field of view varies with wavelength due to anamorphic demagnification. The values are given in Table 1.

The point-like sources were all observed by nodding along the 70 arcsec long slit, which was orientated north-south on the sky. The separation of the two beams was 15 arcsec and the dwell-time in each beam was 40 seconds.

Data reduction was done using software written in the IDL language. Pairs of frames from different nod positions were subtracted, giving a set of difference frames each containing a positive and a negative version of the source. In each frame, the positive and negative versions were combined to give a single 2D spectrum. Before the set of 2D spectra were combined into a final image, the dataset was despiked using an iterative sigma cut. To do this, all of the 2D spectra were compared, and datum were flagged as bad if they were further than a specified number of standard deviations from the mean of their pixel. This sigma cut was done three times with threshold settings of 6, 4 and 3 sigma.

Once a final 2D spectrum had been produced, 1D spectra were extracted in two ways: a wide extraction which summed all the emission in a 6.5 arcsec region centered on the source, and an optimal extraction of the continuum. The optimal extraction method takes a weighted mean of the pixels around the source, giving more weight where the continuum is brighter. This method gives the lowest possible noise on the continuum level, but if the H$_2$ emission region is more extended than the continuum emission then it will underestimate the H$_2$ line flux. For both extraction methods a sky subtraction was done first, estimating the residual sky signal in each column using pixels between 3.5 and 7 arcsec from the source.

Figure 1. Spectra of the H$_2$ J = 3 → 1 transition for AB Aur and CQ Tau. For comparison, gaussians are shown with the same integrated flux as the ISO measurements reported in [Thi et al. 2002], assuming an intrinsic line width of 20 km s$^{-1}$. The CQ Tau spectrum has been masked out at regions of high noise (shown by the use of dotted lines); the lower panel shows the standard star observation, scaled from 0.0 to 1.0, to demonstrate that the masked regions correspond to atmospheric absorption lines. For AB Aur, the standard star observation was saturated, which causes the variability in the continuum level.
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Table 1. Summary of observations. The pixel scale on the sky is subject to anamorphic magnification due to the quasi-Littrow mode of operation of the MICHELLE spectrometer. The long axis is along the slit.

| Object | Date       | Wavelength $\mu$m | Slit width pixels | Pixel scale on-sky arcsec | Integration time seconds |
|--------|------------|-------------------|-------------------|--------------------------|--------------------------|
| AB Aur | 29 Dec 2001 | 12.279            | 2                 | 0.50×0.24                | 1900                     |
|        | 29 Dec 2001 | 17.035            | 2                 | 0.50×0.28                | 3400                     |
| CQ Tau | 30 Dec 2001 | 17.035            | 4                 | 0.50×0.28                | 5900                     |

Table 2. Summary of results. All upper limits are 3 sigma. ISO results are taken from Thi et al. (2001).

| Object | Wavelength $\mu$m | Line flux $\times 10^{-14}$ ergs $s^{-1}$ cm$^{-2}$ |
|--------|-------------------|-------------------------------------------------------|
|        |                   | Wide extraction | Optimal extraction | ISO Result |
| AB Aur | 12.297            | $5.4 \pm 3.8$  | $4.8 \pm 2.1$          |            |
|        | 17.035            | $< 14.6$       | $< 8.9$                | $30 \pm 9$ |
| CQ Tau | 17.035            | $< 13.0$       | $< 6.7$                | $40 \pm 12$|

Figure 2. Spectra of the H$_2$ $J = 4 \rightarrow 2$ transition for AB Aur. The vertical dotted line shows to the expected location of the transition. Noisy regions have been masked out and the standard star is shown in the lower panel, as in Figure 1.

3 RESULTS

Figures 1 and 2 show the final spectra produced using an optimal extraction. At the location of sky lines the noise increases dramatically, so these regions have been masked out (i.e. they were not used when estimating the continuum level and the overall noise). On the 17 $\mu$m figures a gaussian with the total line flux measured by Thi et al. (2001) is shown, to allow comparison between the ISO results and our spectra. As the ISO observations do not resolve the line, we have assumed an intrinsic line width of 20 km s$^{-1}$ (see Section 4 for discussion of this value), and an instrumental width of 16 km s$^{-1}$ for AB Aur and 32 km s$^{-1}$ for CQ Tau, giving a total width of 26 km s$^{-1}$ and 38 km s$^{-1}$ respectively. The MICHELLE sensitivities should have produced a clear detection of the line, if all of the flux in the 14 $\times$ 27 arcsec ISO beam were contained within our extracted beams, as expected for emission from an unresolved disk.

To estimate the line flux, all of the flux within a 40 km s$^{-1}$ wide bin centered on the systematic velocity was summed, after subtracting the continuum level. Fluxes and upper limits for all extraction methods are shown in Table 2. There is no evidence of H$_2$ emission in either of the 17 $\mu$m spectra. The 12 $\mu$m optimally extracted spectrum gives flux of $4.8 \pm 2.1$ ergs $s^{-1}$ cm$^{-2}$, but as this is only a 2.3 sigma result should not be regarded as a definite detection. However, this result is consistent with the tentative detection by Richter et al. (2002), who measure $(2.0 \pm 1.0) \times 10^{-14}$ ergs $s^{-1}$ cm$^{-2}$ with a width of 10.5 km s$^{-1}$.

4 DISCUSSION

Despite the enhanced sensitivity to narrow emission lines from a point-like source, these new spectra of AB Aur and CQ Tau show no convincing detections of either the 0-0 S(1)
or 0-0 S(2) lines. In order for the 0-0 S(1) H$_2$ emission to be detectable by ISO but not by MICHELLE, the emission would have to be either spectrally broad or spatially extended. We consider these two explanations in turn.

The spectral resolving power of the ISO observations is $R = \frac{λ}{δλ} = 2400$, and the H$_2$ line observed by MICHELLE (as estimated by Thi et al. (2001a,b)), the thermal broadening would only be 1.5 km s$^{-1}$. The amount of rotational broadening depends on the distance from the star, and the inclination of the disk. If we assume a distance of 2 AU (a reasonable choice, given the gas temperature of 200 K), this gives a width of 15 km s$^{-1}$, assuming an inclination of $\sim 45^\circ$. Therefore, 20 km s$^{-1}$ is a conservative estimate of the line width. In fact, the line FWHM would have to be over 100 km s$^{-1}$ to make the ISO and MICHELLE measurements consistent.

The possibility of extended emission, due to excitation of a remnant cloud of molecular gas by UV photons or by shocks, is plausible. Assuming that the ISO measured flux is uniformly distributed over the 14 $\times$ 27 arcsec aperture, the fluxes are consistent with UV-excited emission strengths predicted by Burton et al. (1992) for moderate UV field strengths ($10^{-2}$ to $10^{-4}$ times that of the interstellar medium) and moderate densities ($n(H_2) \sim 10^3 - 10^4$ cm$^{-3}$). Over the MICHELLE beam used to obtain the spectra shown in Figure 1, the line flux would be an order of magnitude fainter than the sensitivity limit obtained. Moreover, the sky subtraction region (3.5-7 arcsec radius) means that our observations are insensitive to emission at radius >3.5 arcsec. The hypothesis of extended emission is strengthened for AB Aur since a map of $^{12}$CO 3-2 shows an extended molecular cloud around the central source, with a size of at least 30 arcsec (Thi et al. 2001b). For CQ Tau, no $^{12}$CO 3-2 line was detected, but this could be reconciled with extended H$_2$ emission if the CO has been destroyed by photodissociation (Dent et al. 1995).

In interpreting our results, an important question concerns the optical depth of the dust disk. If the dust is optically thick at the wavelengths we observed and the gas and dust are at the same temperature, then the gas would be equally likely to absorb or emit a photon, so no emission line would be produced. Line emission will only occur if there are gaps in the dust disk, or if there is a hot atmosphere above the disk. Though these situations are quite plausible, only a small fraction of the gas in the disk would be observed in this case, and any calculation of the gas mass would underestimate the true mass. It is therefore essential that we know the optical depth of the disk in order to correctly interpret our results.

The optical depth of the disks can be estimated from the SEDs of both AB Aur and CQ Tau, and we can use their fitted parameters to determine whether the disks are optically thick at 12 and 17 $\mu$m. Based on their estimates of disk mass and disk radius, and using the usual assumption that the dust opacity at 1.3 mm is $\kappa_{1.3\mu m} = 0.01$ cm$^2$ g$^{-1}$, the average optical depth of the disks at 1.3 mm is 0.03 for AB Aur and 0.24 for CQ Tau. Then, using a power law dust opacity index ($\kappa \propto \lambda^{-\beta}$, where $\beta$ was estimated to be 2.0 for AB Aur and 1.0 for CQ Tau in Natta et al. (2001), the optical depth can be estimated at shorter wavelengths. This indicates that the disks become optically thick at wavelengths shorter than 200 $\mu$m for AB Aur and 300 $\mu$m for CQ Tau. Both disks must therefore have a high optical depth at 12 and 17 $\mu$m.

In conclusion, we have searched for pure rotational H$_2$ emission lines from the circumstellar disks of AB Aur and CQ Tau. We tentatively detect emission from AB Aur, but find no evidence for emission from CQ Tau. The likely reason for this non-detection is that the disks are optically thick in the mid-IR. Our upper limits on line flux are significantly smaller than previous line flux estimates based on ISO observations, which suggests that the emission detected by ISO is extended on scales of at least 6 arcsec (or >60 AU).

Mapping the emission over the area covered of the ISO beam is one approach to confirming these conclusions. Detecting the faint extended emission will require a considerable gain in sensitivity over these observations, such as is anticipated using MICHELLE on the Gemini North 8-m telescope.

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