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VISIR OBSERVATION OF H_2 EMISSION FROM THE CIRCUMSTELLAR DISK AROUND THE HERBIG Ae STAR HD97048

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Abstract. We present high resolution spectroscopic mid-infrared observations of the circumstellar disk around the Herbig Ae star HD97048 with the *VLT Imager and Spectrometer for the mid-InfraRed* (*VISIR*). We detect the S(1) pure rotational line of molecular hydrogen (H_2) at 17.035 μm arising from the disk around the star. This detection reinforces the claim that HD97048 is a young object surrounded by a flared disk at an early stage of evolution. The emitting warm gas is located within the inner 35 AU of the disk. The line-to-continuum flux ratio is much higher than expected from models of disks at local thermodynamics equilibrium. We investigate the possible physical conditions, such as a gas-to-dust mass ratio higher than 100 and different excitation mechanisms of molecular hydrogen (X-ray heating, shocks, ...) in order to explain the detection. We tentatively estimate the mass of warm gas to be in the range from 10^{-2} to nearly 1 M_{Jup}. Further observations are needed to better constrain the excitation mechanisms as well as the mass of gas.

1 Introduction

Circumstellar (CS) disks surrounding pre-main sequence stars are supposed to be the location of planet building. The characterization of the gaseous component, which initially represents 99% of the total disk mass, is a key research question towards an understanding of protoplanetary disks and planet formation. However, from previous observations, little is known about the gas compared to the dust. Molecular hydrogen (H_2) is the main constituent of the molecular cloud from which the young star is formed and is also expected to be the main component of the CS disk. H_2 is the only molecule that can directly constrain the mass reservoir of warm and hot molecular gas in disks. Indeed, the detection of H_2 excited by collisions allows us to measure the temperature and density of the warm gas. Unfortunately, direct observation of H_2 is difficult. Electronic transitions occur in the ultraviolet to which the Earth's atmosphere is opaque, and rotational and ro-vibrational transitions at infrared (IR) wavelengths are faint because of their quadrupolar origin. However, H_2 rotational lines have been recently detected in the disk around one Herbig Ae star (HAe), namely AB Aur, with the high spectral and spatial resolution TEXES spectrometer (Bitner et al. 2007). These detections imply that H_2 can be observed in the mid-IR domain when particular physical conditions exist in disks.

VISIR has the high spectral ($10\,000 < R < 30\,000$) and spatial resolution (Lagage et al. 2004) necessary to pick up such narrow gas lines from the disks. In addition, high spectral resolution is a key element to disentangle the H_2 line from the absorption lines due to the Earth's atmosphere. The spectral ranges covered by *VISIR* offer access to the most intense pure rotational lines of molecular hydrogen (H_2): S(1) ($v = 0-0, J = 3-1$) at 17.0348 μm, S(2) ($v = 0-0, J = 4-2$) at 12.2786 μm, S(3) ($v = 0-0, J = 5-3$) at 9.6649 μm, and S(4) ($v = 0-0, J = 6-4$) at 8.0250 μm. The S(0) ($v = 0-0, J = 2-0$) transition near 28 μm is not observable from the ground due to the Earth's atmospheric absorption.

A particularly interesting object to study the CS material around a pre-main sequence intermediate mass star is HD97048. HD97048 is a nearby, relatively isolated Herbig A0/B9 star located in the Chameleon cloud at a distance of 180 pc (van den Ancker et al. 1998). Its age has been estimated from evolutionary tracks to be of the order of 3 million years (kindly computed by L. Testi and A. Palacios). This star is known to be

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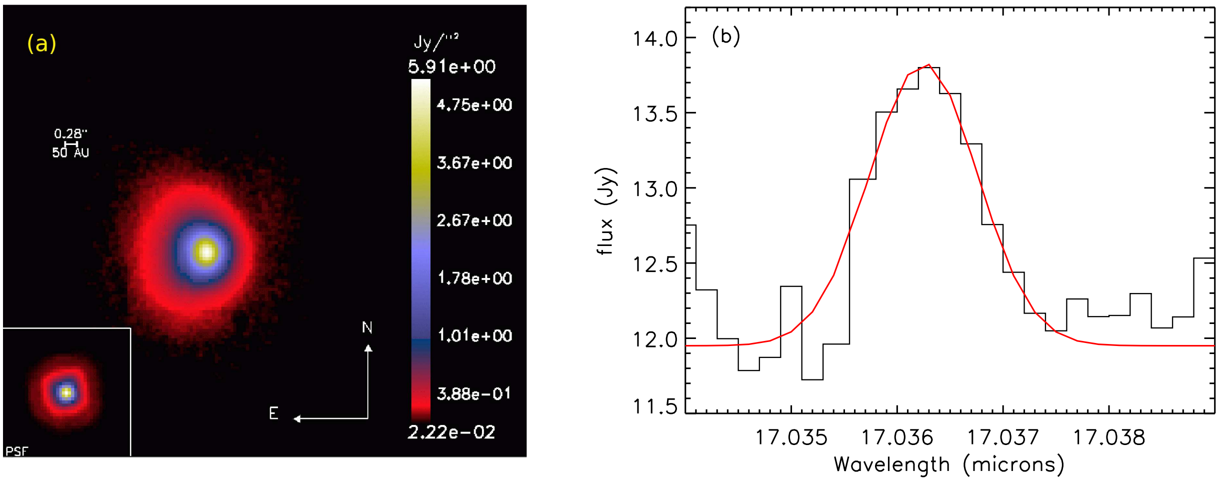

Fig. 1. *(a): VISIR* image at 8.6μm of the PAHs emission around HD97048 which shows an asymmetry, as compared with the PSF (Lagage et al. 2006). *(b):* H_2 S(1) emission line from the disk of HD97048; black line: observed spectrum; red line: gaussian fit with FWHM equal to a spectral resolution element of 30 km s^{-1}.

surrounded by an extended CS disk. The *VISIR* imaging observations of this star conducted in 2005 June 17 and 19, have revealed an extended emission of PAHs (Polycyclic Aromatic Hydrocarbons) at the surface of a flared disk inclined to the line of sight by $42.8^{+0.8}_{-2.5}$ degrees (see Fig. 1*a*; Lagage et al. 2006). This is the only Herbig star for which the flaring of the disk has been observed by direct imaging. The flaring index has been measured to be 1.26$\pm$0.05, in good agreement with hydrostatic flared disk models (Lagage et al. 2006; Doucet et al. 2007). This geometry implies that a large amount of gas should be present to support the flaring structure and that the disk is at an early stage of evolution. This star is thus one of the best candidates to study the gas component in the disks of HAe stars.

2 Observations and data analysis

HD97048 was observed for 1800s with the high spectral resolution long-slit mode of *VISIR* in June 22, 2006. The central wavelength of the observation was set to 17.035 μm. We used the 0.75" slit, providing a spectral resolution about 10 000, i.e. Δv=30 km s^{-1}. The weather conditions were very good and stable during the observations; the optical seeing was less than 0.66" and the airmass (<1.8) was close to the minimum airmass accessible when observing this object from the Paranal ESO observatory. In order to correct the spectrum from the Earth's atmospheric absorption and obtain the absolute flux calibration, we observed the CERES asteroid and the standard star HD89388 (see www.eso.org/VISIR/catalogue) just before and after observing HD97048. HD89388 and CERES were observed at nearly the same airmass and seeing conditions as the object. We have divided the spectrum of HD97048 by that of CERES (which has a much better signal-to-noise ratio than that of the standard star HD89388) to correct for the telluric absorption, and used the HD89388 observed and modelled spectra (Cohen et al. 1999) to obtain the absolute flux calibration. The wavelength calibration is done by fitting the observed sky background features with a model of the Paranal's atmospheric emission.

As shown in Fig. 1*b*, we have detected the H_2 pure rotational S(1) line near 17.03 μm. In the flux-calibrated spectrum, the standard deviation (σ) of the continuum flux was calculated in regions less influenced by telluric absorption, and close to the feature of interest. We deduced a 6σ detection in amplitude for the line, corresponding to a signal-to-noise of about 11σ for the line, when integrating the signal over a resolution element (6 pixels). The line is not resolved as we can fit it with a Gaussian with a full width at half maximum (FWHM) equal to a spectral resolution element of 30 km s^{-1} (see Fig. 1*b*). From our fit, assuming the emission arises from an isothermal mass of optically thin H_2, we derived an integrated flux in the line of 2.4×10^{-14} ergs s^{-1} cm^{-2}.

Once the spectrum is corrected from the Earth's rotation, and knowing the heliocentric radial velocity of HD97048 (+21 km s^{-1}; Acke et al. 2005), we estimated, from the wavelength position of the Gaussian peak, the radial velocity of H_2 to be about 4±2 km s^{-1} in the star's rest frame. We thus considered that the radial velocity of the H_2 is similar to that of the star, implying that the emitting gas is bound to the star. The H_2 line is not resolved spatially. Given the *VISIR* spatial resolution of about 0.427" at 17.03 μm, and the star distance (180 pc from the sun), we can assess that the emitting H_2 is located within the inner 35 AU of the disk (Fig. 1*b*). Under some assumptions, we calculated the corresponding lower limits on the column densities and masses of warm gas as a function of the assumed temperature (for details about the method see the paper by Martin-Zaïdi et al. 2007a). We also estimated the dust mass producing the flux level of the continuum in the spectrum by using a model of optically thin emission of dust at the surface of a disk, and derived gas-to-dust mass ratios for the different temperatures (Table 1).

Table 1. Column density, masses (1 $M_{Jup} \sim 10^{-3}$ $M_{\odot}$), and gas-to-dust mass ratio as a function of the temperature.

	150 K	300 K	1000 K
N(H_2) (cm^{-2})	2.19×10^{23}	1.41×10^{22}	3.27×10^{21}
M(H_2) (M_{Jup})	7.37×10^{-1}	4.51×10^{-2}	1.33×10^{-2}
M_{dust} (M_{Jup})	2.23×10^{-4}	1.03×10^{-5}	9.39×10^{-7}
gas-to-dust ratio	3260	4378	14164

3 Discussion

Our high resolution spectroscopic observation of the S(1) pure rotational line of H_2 at 17.03 μm of HD97048 has revealed the presence of significant amounts of warm gas in the inner 35 AU of the disk. From a gaussian fit of the emission line, we derived very high column densities of warm gas, which are more than two orders of magnitude higher than those generally observed in the CS environment of Herbig Ae stars (Martin-Zaïdi et al. 2007b). This confirms that HD97048 is a young object surrounded by a circumstellar disk at an early stage of evolution. Indeed photoevaporation of the gas is expected to clear up the inner part of the disk within 3 million years (Takeuchi et al. 2005).

We derived masses of the warm gas in the range from 10^{-2} to nearly 1 M_{Jup} (1 $M_{Jup} \sim 10^{-3}$ $M_{\odot}$) depending on the adopted temperature, and assuming LTE (Local Thermodynamics Equilibrium). The masses derived here are lower than those of Lagage et al. (2006) who have estimated a minimum mass of gas in the inner disk to be of the order of 3 M_{Jup}. But it should be pointed out that mid-IR H_2 lines are only probing warm gas located in the surface layer of the disk, when a higher mass of colder gas is expected to be present in the interior layers of the disk. In any case, the finding of warm molecular hydrogen reinforces the claim that a large amount of cold gas is present in the disk to support its flaring geometry (Lagage et al. 2006).

It is generally accepted that the first rotational levels (J) of H_2 are populated by thermal collisions, an excitation mechanism which requires kinetic temperatures higher than 150 K to produce the S(1) transition. Assuming equal dust and gas temperatures, we estimated dust masses responsible for the continuum emission and derived gas-to-dust mass ratios in the range from 3260 to 14164 (Table 1), much larger than the canonical value of 100. These crude estimates are in agreement with more sophisticated models such as two-layer LTE disk models (Dullemond 2001; Carmona et al. 2007). Indeed, by scaling the gas-to-dust mass ratio found here to the canonical value of 100, we obtained a peak line flux of about 0.46% of that of the continuum at 150 K, decreasing to 0.1% of the continuum at 1000 K, which is close to the line-to-conitnuum ratios calculated in disks models by Carmona et al. (2007). Thus one possible interpretation of our observation is that the dust is partially depleted from the disk surface layer, where the H_2 emission originates. The spatial decoupling between the gas and the dust may be due to dust settling or dust coagulation into larger particles.

However, other excitation mechanism cannot be excluded. Several competing mechanisms could contribute to the excitation of molecular hydrogen such as UV pumping, shocks, X-rays, etc..., (see review papers by Habart et al. 2004 and by Snow & McCall 2006) and could be responsible for the observed emission. Weak X-ray emission has been detected from HD97048 by ROSAT (Zinnecker & Preibisch 1994). X-rays and UV photons are likely candidates to heat the gas to temperatures significantly higher than those of the dust (Glassgold et al. 2007) and could partly explain a high line-to-continuum ratio. According to radiative transfer models of disks around T Tauri stars (Nomura & Millar 2005; Nomura et al. 2007), X-ray heating could significantly increase the line-to-continuum flux ratio, but, applying the same increase factor to HAes, the S(1) H_2 line would still be below the detection limit of *VISIR*.

Note that the present *VISIR* observation does not allow us to discriminate between the different possible physical origins of the emission of H_2. New observations of HD97048 will be performed with *VISIR* in order to observe the other pure rotational lines of H_2. The detection of these lines would help to better constrain the temperature (and thus the mass) of the warm gas.

Our results are very similar to those obtained by Bitner et al. (2007) for AB Aur with the TEXES instrument. Indeed, those authors have shown that the emitting warm gas is located in the inner 18 AU of the disk around AB Aur. For the two stars, the gas has not completely dissipated in the inner region of the disk in a lifetime of about 3 Myrs. HD97048 and AB Aur have nearly identical astrophysical parameters (T_{eff}, age, mass, distance). Their disks are flared (Pantin et al. 2005; Lagage et al. 2006) and seem to be in similar evolutionary states, which could well be a disk old enough such that the dust sedimenation/coagulation has already been at work, but young enough such that the gas has not yet been photoevaporated. It is not possible to draw definite conclusions with only two examples and it would be interesting to observe other HAe stars similar to AB Aur and HD97048. The high angular resolution and high spectral resolution available with ground-based instruments are key advantages over space-based instruments such as ISO-SWS in order to obtain firm detections of H_2 from disks.

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References

Acke, B., van den Ancker, M. E., & Dullemond, C. P. 2005, A&A, 436, 209

Bitner, M. A., Richter, M. J., Lacy, J. H., et al. 2007, ApJL, 661, L69

Carmona, A., van den Ancker, M., Henning, T., et al. 2007, A&A, submitted

Cohen, M., Walker, R. G., & Witteborn, F. C. 1999, LPI Contributions, 969, 5

Doucet, C., Habart, E., Pantin, E., et al. 2007, A&A, 470, 625

Dullemond, C. P., Dominik, C., & Natta, A. 2001, ApJ, 560, 957

Glassgold, A. E., Najita, J. R., & Igea, J. 2007, ApJ, 656, 515

Habart, E., Boulanger, F., Verstraete, L., Walmsley, C. M., & Pineau des Forêts, G. 2004, A&A, 414, 531

Lagage, P.-O., Doucet, C., Pantin, et al. 2006, Science, 314, 621

Lagage, P. O., Pel, J. W., Authier, M., et al. 2004, The Messenger, 117, 12

Martin-Zaïdi, C., Lagage, P.-O., Pantin, E., & Habart, E. 2007a, ApJL, accepted

Martin-Zaïdi, C., Deleuil, M., Bouret, J.-C., et al. 2007b, A&A, to be submitted

Nomura, H., Aikawa, Y., Tsujimoto, M., Nakagawa, Y., & Millar, T. J. 2007, ApJ, 661, 334

Nomura, H. & Millar, T. J. 2005, A&A, 438, 923

Pantin, E., Bouwman, J., & Lagage, P. O. 2005, A&A, 437, 525

Snow, T. P. & McCall, B. J. 2006, ARA&A, 44, 367

Takeuchi, T., Clarke, C. J., & Lin, D. N. C. 2005, ApJ, 627, 286

van den Ancker, M. E., de Winter, D., & Tjin A Djie, H. R. E. 1998, A&A, 330, 145

Zinnecker, H. & Preibisch, T. 1994, A&A, 292, 152