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PROBING THE CHEMISTRY AND THE EVOLUTION OF THE CIRCUMSTELLAR ENVIRONMENT OF HERBIG Ae/Be STARS

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Abstract. We present *UVES* (*Ultraviolet and Visual Echelle Spectrograph*) observations of a sample of Herbig Ae/Be stars for which we had already measured the amount of circumstellar molecular hydrogen (H_2) using the *FUSE* (*Far Ultraviolet Spectroscopic Explorer*) satellite. The preliminary analysis of these spectra confirms the well known problem of the formation and excitation of the molecules in the circumstellar environments of our sources, especially those of CH and CH^+. In the future, combined to our H_2 data, these new observations should allow us to constrain the chemical mechanisms of formation/destruction and excitation of these different molecules.

1 Introduction

Molecular hydrogen, from which giant planets are believed primarily to form, is the most abundant molecule in the circumstellar (CS) environment of young stars. The detection of H_2 provides the most direct information about the gaseous content in the CS environment of HAeBes and allows limits to be set on the timescale for the dissipation of the circumstellar matter and the possible planet building. The analysis of far ultraviolet (FUV) spectra of a sample of Herbig Ae/Be stars (HAeBes) demonstrated that the excitation of H_2 is clearly different around most of the HAeBes compared to the interstellar (IS) medium (Martin-Zaïdi et al. 2008, hereafter CMZ08). Moreover, the characteristics of H_2 around Herbig Ae and Be stars give evidence for different excitation mechanisms. In addition, no clear correlation has been found between the ages of the stars and the amount of circumstellar H_2. From this analysis, CMZ08 suggest structural differences between Herbig Ae and Be star environments. This analysis also points to the need for complementary observations to better understand the physical conditions of formation and excitation of H_2 and the origin of the gas.

We thus observed spectral lines of the CH and CH^+ molecules in the optical range at high spectral resolution using the VLT/*UVES* spectrograph of the same sample of HAeBes as previously observed by *FUSE*. These molecules are linked to the formation and excitation of H_2 (Federman 1982, Mattila 1986, Somerville & Smith 1989). The formation of CH is predicted to be controlled by gas-phase reactions with H_2. CH is thus a good tracer of H_2 and their abundances are generally strongly correlated. The formation of the CH^+ molecule through the chemical reaction $C^+ + H_2$ needs a temperature of about 4500 K to occur. Thus, the CH^+ molecule is a probe of hot and excited media, which could be interpreted for our targets as material close to the star, and this would allow us to better constrain the excitation of H_2. The observation of CH and CH^+, if present, could provide direct evidence of warm/hot CS gas close to the star. Combined with the H_2 data, this should allow us to explain the chemical mechanisms of formation/destruction and excitation of the different molecules in the CS environment of HAeBes and to better evaluate the velocity dispersion along the line of sight.

In this paper, we first recall the results obtained about H_2 in the *FUSE* spectra of a sample of 18 Herbig stars (for a detailed analysis, see CMZ08), and present the preliminary results on the CH and CH^+ molecules in the *UVES* spectra.

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2 Molecular hydrogen in the circumstellar environments of Herbig Ae/Be stars probed by FUSE.

FUSE is a spectrograph which covers the spectral range from 905Å to 1187Å with a resolution of R∼15,000 (30"×30" LWRS aperture), which offers acces to the Werner and Lyman electronic bands of H_2. Especially, one would expect to observe H_2 lines if HAeBe stars have greatly extended CS disks and if the lines of sight to the stars pass through the disks. In that case, the H_2 lines may be observable in absorption between 950 Å and 1150 Å, projected against the UV continua of the stars. Alla

CMZ08 have studied the characteristics and excitation conditions of molecular hydrogen in the CS environment of a sample of 18 HAeBes observed with *FUSE.* The *FUSE* data do not enable to constrain the spatial distribution of the detected gas, but allow to set new constraints on the nature and evolution of the CS environment of HAeBes. From the excitation diagram of the H_2 molecule towards each star, those authors showed marked differences between the Herbig Ae/B9 stars on the one hand, and the Herbig Be stars on the other hand. They distinguished two groups of stars: the stars known to possess CS disks (Ae/B9 stars) and the stars with no evidence of disks (Be stars). They interpreted the different excitation characteristics of H_2 as direct probes of the origin of the observed gas: interstellar, circumstellar disk, or circumstellar envelopes.

For most of the Herbig Ae/B9 stars, the inclination angles of the CS disks from the lines of sight are quite high and not favorable to probe the disks using absorption spectroscopy. When molecular hydrogen gas is observed in the *FUSE* spectra of the Herbig Ae/B9 stars, their analysis shows several kinds of excitation, implying different origins and different physical processes.

In one case, namely HD 141569, the origin of the detected gas is clearly interstellar. For AB Aur there is also some evidence for an IS gas origin, but there is a lack of spectral resolution that could allow to probe the velocity distribution along the line of sight and definitively disentangle between a CS or IS origin for the gas. In spite of its relatively high inclination away from edge-on, it is not geometrically impossible for the gas to originate in the upper layers of the outer disk regions at about 800 AU, but the excitation conditions of H_2 towards AB Aur are fairly typical of what is generally observed in the diffuse interstellar medium. However, CMZ08 showed that the excitation diagram could not be reproduced well by a single gaseous component along the line of sight by using the Meudon PDR Code (Le Petit et al. 2006). The large line width value favors the presence of two components along the line of sight, which are not resolved in the spectrum. In that case, one of these components could correspond to the remnant of the molecular cloud in which the star formed, as suggested by (Roberge et al. 2001). The high J-levels absorption could be interpreted as due to a hotter component, probably close to the star, with negligible contribution to the low J-levels.

For HD 100546, HD 163296, and HD 104237, CMZ08 observed excited and probably warm/hot, circumstellar H_2 that has excitation conditions clearly different from those observed in the diffuse interstellar medium. Such excitation conditions for H_2 give evidence of collisionally excited media close to the stars. The measured radial velocities favor a CS origin for the H_2. However, assuming that the gas and dust are coupled, the lines of sight towards these three stars do not pass through their disks, and thus the observed H_2 is not located in the disks. This raises questions about the origin of the detected gas. One interesting possibility could be that the H_2 gas is a FUV-driven photoevaporative wind from the outer parts of the disk, but clues are still missing for a firm conclusion. The Meudon PDR Code did not allow to reproduce the excitation of the observed H_2 gas. This implies that peculiar excitation processes such as shocks or X-Rays, not taken into account in the Meudon PDR Code, may play a role in the environment of these stars.

The excitation conditions of circumstellar H_2 around the stars of the second group (Be stars) are clearly different from those of the first group. CMZ08 found similar excitation conditions for the H_2 from one star to the next. They present similarities to the conditions found in the IS medium. The analysis of the *FUSE* spectra favors an interpretation in terms of spherically symmetric media, not affected by inclination effects. The excitation diagrams are reproduced nicely by PDR models, at least for the cold component that includes more than 90% of the gas. On the other hand, these models systematically underpredicts the high J-levels column densities. The observed environments are very likely complex environments, such as large CS envelopes, remnants of the original clouds in which the stars formed. However, other excitation processes, in addition to those taken into account in the Meudon PDR Code, are probably necessary to fully explain the observed excitation diagrams.

This FUV analysis reinforces the differences between the two subclasses of stars (Ae and Be) already highlighted by different authors (e.g. Natta et al. 2000). It also points to the need for complementary observations to better understand the physical conditions of formation and excitation of H_2 and the origin of the gas.

Table 1. Measured radial velocities of the CH and H_2 molecules to be compared to that of the star (all given in the heliocentric rest frame). Measured column densities of CH, CH^+ and H_2, and ratio CH/H_2.

Star	Sp. Type	$v_{\rm rad}$ star $\rm km\,s^{-1}$	$v_{\rm rad}$(CH) $\rm km\,s^{-1}$	$v_{\rm rad}(H_2)$ $\rm km\,s^{-1}$	log N(CH) $\rm cm^{-2}$	log N(CH^+) $\rm cm^{-2}$	log N(H_2) $\rm cm^{-2}$	log(N(CH)/N(H_2))
HD135344	F4V	-3	–	–	$\leq$12.5	$\leq$12.7	$\leq$15	–
HD36112	A5	+17.6	+19.0±0.6	–	12.53±1.2	$\leq$12.9	$\leq$15.78	–
NX Pup	A0	?	+14.2±1.0	–	12.68±3.27	12.97±0.65	–	–
AB Aur	A0V	+21	+15.0±0.1	+23±3	12.28±1.40	13.08±0.11	$20.03^{+0.15}_{-0.19}$	$-7.75^{+1.25}_{-1.21}$
HD163296	A1V	+4	–	+4±2	$\leq$12.1	$\leq$12.3	$18.16^{+0.27}_{-0.40}$	–
HD141569	B9V	-6.4	-13.0±0.02	-14.0	12.14±1.27	12.56±0.56	$20.32^{+0.20}_{-0.22}$	$-8.18^{+1.07}_{-1.05}$
HD100546	B9V	+17	–	+17±2	$\leq$12.0	$\leq$12.3	$16.46^{+0.24}_{-0.14}$	–
HD176386	B9/B8	+7.3	-5.0±0.2	0	12.61±0.65	12.84±0.14	$20.80^{+0.18}_{-0.26}$	$-8.19^{+0.47}_{-0.39}$
HD250550	B7	+31	–	$+30^{+1.7}_{-2.0}$	$\leq$12.0	$\leq$12.6	$19.26^{+0.17}_{-0.40}$	–
HD85567	B5V	(-5 / 0)	–	$(-1.5\ /\ 4.5)^{+0.3}_{-0.2}$	$\leq$12.3	$\leq$12.6	$19.33^{+0.20}_{-0.17}$	–
HD259431	B5	+43	–	$+56^{+2.2}_{-1.8}$	$\leq$12.0	$\leq$12.4	$20.64^{+0.11}_{-0.19}$	–
HD38087	B5V	+33	+26.0±0.2	$+35.4^{+1.2}_{-2.1}$	12.93±0.47	13.57±0.05	$20.43^{+0.15}_{-0.08}$	$-7.50^{+0.32}_{-0.49}$
HD76534	B2	+17	+20.4±0.2	$+17^{+0.3}_{-1.3}$	12.89±0.46	13.46±0.07	$20.64^{+0.16}_{-0.16}$	$-7.75^{+0.30}_{-0.30}$

3 UVES observations

Nearly the same sample of stars have been observed with VLT/*UVES* to detect lines of the CH and CH^+ molecules, which are linked to the formation and excitation of H_2. We observed 13 HAeBes between ~3700 Å and 5000 Å in the blue arm of *UVES* in order to observe simultaneously CH and CH^+ lines as well as atomic lines such as Ca II. We used no image slicer, low gain with a 1×1 binning of the CCDs and a slit width of 0.4 arcsec providing the maximum resolution of ~80,000. This maximum spectral resolution of *UVES* was required to separate the different gaseous components along the line of sight. For each target, the signal-to-noise ratio is higher than 100 in the whole spectrum.

For 6 out of our 13 targets, both lines of CH and CH^+ are detected. For one target, only CH is detected while CH^+ is not. The 6 other spectra do not present any features of CH and/or CH^+. When observed, we derived the column densities of CH and CH^+ using the Owens line fitting procedure (Lemoine et al. 2002). For most stars of the sample, the mean projected velocity of CH is very close to that of the star and to that of H_2, whithin the resolution of the spectra. This is a clue that the detected CH and H_2 are produced in the same region of the environments of our targets. When H_2 and CH are both observed, their column densities are correlated (Fig. 1) in proportions consistent with those observed in the diffuse interstellar medium (e.g. Welty et al. 2006, Sheffer et al. 2008). It is important to note here that for these stars, the H_2 data implied an IS origin for the gas or a remnant of the parent molecular cloud (close to IS excitation conditions). The present results are thus fully consistent with the H_2 data. On the other hand, Lambert & Danks (1986) presented correlations between N(CH^+) and N(H_2^*), i.e., column densities of excited states of H_2 involving the $J \geq 5$ levels. We do not find obvious correlation between N(CH^+) and N(H_2^*) (see Fig. 1). However, excluding HD 141569 for which the observed gas is clearly IS in origin, a weak correlation $N(CH^+) \propto N(H_2^*)^{-3.5}$ may be seen. Our results are summarized in Table 1. In addition, for the Be stars for which CH and CH^+ are observed (3 out the 13 in our sample), we stress that the best-fit model for H_2 obtained by CMZ08 with the Meudon PDR Code, do not reproduce the present CH and CH^+ data. The observed column densities of CH are at least a factor 3 higher than those given by the model, while the observed column densities of CH^+ are more than 100 times higher that those given by the model. This confirms the well known problem of CH and CH^+ formation (see Sect. 4). It is known that CH^+ is likely formed in shocked regions, and the Meudon PDR Code is stationary, thus it cannot explain the observed CH^+. One way to solve this problem is to use non-stationary codes such as shocks or turbulent dissipation region (TDR) models. At the present time, this work is in progress.

4 Discussion

We presented here our preliminary results about the observation of the CH and CH^+ molecules with *UVES* in the circumstellar environments of Herbig Ae/Be stars, in relation with previous *FUSE* observations of H_2. We

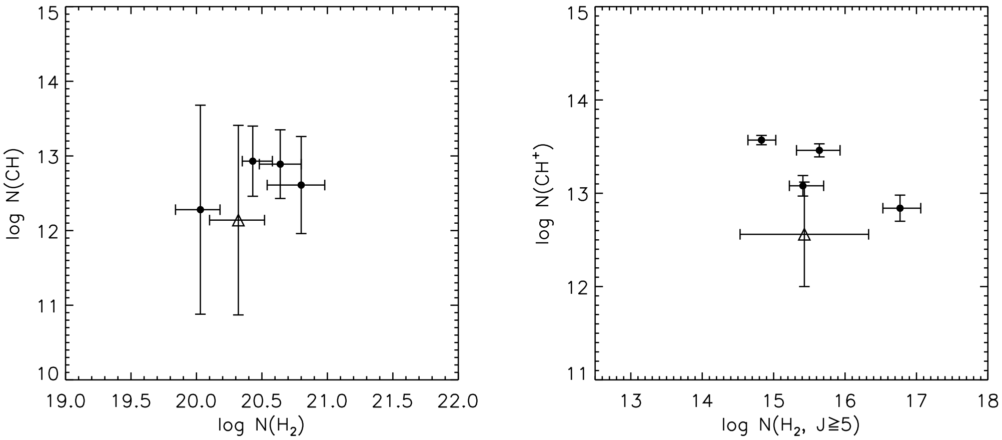

Fig. 1. *Left:* Total column density of H_2 versus column density of CH. *Right:* Column densities of excited levels of H_2 ($J \geq 5$) versus column density of CH^+ (see text). The triangles distinguish HD 141569 since the observed gas is clearly IS in origin (see CMZ08).

showed that there is a clear correlation between the column densties of CH and H_2 as observed in the interstellar medium and that these two molecules are likely produced in the same region of the CS environment of our target stars. No correlation has been found between CH^+ and excited levels of H_2. Althought the Meudon PDR Code reproduces well the H_2 data, it fails to reproduce the CH and CH^+ observations. This raises the well known problem of the formation of these molecules.

It is generally agreed that non-equilibrium chemistry is the key to solve the CH^+ abundance problem in diffuse clouds. However, the exact physical mechanism producing CH^+ is still unclear. Formation of CH^+ have been quantitatively investigated in the specific cases where dissipation occurs within MHD shocks (e.g. Flower & Pineau des Forets 1998) or coherent vortices in MHD turbulence (Godard et al. 2009). In such models the temperature of the warm gas and the ratio between CH^+ and warm H_2 column densities depends strongly on local physical conditions (e.g. shock velocity, gas density, magnetic field value). However, the lack of velocity differences between CH and CH^+ (e.g. Gredel et al. 1993) argues against shocks. Recently, Lesaffre et al. (2007) modeled the effects of turbulent diffusion on diffuse cloud chemistry, determining that this mechanism can increase the CH^+ abundance by up to an order of magnitude, which is still lower than observed.

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