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GASEOUS COMPONENT IN THE CIRCUMSTELLAR ENVIRONMENT OF HERBIG AE/BE STARS.

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Abstract. A long-standing question of modern astrophysics is how stars and planets form from their parent molecular clouds. It is generally accepted that the collapse of an interstellar molecular cloud core to form a protostar naturally produces a disk-shaped nebula in which planets might form. Evidence is accumulating that a significant fraction of Herbig Ae/Be stars (HAeBes) present us with signatures of massive circumstellar (CS) disks. In this context, HAeBes have gained a lot of interest as possible precursors of β-Pictoris and Vega-type stars, whose CS debris disks are believed to host planetary bodies. This raises the possibility that the environment around the HAeBes truly represents a very early phase of planet formation.

We present the results obtained from spectroscopic observations of HAeBes in different wavelength ranges. Our goal was to better constrain the nature and evolution of the gaseous component in the CS environment of Herbig stars, and in particular, understand the mechanisms of formation and excitation of molecular hydrogen.

1 Introduction

The pre-main sequence Herbig Ae/Be stars (HAeBes) are often considered to be the higher mass counterparts of the classical T Tauri stars. However, while the characteristics of the classical T Tauri stars are generally thought to be linked to the presence of massive accretion disks, the nature of the close environment of the HAeBes remains a subject of considerable controversy.

In order to better understand the nature and evolution of the gaseous component in the CS environment of HAeBes, we analyzed spectroscopic observations of HAeBes in different wavelength ranges. In particular we present observations of molecular hydrogen in the FUV domain, and the preliminary results of observations of the pure rotational lines of H_2 in the IR spectral range, and observations the CH and CH^+ molecules at optical wavelengths that are directly linked to the formation and excitation of H_2.

2 FUSE observations

2.1 The sample stars

We analysed a sample of 18 HAeBes of spectral types from F4 to B2, and the main-sequence A5 star β-Pictoris. All the stars are plotted in the HR diagram presented in Fig. 1 which gives their evolutionary status. All the stars have been observed with the *FUSE* (*Far Ultraviolet Spectroscopic Explorer*) satellite. *FUSE* offers access to spectral lines that can probe the circumstellar environment of HAeBes as H_2 lines, which one would expect to be present if HAeBes have greatly extended CS disks or envelopes. The *FUSE* observations cover the wavelength spectral range from 905 Å to 1187 Å at a spectral resolution of $R \sim 15\,000$. We performed the molecular and/or atomic absorption lines analysis using the Owens profile fitting procedure written by Dr. M. Lemoine (Hébrard et al. 2002). The data reduction and analysis method we used are presented in the papers by Bouret et al. (2003), Martin et al. (2004) and Martin-Zaïdi et al. (2005). We refer the reader to these papers for more details.

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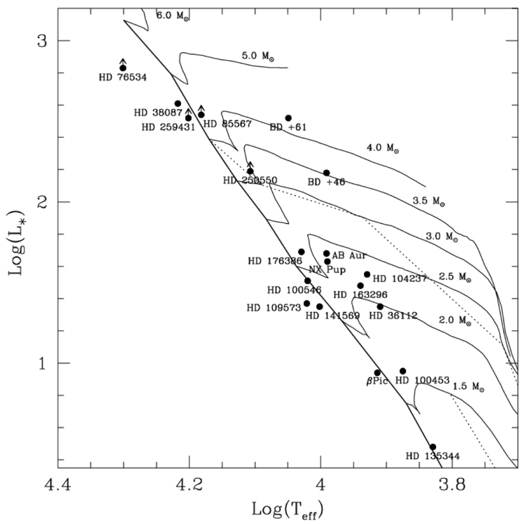

Fig. 1. The whole sample is plotted on this HR diagram (kindly provided for us by L. Testi). The evolutionary tracks between the pre-main sequence phase and the ZAMS is clearly shown for the Ae/B9 stars. For the more massive Be stars, the pre-main sequence stage is less clear due to the faster evolution of these stars.

When H_2 is detected in the *FUSE* spectra, we have plotted the excitation diagrams toward each star from the derived column densities. These diagrams show the ratio of the column density to the statistical weight of each energy level against the energy of the level. These diagrams characterize the excitation conditions: temperature of the gas and its physical conditions. When H_2 is observed, the excitation conditions are clearly different between Herbig Ae/B9 stars and Herbig Be stars. We then distinguished these two sub-groups of stars in our analysis: the Ae/B9 stars (including the F4 one), and the Be stars.

2.2 Ae/B9 stars

The first group (Ae/B9 stars) is very inhomogeneous. Except for β-Pictoris and HD109573, for all the other stars of this group, the *FUSE* lines of sight do not pass through the disks, due to their high inclination angles. When H_2 is observed, we highlighted different physical conditions apparently related to different location for the gas (Fig. 2).

HD141569 and AB Aurigæ: in this two cases, the excitation conditions are typical of what is generally seen in the diffuse interstellar medium. In the case of HD141569, the radial velocity of the different species observed in the *FUSE* spectrum is identical to that of the IS dark cloud L134N (Sahu et al. 1998). For this star, the H_2 we observe is located in the low extinction envelope of this cloud. We do not observe CS gas, which implies that all the gas has had time to collapse into the disk. As far as AB Aurigæ is concerned, the excitation of the H_2 is typical of what is generally observed in the diffuse interstellar medium. This star is known to possess a very extended CS disk nearly seen face-on and thus not observed in absorption. But the gas seen in absorption with *FUSE* has a radial velocity close to that of the star. Two interpretations are thus possible: (1) the gas is IS in origin, (2) the observed gas is located in the remnant of the molecular cloud in which the star was formed.

HD 100546, HD 163296 and HD 104237: The excitation diagrams show that the H_2 is thermalized up to $J = 4$ with high excitation temperatures (from $\sim$300 to $\sim$750 K). For HD 100546, the column densities of the higher J-levels are consistent with a temperature about 1500 K. This gives evidences for the presence of a collisionally excited medium very close to the stars (Lecavelier des Etangs et al. 2003). However, the inclination angles to the lines of sight estimated for the disks are greater than 50 degrees (Augereau et al. 2001; Grady et al. 2000, 2004), and we do not observe the disks in absorption. We thus suggest two possible origins for the observed excited circumstellar H_2: it could arise from the outer region of the chromosphere, as well as from a photoevaporation mechanism in the surface layer of the disk.

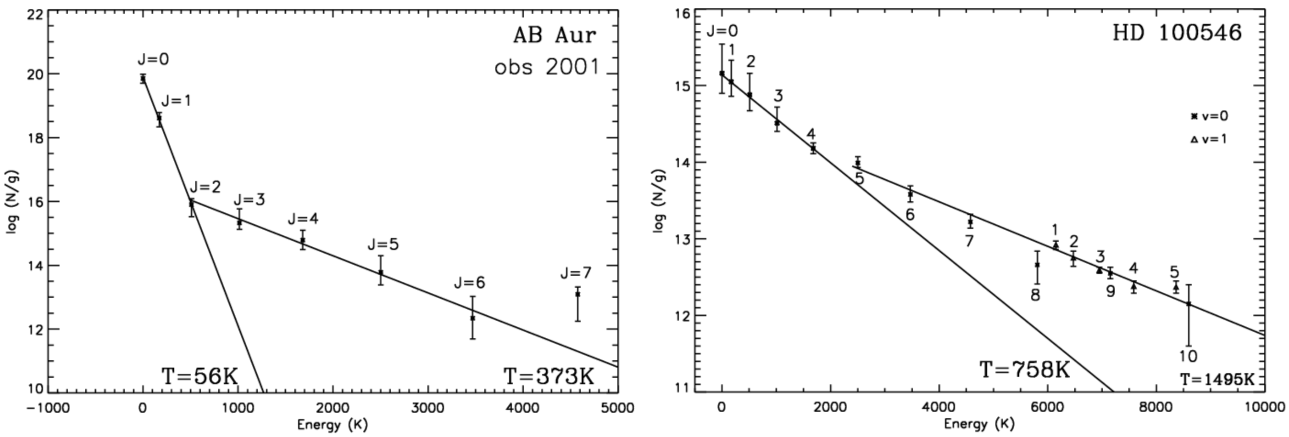

Fig. 2. Excitation diagram of H_2 towards AB Aur and HD100546 (see text).

2.3 Be stars

The excitation conditions of circumstellar H_2 around the stars of our second group (Be stars), are clearly different of that of the first group. This reinforces the differences between the two subclasses of stars (Ae and Be). For this second group, the excitation conditions of H_2 are similar from one star to the other. The H_2 is thermalized up to $J = 3$ with temperatures around 100 K, and the column densities of the higher J-levels are consistent with temperatures from ~500 to 1600 K (example for HD259431 on Fig. 3). This shows that we probe similar environments around all the stars. Since the *vsini* are in a wide range of values, these stars are likely not seen under the same angle (from pole-on). Our analysis favors an interpretation in terms of spherically symmetric media which are not affected by inclination effects, contrary to the case of CS disks. In addition, the excitation diagrams are well reproduced by the "Meudon PDRs code" (Le Petit et al. 2006, Fig. 3), at least for the cold component which includes more than 90% of the gas. This cold component seems to correspond to the outer layer of the parent cloud of the stars. However, the high column densities of the rotational levels of the first vibrational level, which probe the inner part of the envelope, are not well reproduced and can not be explained by the PDRs model. This phenomenon is presently under study, and could be explained by time-dependent mechanisms such as shocks.

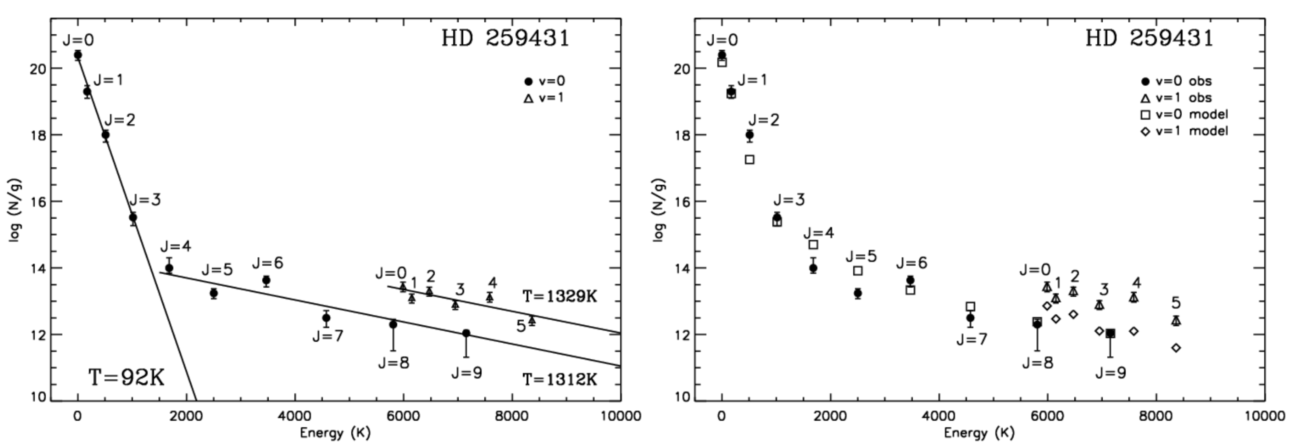

Fig. 3. *Left*: Excitation diagram of H_2 towards HD259431. *Right*: PDRs model overplotted on the excitation diagram towards HD259431.

3 Preliminary results: UVES and VISIR observations

3.1 UVES observations

The same sample of stars have been observed with VLT/UVES (PI: C Martin-Zaïdi, some observations are still pending). Optical spectroscopic observations of all these stars at high resolution are necessary to observe other absorption features, especially lines of the CH and CH^+ molecules if present, which are linked to the formation and excitation of H_2 (e.g. Federman 1982). Indeed, the CH formation is predicted to be controlled by gas-phase reactions with H_2, thus CH is a good tracer of H_2 and their abundances are generally strongly correlated. With the presence of a shock, the formation of the CH^+ molecule through the chemical reaction $C^+ + H_2$ needs a temperature about 4500K to be produced. Thus, the CH^+ molecule is a probe of excited media close to the star and will allow to better constrain the excitation of H_2. The observation of CH^+, if present, provides the most direct and most definitive evidence for the presence of circumstellar gas close to the star.

The first observations obtained with UVES show that the column densities of CH are correlated with those of H_2 as already known for the diffuse interstellar medium. Moreover, when highly excited H_2 is observed in the *FUSE* spectra, we always observe CH^+ in UVES spectra. This implies that excited H_2 is probably located warm and/or hot regions close to the stars (Martin-Zaïdi et al. 2006b).

3.2 VISIR observations

Although the spectroscopic absorption lines studies allow measurements of the column densities of the CS gas and its excitation/formation conditions, they do not constrain its spatial distribution around the star. High resolution observations at infrared wavelengths of emission lines corresponding to the pure rotational and ro-vibrational transitions of H_2 would help to constrain the excitation and the spatial distribution of the observed gas. Such infrared observations would also provide informations about the circumstellar dust as PAHs. New generation instruments like VLT/VISIR could provide these kind of observations.

In June 2006, we observed for the first time the 17μm pure rotational line of H_2 arising from the disk of the Herbig Ae star HD97048. These data are presently under study.

4 Conclusion

All the *FUSE* observations are detailed in the papers by Bouret et al. (2003), Martin et al. (2004), Martin-Zaïdi et al. (2005), and Martin-Zaïdi et al. (2006a). We found evidences for several mechanisms of H_2 excitation depending on the structure of the CS environment of the stars. These results confirm the structural differences between Herbig Ae and Herbig Be stars emphasized by Natta et al. (2000).

In addition, combined with the *FUSE* data, the UVES and VISIR observations will give the unique opportunity to obtain a global picture of both structure and evolution of the CS environment of HAeBes.

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