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MOLECULAR HYDROGEN IN THE DISK OF THE HERBIG STAR HD 97048

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Abstract. We present high-resolution spectroscopic mid-infrared observations of the circumstellar disk around the Herbig Ae star HD 97048 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 HD 97048 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. This detection implies that particular physical conditions, such as a $T_{gas} > T_{dust}$, are present in the inner disk surface layer. We do not detect the S(2) and S(4) H_2 lines, but we derive upper limits on the integrated line fluxes which allow us to estimate an upper limit on the gas excitation temperature. This limit on the temperature sets new contraints on the mass of warm gas in the inner regions of the disk.

1 Introduction

Circumstellar (CS) disks surrounding pre-main sequence stars are thought 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. Recently, Carmona et al. (2008) discussed the detectability of H_2 mid-IR lines by modeling the surface layers of a gas-rich disk, seen face-on, surrounding a Herbig Ae star (HAe) at 140 pc from the Sun. By assuming that the gas and dust were well-mixed in the disk, a gas-to-dust ratio of about 100, and that $T_{gas} = T_{dust}$, those authors demonstrated that mid-IR H_2 lines could not be detected with the existing instruments. Surprisingly, H_2 rotational lines have been detected in the disk around one HAe, namely AB Aur, with the high spectral and spatial resolution TEXES spectrometer (Bitner et al. 2007). These detections demonstrate that H_2 can be observed in the mid-IR domain when particular physical conditions exist in disks.

VISIR has a sufficiently high spectral and spatial resolution (Lagage et al. 2004) 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 H_2: the S(1) line at 17.0348 μm, S(2) at 12.2786 μm, and S(4) at 8.0250 μm. The S(0) transition close to 28 μm is not observable from the ground due to the Earth's atmospheric absorption, and the S(3) line at 9.6649 μm, is located amidst a forest of telluric ozone features, and is thus only observable for extremely favorable Doppler shifts.

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Table 1. Summary of the observations. Airmass and seeing intervals: from the beginning to the end of the observations.

λ μm	t_{exp} (s)	Airmass	Optical seeing (")	Slit (")	R	Stand. Star	Asteroid
17.0348	1800	1.72-1.79	0.52-0.66	0.75	14 000	HD89388	CERES
12.2786	960	1.81-1.87	1.97-2.16	0.4	13 600	HD91056	VESTA
8.0250	1872	1.66-1.69	0.51-0.65	0.4	13 300	HD92305	VESTA

HD 97048 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 Mys (kindly computed by L. Testi and A. Palacios). This star is known to be surrounded by an extended CS disk. The *VISIR* imaging observations of this star have revealed an extended emission of PAHs (Polycyclic Aromatic Hydrocarbons) at the surface of a flared disk (Lagage et al. 2006; Doucet et al. 2007). This is the only Herbig star for which the flaring of the disk has been observed by direct imaging. 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 HAes.

2 Observations and data reduction

HD 97048 was observed at 3 different periods. The observations at 17.035 μm presented in Martin-Zaïdi et al. (2007), were performed in 2006 June 22, the 8.025 μm observations in 2007 April 07, and the 12.278 μm observations in 2007 July 03 (Martin-Zaïdi et al. 2008, in prep). The three sets of observations were obtained with the high resolution spectroscopic mode of *VISIR*. The exposure time, slit width, and atmospheric conditions during the observations are presented in Table 1. For all the three observations, the standard "chopping and nodding" technique was used to suppress the large sky and telescope background dominating at mid-IR wavelengths (for details on the observation technique see Martin-Zaïdi et al. 2007). Asteroids and standard stars were observed just before and after observing HD 97048, at nearly the same airmass and seeing conditions as the object. In order to correct the spectra from the Earth's atmospheric absorption, we divided each spectrum of HD 97048 by that of the corresponding asteroid (which has a much better signal-to-noise ratio than that of the standard star), and used the standard stars' observed and modeled 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 Paranal's atmospheric emission. We note that $A_v = 0.24$ mag for HD 97048 (Valenti et al. 2000), thus we have not corrected the spectra for dust extinction, since it is negligible in our wavelength range for any $A_v < 40$ mag (Fluks et al. 1994).

3 Data analysis

As shown in Fig. 1, 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 ratio 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 $\mathrm{km\,s^{-1}}$ (see Fig. 1). From our fit, assuming the emission arises from an isothermal mass of optically thin H_2, we derived the integrated flux in the line (see Table 2).

Once the spectrum is corrected from the Earth's rotation, and knowing the heliocentric radial velocity of HD 97048 (+21 $\mathrm{km\,s^{-1}}$; 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 $\mathrm{km\,s^{-1}}$ 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. We calculated the corresponding column density for the $J = 3$ rotational level (see Table 2; for details about the method see Martin-Zaïdi et al. (2007).

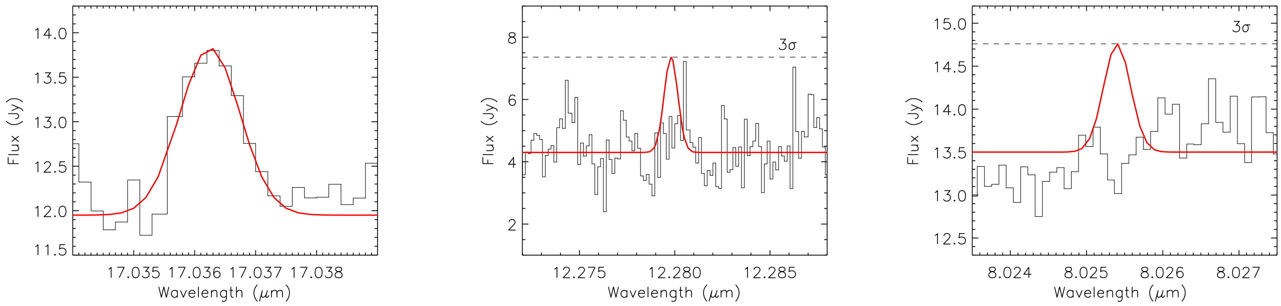

Fig. 1. *(Left):* H_2 S(1) emission line from the disk of HD 97048. *(Middle and Right):* regions of the HD 97048 spectrum where the S(2) and the S(4) lines, respectively, could have been observed. Gaussians with amplitudes of 3σ line-flux upper limits are overplotted. For each plot: black line: observed spectrum; red line: gaussian fit with FWHM equal to a spectral resolution element.

HD 97048 spectra showed no evidence for H_2 emission neither at 12.278 μm nor at 8.025 μm (Fig. 1). From the flux-calibrated spectra, we calculated the standard deviation (σ) for wavelength ranges relatively unaffected by telluric absorption, and close to the wavelengths of interest. The 3σ upper limits on the integrated line fluxes were calculated by integrating over a Gaussian of FWHM equal to a spectral resolution element and an amplitude of about 3σ flux, centered on the expected wavelength for the S(2) and S(4) lines respectively (Fig. 1). From the limits on integrated intensities and by assuming that the emitting H_2 is optically thin at LTE, we estimated the upper limits on the column densities of the corresponding upper rotational levels of each H_2 transition (see Table 2).

Table 2. Integrated fluxes, Intensities and column densities of each observed mid-IR transitions of H_2. v_{up} and J_{up} are respectively the vibrational and rotational upper levels of the transition of interest.

Wavelength (μm)	Transition	v_{up}	J_{up}	Integrated flux (ergs s^{-1} cm^{-2})	Intensity (ergs cm^{-2} s^{-1} sr^{-1})	$N_{J_{up}}(H_2)$ (cm^{-2})
17.035	S(1)	0	3	2.4×10^{-14}	5.7×10^{-3}	1.29×10^{21}
12.278	S(2)	0	4	$<5.5\times10^{-14}$	$<2.6\times10^{-2}$	$<7.46\times10^{20}$
8.025	S(4)	0	6	$<2.6\times10^{-14}$	$<2.9\times10^{-2}$	$<5.54\times10^{19}$

4 Discussion

Our high resolution spectroscopic observation of the S(1) pure rotational line of H_2 at 17.03 μm of HD 97048 has revealed the presence of significant amounts of warm gas in the inner 35 AU of the disk. This detection confirms that HD 97048 is a young object surrounded by a circumstellar disk at an early stage of evolution. Indeed photoevaporation of the gas and planet formation are expected to clear up the inner part of the disk within about 3 million years (Takeuchi et al. 2005).

The estimates of the column densities of the $J = 3$, $J = 4$, and $J = 6$ rotational levels of H_2 allowed us to plot the excitation diagram of the molecule (see Fig. 2). Assuming that all three levels are populated by thermal collisions (LTE), we estimated that the temperature of the observed gas should be less than 920 K. However, as shown by Martin-Zaïdi et al. (2007) from the observation of the S(1) line, such a detection can only be explained if the physical conditions of the gas differ from LTE ones. Indeed, the S(1) line detection implies that particular conditions have to be assumed for the gas and dust, such as $T_{gas} > T_{dust}$, and that the H_2 gas is likely excited by other mechanisms than thermal collisions. In any case, even if these three levels are not thermally populated, their populations give strong constraints on the gas kinetic temperature. Indeed, the kinetic temperature is given by the population of the first rotational levels (namely $J = 0$ and $J = 1$), and is always lower than the excitation temperature given by the higher energy levels. Our upper limit on

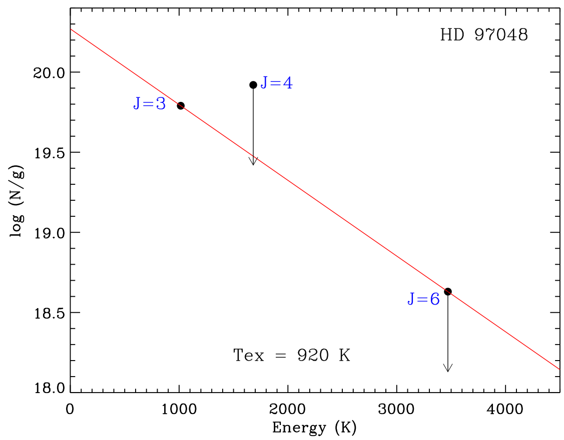

Fig. 2. Excitation diagram for H_2 towards HD 97048. If the three rotational levels are populated by thermal collisions, their populations follow the Boltzmann law, and the gas temperature should be less than 920 K (red line).

the temperature of about 920 K is thus reliable whatever the mechanisms responsible for the excitation of the observed gas.

This constraint on the temperature of the gas confirms the estimates by Martin-Zaïdi et al. (2007) concerning the mass of warm H_2 in the inner 35 AU of the disk. Indeed, those authors have 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. Theses masses 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 H_2 reinforces the claim that a large amount of cold gas is present in the disk to support its flaring geometry (Lagage et al. 2006).

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