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FUSE observations of H_2 around the Herbig AeBe stars HD 100546 and HD 163296

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Abstract. We present the analysis of *FUSE* observations of two Herbig AeBe stars known to harbor young circumstellar disks: HD 100546 and HD 163296. In both cases we detect absorption lines from warm and dense H_2. The thermalization of the rotational levels up to $J \sim 4$ allows evaluation of the temperature, density and typical size of the absorbing layer. These quantities are consistent with absorption of the light of the central star by a thin layer of a circumstellar disk seen at an intermediate inclination.

Key words. planetary systems: protoplanetary disks – circumstellar matter – stars: individual: HD 100546 – stars: individual: HD 163296 – stars: pre-main sequence

1. Introduction

HD 100546 and HD 163296 are two Herbig AeBe stars harboring young circumstellar disks. Herbig AeBe stars are intermediate-mass (2–10 $M_\odot$) young emission-line stars still in the pre-main sequence phase (Herbig 1960). Material surrounding Herbig stars is thus considered as the constituent of protoplanetary disks, similar to the disks seen around the less massive T-Tauri stars. These disks are the material from which (and the places where) planets are supposed to form according to the standard model of planetary formation (Lissauer 1993).

HD 100546 (B9Vne, $d = 103^{+7}_{-6}$ pc, $t > 10$ Myr; van den Ancker et al. 1998) is older than HD 163296 (A1Ve, $d = 122^{+17}_{-13}$ pc, $t = 4^{+6}_{-2.5}$ Myr; van den Ancker et al. 1998). However, both stars present very similar characteristics. In the two cases, ISO detected silicate features resembling cometary materials (Malfait et al. 1998; van den Ancker et al. 2000; Bouwman et al. 2000, 2001). Disks have recently been imaged around both stars (Pantin et al. 2000; Grady et al. 2000, 2001; Augereau et al. 2001). The images show dusty disks at intermediate inclination (~60°). Absorption spectroscopy also revealed the presence of circumstellar gas around HD 100546, including spectral variabilities which are interpreted as accreting material (Grady et al. 1996, 1997).

In the case of HD 163296, a CO disk of about 310 AU in semi-major axis has been detected (Mannings & Sargent 1997). H_2 infrared emission lines have also been reported by Thi et al. (2001) at 17 and 28 μm. From their ISO observations and assuming thermal equilibrium up to $J = 3$, they derive a total H_2 mass of $0.4(\pm 0.2) \times 10^{-3} M_\odot$, and the ratio of the two emission lines ($v = 0$, $J = 2 \rightarrow 0$ and $J = 3 \rightarrow 1$) gives a temperature of 220(±22) K. However, this detection has been challenged by more recent ground based observation at 17 μm which shows no detection with three times better sensitivity (Richter et al. 2002).

These controversial observations raise the question of the molecular content of such disks, where most of the mass is in the form of molecules, and particularly H_2. The formation of giant planets requires a large reservoir of molecular gas. Moreover some of these planets migrate close to their parents where they are observed. This migration also needs a massive disk to allow the angular momentum exchange between the migrating planet and the disk. The H_2 content is thus a key ingredient in the recipe for the formation of giant planets. But H_2 is a symetrical molecule, and infrared emission by quadrupole rotational transitions is very inefficient. In contrast, when seen against a UV bright source, far-UV absorption lines due to electronic transitions allow sensitive observation of H_2 even at low temperatures. *FUSE* offers a unique opportunity to scrutinize in detail the H_2 content of protoplanetary disks around Herbig stars.

2. Observation and data analysis

HD 100546 was observed with *FUSE* through the LWRS aperture (30″×30″) for a total time of 5.8 hours on March 26, 2000

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(Program P1190303) and March 3, 2002 (Program P2190401) (for an overview of *FUSE*, see Moos et al. 2000 and Sahnow et al. 2000). HD 163296 was observed twice, on April 27, 2001 and April 29, 2001 for a total time of 8.9 hours (Programs P2190601 and Q2190101, respectively). The data of both targets were reprocessed with the version 2.0.5 of the `CALFUSE` pipeline. The output of the pipeline is a total of 5 and 10 sub-exposures for HD 100546 and HD 163296, respectively. The sub-exposures have been aligned and coadded resulting in a set of four independent spectra, one for each *FUSE* channel (2 LiF spectra and 2 SiC spectra).

The version 2.0.5 of the `CALFUSE` pipeline is known to slightly over-estimate the tabulated errors on each pixel. We compared the data used in the present work with data of the same observations but obtained with the version 2.2.1 of the `CALFUSE` pipeline; we conclude that the error bars given below are not significantly affected by the improvement in the error propagation of the different pipelines.

Apart from the observation of the molecular hydrogen, the spectra are rich in emission and absorption lines from atomic and ionic species. For instance, a large number of Fe II lines from the ground level as well as from excited levels are clearly detected. As already observed in AB Aur and β Pic (Roberge et al. 2001; Deleuil et al. 2001), bright emission from C III and O VI are also detected in the two spectra. All these features indicate the presence of circumstellar material, chromospheric activity and/or accretion (Bouret et al. 2002). A detailed analysis of the whole *FUSE* spectrum will be made in a forthcoming paper (Deleuil et al. 2003). Here we focus on the analysis of the H_2 lines, probing the molecular portion of the disk.

In the far-UV, HD 100546 is brighter than HD 163296 and the observed spectrum has a better S/N ratio allowing detection of H_2 in its pure rotational level ($v = 0$) up to $J = 9$ (a line of $v = 0$, $J = 10$ is also marginally detected at 1058.6 Å) and in its first vibrational level ($v = 1$) up to $J = 5$ (Fig. 1). In the HD 163296 spectrum, H_2 lines are detected up to $v = 0$, $J = 4$. Higher J-levels are beyond the detection limit. The data analysis and profile fitting has been done using the `Owens` code kindly made available to us by Dr. M. Lemoine (see for example Lemoine et al. 2002 and Hébrard et al. 2002). For the electronic transitions, we used the wavelengths and oscillator strengths tabulated by Abgrall et al. (1993a and 1993b for the Lyman and the Werner system, respectively), and the inverses of the total radiative lifetimes tabulated by Abgrall et al. (2000).

With low H_2 column densities in HD 100546 ($N \leq 10^{16}$ cm^{-2} for each J-level), we can choose to fit only the unsaturated lines having low oscilator strength ($f \lesssim 10^{-2}$). This allows us to avoid systematic errors in the estimates of column densities which could be included by the fit of saturated lines with uncertain instrumental line spread function. Note, however, that additional fits have been performed with saturated lines ($f \gtrsim 10^{-2}$). They give very similar column densities and allow the determination of the intrinsic line width (b). In HD 163296 the column densities are larger, and all the H_2 lines are saturated. Therefore the error bars on the column densities are also larger than in HD 100546. An example of the fit of two H_2 lines ($J = 3$ and $J = 4$) which are superimposed on the O VI stellar emission line is given in Fig. 2.

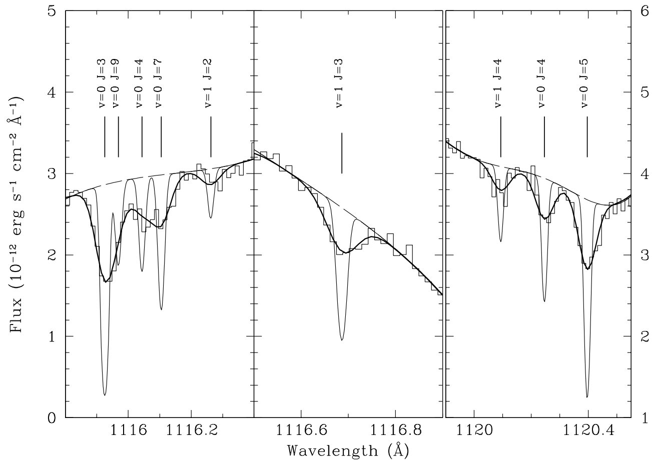

Fig. 1. Sample of H_2 lines detected toward HD 100546. The histogram shows the data. The final fit to the data is shown (thick line) together with the theoretical spectrum without convolution with the instrumental line spread function (thin line). This shows that the fitted lines are not saturated. In the selected sample, some lines are blended together. Consequently, a profile fitting is needed to use the information included in the data but which cannot be translated into an equivalent width.

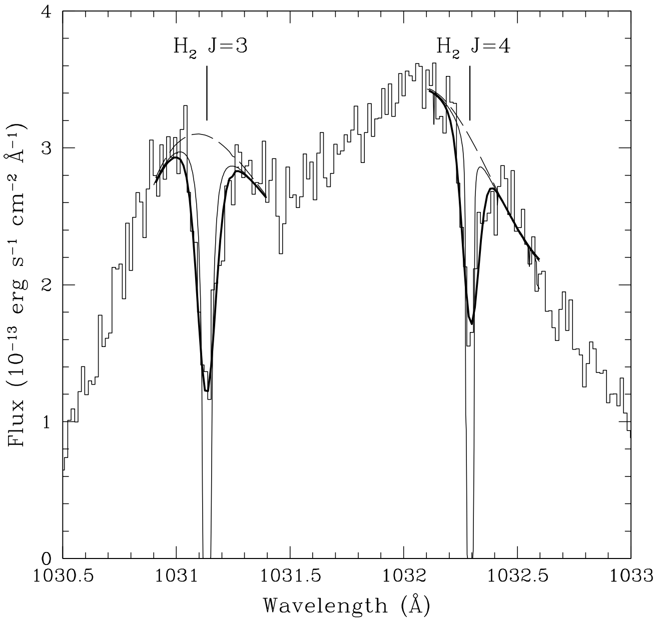

Fig. 2. Two H_2 absorption lines detected over one emission line of the O VI doublet toward HD 163296. Here the theoretical spectrum without convolution with the instrumental line spread function (thin line as in Fig. 1) shows that these H_2 absorption lines are saturated.

The estimated column densities are tabulated with 2σ error bars (Table 1). We obtain the total column densities

$$N_{H_2}(\text{HD } 100546) \approx 2.8 \times 10^{16} \text{ cm}^{-2}$$

and

$$N_{H_2}(\text{HD } 163296) \approx 1.4 \times 10^{18} \text{ cm}^{-2}.$$

The error bars are estimated by the classical method of the $\Delta\chi^2$ increase of the χ^2 of the fit (see Hébrard et al. 2002 for a full

Table 1. H_2 column density toward HD 100546 and HD 163296.

HD 100546				HD 163296		
J	v	$\log N_{H_2}$ [a] (cm^{-2})		J	v	$\log N_{H_2}$ [a] (cm^{-2})
0	0	$15.16^{+0.38}_{-0.26}$		0	0	$17.1^{+0.4}_{-0.7}$
1	0	$16.00^{+0.28}_{-0.19}$		1	0	$17.9^{+0.2}_{-0.3}$
2	0	$15.58^{+0.28}_{-0.21}$		2	0	$17.4^{+0.4}_{-1.0}$
3	0	$15.83^{+0.21}_{-0.11}$		3	0	$17.4^{+0.2}_{-0.3}$
4	0	$15.13^{+0.07}_{-0.07}$		4	0	$16.4^{+0.4}_{-0.8}$
5	0	$15.51^{+0.08}_{-0.06}$				
6	0	$14.69^{+0.11}_{-0.10}$				
7	0	$14.87^{+0.10}_{-0.08}$				
8	0	$13.89^{+0.18}_{-0.25}$				
9	0	$14.31^{+0.08}_{-0.07}$				
10	0	$13.47^{+0.25}_{-0.55}$	(3σ detection)			
1	1	$13.87^{+0.05}_{-0.06}$				
2	1	$13.45^{+0.09}_{-0.11}$				
3	1	$13.91^{+0.04}_{-0.04}$				
4	1	$13.33^{+0.07}_{-0.09}$				
5	1	$13.89^{+0.08}_{-0.08}$				

[a] The error bars are 2$-\sigma$ error bars.

discussion on the fit method and error estimates with `owens` profile fitting). These error bars include the uncertainties in the continuum fits, intrinsic line widths (b) and the instrumental line spread function. We note that the observation of different lines with different oscillator strengths for the same species allows us to constrain all these quantities. In particular the fit to saturated lines constrains the line widths and the instrumental line spread function. This last one is allowed to slowly vary with the wavelength. The results are obtained from a final self-consistent fit to all the data in which the continuum, the instrumental line spread function, and physical parameters of the absorption lines are free parameters and estimated by the determination of the best χ^2 in the parameters' space. For the intrinsic line widths, we obtain $b_{\rm HD\,100546} = 3.4^{+0.8}_{-0.5}$ km s^{-1} and $b_{\rm HD\,163296} = 2.2^{+0.5}_{-0.7}$ km s^{-1}.

3. Results

3.1. Excitation diagrams

The excitation diagrams corresponding to the derived H_2 column densities are presented in Figs. 3 and 4, for HD 100546 and HD 163296, respectively. For the $v = 1$ levels observed toward HD 100546, we see that the column densities are above a simple extrapolation of the $v = 0$ levels as plotted on the excitation plot (Fig. 3). This effect is also observed in the vibrationally excited interstellar H_2 detected toward HD 37903 (Meyer et al. 2001), where the high energy levels are not thermally populated. Note also that the level degeneracies (g) of the $v = 1$ levels are smaller than the degeneracies of the $v = 0$ levels with similar energy, hence in the same region of the plot.

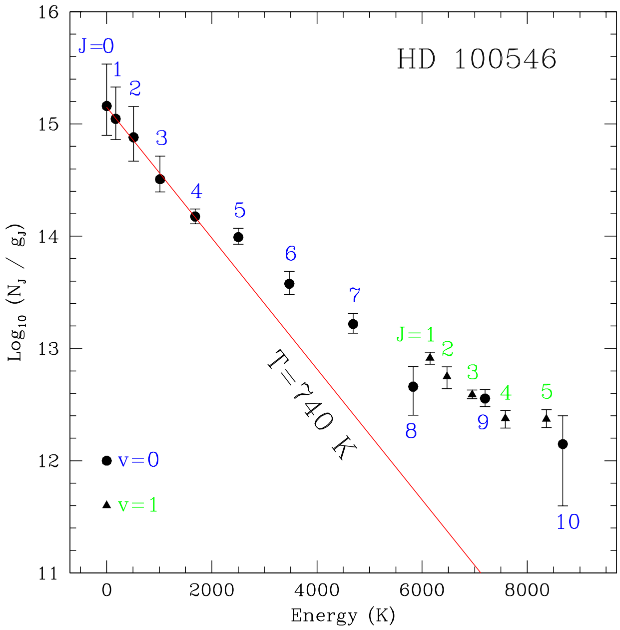

Fig. 3. Excitation diagram of the H_2 lines detected toward HD 100546. The column densities of the rotational levels with $J \leq 4$ are consistent with a single temperature of $T \sim 740$ K. This shows that the H_2 volume density must be higher than the critical value of $n_{H_2} \approx 10^4$ cm^{-3}.

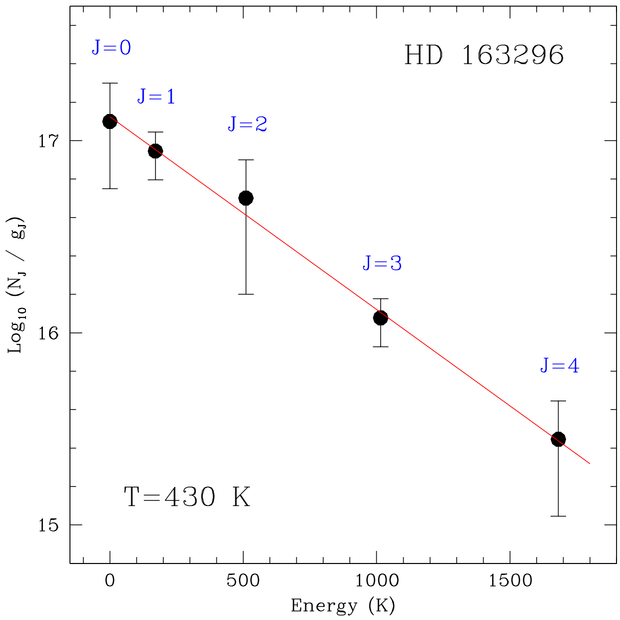

Fig. 4. Excitation diagram of the H_2 lines detected toward HD 163296. The column densities of all the detected J-levels are consistent with a single temperature of $T \sim 430$ K. This shows that the H_2 volume density must be higher than the critical value of $n_{H_2} \approx 8 \times 10^4$ cm^{-3}.

The plotted values of N/g are thus larger for these $v = 1$ levels than for the nearby $v = 0$ levels (Fig. 3).

3.2. Turbulence

The simultaneous determination of temperature and line broadening can be used to constrain the turbulence of the gas. The observed line width b is a combination of the thermal broadening, the intrinsic turbulence $v_{\rm turb}$, and the projected radial component of the gas motion seen along the star diameter. With the knowledge of the temperature, and considering that the motion can only increase the line width, we can estimate a lower limit on the turbulence velocity of the gas. We have

$$b \geq \sqrt{\frac{2kT}{\mu_{\rm H_2}} + v_{\rm turb}^2}$$

where $\mu_{\rm H_2}$ is mass of molecular hydrogen. This can be written as

$$\left(\frac{v_{\rm turb}}{\rm km\,s^{-1}}\right)^2 \leq \left(\frac{b}{\rm km\,s^{-1}}\right)^2 - 8.31 \times 10^{-3}\frac{T}{\rm K}.$$

Using the temperature given above and the 2σ upper limits on the measured line widths ($b^{2\sigma}_{\rm HD\,100546} \leq 4.2\,{\rm km\,s^{-1}}$ and $b^{2\sigma}_{\rm HD\,163296} \leq 2.7\,{\rm km\,s^{-1}}$), we find that $v_{\rm turb,HD\,100546} \leq 3.4\,{\rm km\,s^{-1}}$ and $v_{\rm turb,HD\,163296} \leq 1.9\,{\rm km\,s^{-1}}$.

3.3. Nature and origin of the H_2 gas

Many characteristics show that the detected H_2 is not interstellar but circumstellar; this favours the interpretation that the detected lines arise from protoplanetary material. First, in both cases the radial velocity of H_2 is similar to the radial velocity of the atomic lines due to the circumstellar gas. Lines from exited levels of Fe II (like Fe II* and Fe II**, Deleuil et al. 2003) cannot be due to the interstellar medium. They must be linked to dense circumstellar material. The similarity of their radial velocity with the radial velocity of H_2 is a first clue that the H_2 is linked with the circumstellar matter.

Importantly, the excitation diagrams show that the H_2 is thermalized up to about $J = 4$, with high temperatures. Hot H_2 has also been observed around the T-Tauri star TW Hya (T = 3000 K, Herczeg et al. 2002). Here we obtain

$$T \approx 740 \pm 30 \text{ K for HD 100546}$$

$$\text{and} \quad T \approx 430 \pm 20 \text{ K for HD 163296.}$$

Seen in absorption, it is very unusual to observe such a thermalization at high temperature up to $J = 4$ (to our knowledge, this is the first case). This shows that the absorbing medium has very particular physical conditions, different from what is commonly seen in the diffuse interstellar medium. Indeed this requires a line of sight which presents simultaneously high density for the thermalization and low thickness to have column densities low enough for a detection of the far-UV stellar continuum. In the diffuse and transluscent interstellar media, levels higher than $J = 1$ or $J = 2$ are populated by mechanisms other than the collisional pumping. In these low density media, the collisional pumping is less efficient than the UV-pumping and mecanical processes such as C shocs or turbulence. Here levels up to $J = 4$ show a dominant collisional pumping. This is a clue of a high density medium.

Note here that for the levels higher than $J = 4$ as detected in HD 100546, it is not possible to discriminate between a collisional pumping within a higher temperature component of the absorber and other mecanical or radiative processes.

The observed high temperatures give additional clues that the detected H_2 is circumstellar and close to the exciting stars. Using the numerical model developed by Le Bourlot et al. (1993), we find that the incident radiation on the H_2 must be $\sim 10^4$ times larger than the mean galactic UV radiation field. This shows that the observed H_2 is circumstellar and really close to its central star. These temperatures correspond to ∼1.5 AU from HD 100546 and ∼4 AU from HD 163296.

Most importantly, the thermalization allows us to estimate the H_2 volume density ($n_{\rm H_2}$). Using the critical density given by Le Bourlot et al. (1999), we find:

$$n_{\rm H_2}(\text{HD 100546}) \gtrsim 10^4 \text{ cm}^{-3}$$

$$\text{and} \quad n_{\rm H_2}(\text{HD 163296}) \gtrsim 8 \times 10^4 \text{ cm}^{-3}.$$

Assuming these volume densities, we can estimate the typical size of the absorbing layer responsible for the observed absorptions. Note that with low column densities and large volume densities, the absorbing cloud must be thin. The ratios of the H_2 column densities to the volume densities give a typical thickness of $\lesssim$0.2 AU for HD 100546 and $\lesssim$1.2 AU for HD 163296.

All the observed and estimated quantities are consistent with absorption of the star light by a thin outer layer of a disk seen at an intermediate inclination. Because the disks of HD 100546 and HD 163296 are both inclined by about 60°, it is likely that we observed a line of sight grazing the disk surface. In any case, this shows that the H_2 gas is not confined to a very flat disk. Alternatively, there is still a possibility that there might be shocked molecular gas in the vicinity of these stars, due to the combination of a bipolar jet (as observed around HD 163296) and a circumstellar envelope. However it is not possible to discriminate between these two possibilities with solely spectroscopic observation with no spatial information.

4. Conclusions

We observed the molecular hydrogen toward two Herbig stars surrounded by young protoplanetary disks. The observation of an extremely large number of rotational and vibrational levels allows for the first time the determination of the H_2 physical conditions within circumstellar gas around two HAeBe stars. With this detailed view of the population of the H_2 excited levels, we now need a full modeling in which all the cooling and heating terms must be taken into account. Such a modeling is under development. This opens a new window into the physical conditions operating in the protoplanetary disks surrounding massive stars.

The present observations of material surrounding stars with typical age between 10^6 and 10^7 years give new constrains on the relation between the radiation and the molecular protoplanetary disk in which planets are supposed to form and migrate (Terquem et al. 2000). This gives information on the interface between the dense part of the disks and the interstellar medium, and can help to better understand the late stages of the planetary formation. The radiation is indeed a key element in the evaporation of the protoplanetary disks whose lifetime seems to be limited (Zuckerman et al. 1995) although the process responsible for the clearing of the disks remains unclear.

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