CO emission and variable CH and CH\textsuperscript{+} absorption towards HD 34078: evidence for a nascent bow shock?*

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ABSTRACT

Context. The runaway star HD 34078, initially selected to investigate small scale structure in a foreground diffuse cloud, has been shown to be surrounded by highly excited H\textsubscript{2}, the origin of which is unclear.

Aims. We first search for an association between the foreground cloud and HD 34078. Second, we extend previous investigations of temporal absorption line variations (CH, CH\textsuperscript{+}, H\textsubscript{2}) in order to better characterize them and understand their relation to small-scale structure in the molecular gas.

Methods. We have mapped the \textsuperscript{12}CO(2–1) emission at 12'' resolution around HD 34078’s position, using the 30 m IRAM antenna. The follow-up of CH and CH\textsuperscript{+} absorption lines has been extended over 5 more years: 26 visible spectra have been acquired since 2003 at high or intermediate resolution. In parallel, CH absorption towards the reddened star \zeta Per has been monitored to check the instrumental stability and homogeneity of our measurements. Three more FUSE spectra have been obtained to search for N(H\textsubscript{2}) variations.

Results. CO observations show a pronounced maximum near HD 34078’s position, clearly indicating that the star and diffuse cloud are associated. The optical spectra confirm the reality of strong, rapid and correlated CH and CH\textsuperscript{+} fluctuations (up to 26\% for N(CH\textsuperscript{+}) between 2007 and 2008). On the other hand, N(H\textsubscript{2}, J = 0) has varied by less than 5\% over 4 years, indicating the absence of marked density structure at scales below 100 AU. We also discard N(CH) variations towards \zeta Per at scales less than 20 AU.

Conclusions. Observational constraints from this work and from 24 \mu m dust emission appear to be consistent with H\textsubscript{2} excitation but inconsistent with steady-state bow shock models and rather suggest that the shell of compressed gas surrounding HD 34078 or lying at the boundary of a small foreground clump is seen at an early stage of the interaction. The CH and CH\textsuperscript{+} time variations as well as their high abundances are likely due to chemical structure in the shocked gas layer located at the stellar wind/ambient cloud interface. Finally, the lack of variation in both N(H\textsubscript{2}, J = 0) towards HD 34078 and N(CH) towards \zeta Per suggests that quiescent molecular gas is not subject to pronounced small-scale structure.

Key words. ISM: molecules -- stars: individual: HD 34078 -- ISM: structure -- ISM: individual objects: HD 34078

1. Introduction

During the past decade strong evidence has accumulated indicating that the spatial distribution of species like Na I and Ca II within neutral interstellar (IS) gas displays significant structure at AU scales (Crawford 2003; Lauroesch 2007; Welty 2007; Welty et al. 2008). H\textsubscript{2} itself, within the cold neutral medium at least, shows such structure (Frail et al. 1994; Heiles 1997; Deshpande 2007; Weisberg & Stanimirovic 2007). In diffuse molecular gas, similar conclusions have been reached for tracers like H\textsubscript{2}CO, HCO\textsuperscript{+}, and OH (Moore & Marscher 1995; Liszt & Lucas 2000). Whether or not these spatial variations correspond to true density structure [i.e. to local fluctuations of n(H\textsubscript{2})] is obviously of key importance for the modelling of physical and chemical processes within molecular gas.

To investigate this question, a time variation study of H\textsubscript{2}, CH, and CH\textsuperscript{+} interstellar absorption lines towards the O9.5V runaway star AE Aur, HD 34078 has been undertaken by Rollinde et al. (2003, hereafter R03) and Boissé et al. (2005, hereafter B05). This bright star is significantly reddened [E(B – V) = 0.53] and its optical spectrum displays strong absorption lines

* Based on observations made mainly at IRAM, Observatoire de Haute Provence (France), McDonald Observatory (USA) and with FUSE.
Table 1. Observation parameters. The projection center of all the data is: $\alpha_{2000} = 05^h16^m18.15^s$, $\delta_{2000} = 34^\circ18'44.3''$.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Transition</th>
<th>Frequency</th>
<th>Instrument</th>
<th># Pix.</th>
<th>$F_{\text{eff}}$</th>
<th>$B_{\text{eff}}$</th>
<th>Resol.</th>
<th>Resol.</th>
<th>Int. Time</th>
<th>$T_{\text{sys}}$</th>
<th>Noise</th>
<th>Obs. date</th>
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<td>$J = 1-0$</td>
<td>115.271202</td>
<td>30 m/AB100</td>
<td>2</td>
<td>0.95</td>
<td>0.74</td>
<td>22</td>
<td>0.20</td>
<td>0.7</td>
<td>240</td>
<td>20</td>
<td>13 Feb. 2004</td>
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<td>230.538000</td>
<td>30 m/HERA</td>
<td>9</td>
<td>0.91</td>
<td>0.52</td>
<td>11</td>
<td>0.40</td>
<td>0.7</td>
<td>300</td>
<td>10</td>
<td>13–11 Feb. 2004</td>
</tr>
</tbody>
</table>

from e.g. CH, CH$^+$, CN (Federman et al. 1994), typical of diffuse molecular clouds. HD 34078 has a high proper motion of $\mu = 43$ mas yr$^{-1}$, corresponding to a transverse velocity of $103 \text{ km s}^{-1}$ or $22 \text{ AU yr}^{-1}$ for a distance $D = 530$ pc (this value will be used in the following for consistency with B05; it is compatible with the trigonometric parallax estimate of 446$^{+220}_{-111}$ pc). The line of sight is thus drifting rapidly through the foreground gas; successive column density measurements then provide a “cut” through the cloud revealing its spatial density structure over scales which typically range from 1 to 100 AU for time separations ranging from a few weeks to a few years.

The first five FUSE spectra discussed in B05 showed that highly excited H$_2$ gas is present along the line of sight, together with more standard quiescent gas at $T \approx 80 \text{ K}$. The presence of significant amounts of H$_2$ with an excitation energy higher that 2500 K (corresponding to the $v = 0, J = 5$ state) is very rare (another remarkable case is that of HD 37903 studied by Meyer et al. 2001). This is certainly related to the fact that by chance, along its long path from the Orion nebula where it was ejected, HD 34078 might be more closely related to the cold cloud than the CH$/$CH$^+$ velocity of both components appears as a coincidence. Further, in this scenario, the close similarity of the radial velocities of HD 34078 and other species typical of translucent material (CH, CO, CN).

However, in this scenario, the close similarity of the radial velocity of both components appears as a coincidence. Further, the CH//H$_2$ ratio towards HD 34078 displays an anomalously high value, about three to four times larger than the one commonly found for other lines of sight. This led us to suspect that HD 34078 might be more closely related to the cold cloud than assumed in the above model, even if at first sight, this appears difficult to reconcile with the low H$_2$ temperature ($T = 77 \text{ K}$) derived from the population of the $J = 0$ and $J = 1$ levels and the presence of a variety of molecules that HD 34078 might easily photodissociate.

The potential relation between HD 34078 and the cloud probed has important implications regarding the investigation of small-scale structure. Indeed, in the case of a real association, any mechanical or radiative interaction might significantly affect the initial structure. Further, the gas flow in the bow shock may be subject to instabilities which could lead to time variations of a different nature, not necessarily associated with spatial structure.

Thus, one objective of the present study is to clarify the relation between HD 34078 and the cold cloud. To this end, we have undertaken observations of CO emission in the field surrounding the O star. The second goal of our work is to extend the search for absorption line variations in ground-based spectra (CH and CH$^+$ mainly) and in FUSE spectra (H$_2$) by adding recent data obtained after the initial studies by R03 and B05 were completed.

This paper is organised as follows. We first present high spatial resolution $^{12}\text{CO}(2–1)$ and $^{12}\text{CO}(1–0)$ observations performed at the 30 m IRAM telescope and their implications concerning the location and properties of the quiescent component (Sect. 2). In Sect. 3, we analyse a new series of optical spectra which allow us to study in detail the variations of CH and CH$^+$ column densities [hereafter N(CH) and N(CH$^+$)] and velocity profiles. Time variations of H$_2$ column densities [hereafter N(H$_2$)] are then discussed in the light of the observed CH and CH$^+$ variations (Sect. 4). In Sect. 5, we summarize the main observational results for $\zeta$ Per and HD 34078, in particular for readers not interested in details concerning observations. Then, we discuss the implications of our observations in terms of processes related to the interaction between HD 34078 and the surrounding gas and small-scale structure in foreground unpeperaged gas (Sect. 6). Finally, we summarize our conclusions and present some prospects concerning possible observational signatures of the future evolution of HD 34078’s close environment.

2. CO emission towards HD 34078

$^{12}\text{CO}$ emission can be used to investigate a possible connection between HD 34078 and the molecules seen in absorption. Indeed, in the two-component model presented in B05, CO molecules (as well as CH, CH$^+$ etc.) lie far in front of HD 34078 and if this picture were correct, the morphology of the CO emission should not correlate in any manner with the star position. Otherwise, any relation between the CO emission map and HD 34078’s position would be a clear indication that the star is closely related to the foreground cloud.

2.1. IRAM-30 m observations

Emission of the rotational transitions of $^{12}\text{CO}$ was observed with the IRAM-30 m telescope during three consecutive nights on February 11, 12 and 13, 2004. Using the HERA 3 x 3 multi-beam array (Schuster et al. 2004), we mapped the $^{12}\text{CO}(2–1)$ emission in a 66 x 66 arcsec$^2$ region centred on HD 34078’s position. The single side-band receiver temperature was in the range 120 to 180 K. Observations were performed under good weather conditions with 2 mm water vapor and a zenith sky opacity at 230 GHz $\tau_{230} = 0.15$, resulting in system temperatures in the range 250–350 K. Chopper-wheel calibration was done every 10–15 min. Pointing was checked frequently, ensuring an accuracy of 2". We used the VESPA autocorrelator as a spectrometer covering 160 km s$^{-1}$ with a resolution power of $7 \times 10^5$ or $\Delta v = 0.4 \text{ km s}^{-1}$ (\$v = 0.3 \text{ MHz}$; see Table 1 for CO
Fig. 1. $^{12}\text{CO}(2–1)$ spectra overlaid on the MIPS 24 $\mu$m emission of France et al. (2007) (color scale; note that the IR map is saturated near the maximum at the (3, 12) position). The CO LSR velocity scale is in the range $0–13$ km s$^{-1}$ and the antenna temperature scale ranges from $–0.1$ to 0.6 K. The observed positions correspond to the center of each panel; the dotted line indicates a constant velocity $V_{\text{LSR}} = 5.9$ km s$^{-1}$, associated with the CH and CH$^+$ lines (see below). HD 34078 is located at offsets (0, 0); the direction of its proper motion is indicated by the arrow.

observation parameter values). Observations were performed in raster mode to allow deep integration of about 40 min to ensure a rms of 15 mK (antenna temperature scale) in each velocity channel. The map consists of a regular grid of $12 \times 12$ positions observed with a sampling of 6$''$, and the data are thus only slightly undersampled ($HPBW = 11.7''$ at 230 GHz). A 5-point cross centred at offsets ($-3, 3$) with 12$''$ steps was observed simultaneously with the single-pixel receivers facility, in the $^{12}\text{CO}(1–0)$ and (2–1) transitions ($HPBW = 22''$ at 115 GHz) to derive the excitation conditions of the gas.

### 2.2. Results and analysis of the CO data

The resulting map of the $^{12}\text{CO}(2–1)$ emission is shown in Fig. 1, in which the nearly fully-sampled spectra were projected on a 6$'' \times 6''$ grid centred on the (0, 0) offset. Thermal dust emission has also been observed recently by France et al. (2007) and their MIPS 24 $\mu$m is overlaid by the CO spectra.

We also present a map of the integrated $^{12}\text{CO}(2–1)$ intensity superimposed onto the MIPS 24 $\mu$m emission (Fig. 2) as well as channel maps (Fig. 3). The $^{12}\text{CO}(2–1)$ integrated intensity is clearly stronger around the star position (0, 0). While the NE and SW region are nearly devoid of emission, the region of enhanced $^{12}\text{CO}(2–1)$ emission is resolved and displays an elongated morphology (in the NE-SW direction) and extent which are both relatively similar to those of the brightest part of the IR arc. The $^{12}\text{CO}(2–1)$ peak is apparently offset southward by about 9$''$ with respect to the 24 $\mu$m maximum but, given (i) the accuracy of absolute positions in the IR map ($\approx 1''$; K. France, private communication) and $^{12}\text{CO}(2–1)$ emission ($\approx 2''$) and (ii) the presence of saturation in the 24 $\mu$m map, it is not clear whether this offset is really significant.

Fig. 2. The integrated $^{12}\text{CO}(2–1)$ emission (contours) overlaid on the MIPS 24 $\mu$m emission of France et al. (2007) (color scale). The CO profiles have been integrated in the interval 2.5–10 km s$^{-1}$; the first contour level and spacing between successive contours is 0.189 K km s$^{-1}$.

Fig. 3. Channel maps of the $^{12}\text{CO}(2–1)$ emission averaged over an interval of 0.41 km s$^{-1}$ (the value in the upper left corner is the center of the velocity interval considered). Each panel corresponds to the region shown in Fig. 1. The first contour level and spacing between successive contours is 3.5 mK.
The profiles are double peaked close to the star (in an approximate circle of diameter 20–30′′; note the blue and red components appearing on each side of the vertical dotted line at 5.9 km s\(^{-1}\) plotted in Fig. 1). The spectra closest to the star display a mirror symmetry about an axis coincident with HD 34078’s path, with the blue emission line stronger to the E and the red one stronger to the W. This is apparent in the channel maps (Fig. 3), where the red component peaks to the W while the blue one peaks to the NE. The symmetry quickly disappears as the profiles become single, peaked further away. Averaging spectra in the NW or SE areas clearly shows that weak wings are present there over the entire velocity range (\(V_{\text{LSR}} = 3–10\) km s\(^{-1}\) covered by the more intense emission seen in the central part. The systemic velocity of the ambient molecular gas is \(V_{\text{LSR}} \approx 6.5\) km s\(^{-1}\).

We now consider the additional \(^{12}\)CO(1–0) spectra (Fig. 4) to investigate the excitation of the CO gas at the (−3, 3) position (at other positions, the \(^{12}\)CO(1–0) spectra are of lower S/N due to a shorter integration time and are less appropriate to measure the excitation ratio). For this purpose, \(^{12}\)CO(1–0) and \(^{12}\)CO(2–1) spectra are brought into the main beam temperature scale; the forward and beam efficiencies are given in Table 1. We next synthetize the \(^{12}\)CO(2–1) emission over the (1–0) beam using the spectra obtained at adjacent positions [(−9, 3), (−3, 9), (3, 3), (−3, −3)] with the appropriate weighting. The resulting (2–1)/(1–0) integrated intensity ratio appears to be around 1.5, a large value compared to that (≈0.7) commonly observed towards diffuse clouds (Falgarone et al. 1998; Liszt & Lucas 1998; Pety et al. 2008). Moreover, the (2–1)/(1–0) ratio is significantly different for the two main components around \(V_{\text{LSR}} \approx 5\) and 7 km s\(^{-1}\) for which we obtain values of about 1.8 and 1.3, respectively.

The above results on the (−3, 3) position can be used to set constraints on the physical conditions prevailing in the gas. With the help of a large velocity gradient model (Hily-Blant & Falgarone 2007), we find that acceptable solutions can be obtained for \(T > 12\) K and that above \(T = 20\) K, the gas density is well constrained and must lie in the range \(n = 10^4–10^6\) cm\(^{-3}\) (\(n\) is the ambient \(H\) number density). All solutions obtained correspond to optically thin emission. For instance, at \(T = 80\) K, a value close to the temperature estimated for the dust by France et al. (2007), we get \(n = 2 \times 10^3\) cm\(^{-3}\) and \(N(CO) = 3.7 \times 10^{14}\) cm\(^{-2}\) at \(V_{\text{LSR}} = 5\) km s\(^{-1}\) and \(n = 1.8 \times 10^3\) cm\(^{-3}\) and \(N(CO) = 6.0 \times 10^{14}\) cm\(^{-2}\) for the \(V_{\text{LSR}} = 7\) km s\(^{-1}\) component. Note that the above CO column densities are comparable to the value \(N(CO) = 5.7 \times 10^{14}\) cm\(^{-2}\) inferred either from IUE data by McLachlan & Nandy (1984) or from FUSE by Sheffer et al. (2008) for the gas in front of HD 34078.

We end this section by concluding that our CO observations allow us to unambiguously answer the question which motivated this study: HD 34078 is indeed closely associated with molecular gas located in its immediate vicinity (which was previously assigned to a foreground quiescent cloud by B05). Moreover, the anomalous CO excitation observed, the large inferred gas density and peculiar velocity field very likely result from the interaction between the stellar wind/radiation and the ambient molecular material (in Sect. 6, we discuss in more detail the implications of the CO observations).

### 3. Variation of CH and CH\(^+\) absorption lines

#### 3.1. Description of optical observations

In the visible, we add 26 spectra to the data considered in R03. Twelve spectra were taken at OHP, eight at McDonald Observatory (hereafter McD) while three spectra were obtained at the Boyunsan Optical Astronomy Observatory (BOAO, South Korea), two at the Terskol Observatory and one at Calar Alto. Altogether, these observations probe the evolution of CH and CH\(^+\) abundances between 1989 and 2008, with good sampling since 2000. In particular, our recent data well cover the period during which the eight FUSE spectra were obtained. The date of each observation and spectral resolution are given in Table 2.

To check in a direct way the consistency of measurements performed at different telescopes, in 2003 we started parallel observations of the bright star \(\zeta\) Per. The latter has been observed in nearly all OHP and McD runs, in addition to HD 34078 (cf. Table 2). This nearby reddened star [\(d = 400\) pc, \(E(B − V) = 0.33\)] has a small proper motion of 10.2 mas yr\(^{-1}\), corresponding to a transverse velocity of 4.1 AU yr\(^{-1}\), much smaller than the value for HD 34078 (22 AU yr\(^{-1}\)). Thus, in principle we expect much less variation due to structure in the foreground IS gas towards \(\zeta\) Per and absorption lines seen in the spectra of that star should be a good indication of the instrumental stability and homogeneity of our measurements. Data from the literature (Allen 1994; Crane et al. 1995) do show that \(W_j\) values for CH, CH\(^+\), CN, Ca i, and Ca ii are constant within errors for \(\zeta\) Per.

OHP observations were made in service mode using the ELODIE spectrograph (Baranne et al. 1996), as in R03, except for the four latest runs which were performed with SOPHIE, the new spectrograph that now supersedes ELODIE at the 1.93 m telescope (Bouchy & The Sophie Team 2006). SOPHIE provides an improved spectral resolution (\(R = 75\ 000\)) and sensitivity, as well as an extended wavelength range (including CH \(\lambda\lambda 3886, \lambda 3890,\) and CH\(^+\) \(\lambda\lambda 3957\); as the blue CN lines are close to the blue edge of the spectra the S/N is too low for these features to be usable). Since SOPHIE has been optimized for the detection of extrasolar planets by radial velocity measurements, it
Table 2. List of observations and measured CH and CH⁺ equivalent widths (in mÅ; uncertainties as estimated in Sect. 3.2.1 are given in upper index).

<table>
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<th>Epoch</th>
<th>Observatory</th>
<th>R°</th>
<th>(W_{4300}(\text{CH})) [mÅ]</th>
<th>(W_{4232}(\text{CH}^+))</th>
<th>(W_{4300}(\text{CH}))ζ Per</th>
<th>(N(\text{CH}))</th>
<th>(N(\text{CH}^+))</th>
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<td>2002.73</td>
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<td>57.35⁺⁻₀²</td>
<td>47.30⁺⁻₀¹</td>
<td>—</td>
<td>0.97⁺⁻₀²</td>
<td>0.69⁺⁻₀²</td>
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</tr>
<tr>
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<td>0.63⁺⁻₀²</td>
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<td>0.84⁺⁻⁰²</td>
<td>0.57⁺⁻⁰¹</td>
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</table>

* Resolution near CH \(4300\). ° \(W_{4300}(\text{CH})\) and \(W_{4232}(\text{CH}^+)\) values from OHP/ELODIE spectra have been corrected by +6% and +8% respectively (see text). ° Column densities in units of \(10^{16}\) cm⁻², measured directly from line profiles for high resolution spectra (McDonald) or computed from \(W\) values using Eqs. (1) and (2) for other data.

provides an accurate wavelength scale (better than 0.01 km s⁻¹; this scale is relative to the barycentre of the solar system). Each observation consisted of 4 to 8 individual exposures totalling about 1 h for HD 34078 and 10⁸ for ζ Per; these two targets were generally observed consecutively or, occasionally, during two successive nights. Spectra were extracted using the pipeline data reduction software. The latter were designed specifically for these spectrographs (Baranne et al. 1996; Bouchy & The Sophie Team 2006) and include all required steps (in particular bias and flat field corrections, using appropriate exposures). For observations of bright stars such as ζ Per and HD 34078, this procedure has been shown to work efficiently, which we checked whenever it was possible, e.g. by comparing independent spectra taken at short time intervals before merging them, or by comparing \(W\) values for those lines seen twice, on two consecutive orders.

At McDonald Observatory echelle spectra of HD 34078 were obtained with the Harlan J. Smith 2.7 m telescope. The strongest molecular features from CN, CH*, and CH are detected, as are the K line of Ca II and Ca I \(4226\), although the latter falls next to a CCD glitch and thus cannot be reliably extracted. The data were reduced in the same fashion as before (cf. R03). A global multi-order fit of the entire CCD chip was performed for each Th-Ar spectrum, yielding residuals below 0.001 Å (or 0.08 km s⁻¹). Measured radial velocities of (non-variable) absorption lines towards the comparison star ζ Per show a scatter that is consistent with the residuals from the wavelength calibration. From the Th-Ar data we measured the instrumental resolution of our spectra, which turned out to be \(R = 170,000\). Stellar exposures were 30⁸ long for HD 34078, and typically 5⁸ for ζ Per.

A few observations of HD 34078 were also performed at other telescopes. Two spectra were obtained using the MAESTRO spectrograph, fed by the 2-m telescope at the Terskol Observatory (TE) in Northern Caucasus (the resolution was 120000). Three more spectra were obtained using the fiber-fed echelle spectrograph installed at the 1.8-m telescope of the Bohyunsan Optical Astronomy Observatory (BOAO) in South Korea (a description can be found in Galazutdinov et al. 2005). Modes providing resolutions, \(R = 30,000\) or 45,000, were employed (Table 2). Finally, a spectrum was taken in service mode at the Calar Alto observatory with the FOCES spectrograph (\(R = 40,000\), Pfeiffer et al. 1998). For these additional runs, ζ Per was not observed; we are nevertheless confident that these data are homogeneous with respect to the other spectra obtained.

3.2. Equivalent widths and column densities

3.2.1. Equivalent width estimates

Equivalent width measurements were performed in a similar way as in R03 for CH \(4300\). Regarding \(W_{4232}(\text{CH}^+), the accuracy is limited by the poor definition of the continuum due to blending with a stellar line (cf. Fig. 7 in R03). Then, to avoid possible resolution-dependent effects on the estimate of \(W\) values and to improve the homogeneity and accuracy of our measurements, we fitted this stellar line with a Gaussian. Its
position \((\delta \lambda = -0.364 \text{ Å} \text{ with respect to the CH}^+ \text{ absorption})\) and FWHM \((0.46 \text{ Å})\) were fixed while the depth was varied so as to match the continuum blueward of the CH\(^+\) absorption as well as possible (a typical value for the depth is 3\% of the continuum). Once the spectra have been normalised in this way, we measure \(W\) and its uncertainty as done for CH \(\lambda \text{4300}\). This procedure was applied to all spectra, including those obtained prior to 2003; for the latter, this results in \(W\) values which differ slightly from those given in R03.

Some observations of HD 34078 were spread over 2 or 3 consecutive nights (in particular the recent, high S/N, McD and OHP/SOPHIE spectra), which allowed us to check that no significant day-to-day variations are present; we then measured \(W\) on the co-added spectrum. For the same reason, one BOAO and one TE measurement obtained two days apart in March 2004 were combined (thus Table 2 contains 25 entries).

Uncertainties were estimated in a conservative way, including the error due to finite pixel-to-pixel S/N ratio and the one in continuum placement; we assume as in R03 that the two sources of errors combine quadratically. \(W\) estimates for HD 34078 and their associated errors are given in Table 2 for HD 34078 (CH \(\lambda \text{4300}\) and CH\(^+\) \(\lambda \text{4232}\)) and \(\zeta\) Per (CH \(\lambda \text{4300}\)); note that concerning OHP/ELODIE spectra, values corrected as explained below are given for both HD 34078 and \(\zeta\) Per.

### 3.2.2. Consistency of all measurements

In Fig. 5 (upper panel), we show results from the CH \(\lambda \text{4300}\) \(\zeta\) Per observations performed between 2003 and 2007, to which we add older measurements from Crane et al. (1995) and Allen (1994). These are consistent with a constant value of \(W_{\text{4300}}(\text{CH})\).

However, careful examination reveals a small offset of about \(-6\%\) for the OHP/ELODIE values with respect to the other measurements. Since the same offset appears to be present in the HD 34078 \(W_{\lambda \text{4232}}(\text{CH})\) values (lower panel, empty triangles), this effect is very likely due to scattered light in the ELODIE spectrograph (Ilovaisky and Prugnel, personal communication). Thus, we applied a \(+6\%\) correction (scattered light from the target does lead to a multiplicative correction on \(W\) values) to all OHP ELODIE CH \(\lambda \text{4300}\) values (filled triangles), including those presented in R03.

Unfortunately, the CH\(^+\) \(\lambda \text{4232}\) line towards \(\zeta\) Per is too faint \((W \approx 2.5 \text{ mÅ})\) to assess whether OHP/ELODIE measurements of this transition are also affected by scattered light. Then, to determine the correction for CH\(^+\) \(\lambda \text{4232}\) (which may be different from that for CH \(\lambda \text{4300}\)), we have to rely on the HD 34078 data themselves (Fig. 6). By comparing the sets of OHP and McD values, we find that an offset of about \(+8\%\) needs to be applied to the OHP/ELODIE values to bring both sets of points to good mutual agreement (filled triangles in Fig. 6). After correcting the OHP/ELODIE \(W\) values in this way, it is apparent in Figs. 5 and 6 that nearly simultaneous measurements performed at different telescopes yield consistent values, within errors. This is a direct indication that uncertainties are not underestimated and that, after correction of the OHP/ELODIE \(W\) values, the whole set of data is homogeneous.

The OHP/ELODIE \(W\) measurements of CH\(^+\) \(\lambda \text{3957}\) are not accurate enough in comparison to those for CH \(\lambda \text{4300}\) or CH\(^+\) \(\lambda \text{4232}\) to be really useful (further, they are affected by scattered light in an unknown way). In contrast, the recent OHP/SOPHIE spectra provide good S/N values for \(W_{\lambda \text{3957}}(\text{CH}^+)\). In Fig. 7 (panels c and d) we show the variation of \(W\) versus time for both CH\(^+\) transitions since September 2006; as can be seen, the two sets of measurements are very consistent. We also display for the same epochs the behavior of \(W_{\text{4300}}(\text{CH})\) for both
HD 34078 (panel a) and ζ Per (b); the latter values remained constant while the variations seen for CH in HD 34078 are qualitatively similar to those observed for CH⁺. The whole set of values for $W_{4232}(\text{CH}^+)$ and $W_{3400}(\text{CH})$ shows a fairly smooth variation, with apparently little or no variations with timescales smaller than a few months.

Figures 5–7 strongly suggest that the equivalent widths varied for HD 34078 while $W_{3400}(\text{CH})$ remained constant for ζ Per. Let us now assess in a quantitative way the statistical significance of the $W_{3886}$ and $W_{3890}$ values for both the OHP and McD data. We use a Bayesian inversion procedure as done by Pichon et al. (2001) in the context of Lyα absorption in QSO spectra. Equally populated subsamples are assumed (we checked that the relative strength of the CH λ3886 and CH λ3890 lines in the OHP/SOPHIE spectra is consistent with this hypothesis; see also Lien 1984, for other lines of sight). We find in the end that taking into account a doublet induces corrections on $N(\text{CH})$ which are no larger than 1.3%.

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absorption lines span different ranges in opacity which helps to constrain the best linear fit (dotted line: $y = -15.232 + 0.676 \times x$). A curve of growth with $b = 3.2$ km s$^{-1}$ also provides a good fit to the data (plain line; the two additional lines correspond to $b = 2.8$ and $b = 3.5$ km s$^{-1}$ and bracket the data points well). The large $b$ curve (i.e. optically thin limit) is shown (dashed line).

We now consider the CH$^+$ measurements shown as empty squares in Fig. 9. The $+8\%$ correction applied to the OHP/ELODIE data somewhat affects the previous conclusion of R03 of a possible decrease of $N$(CH$^+$) between 1990 and 2002: $N$(CH$^+$) now looks essentially constant over the long term, with no large amplitude variations such as those seen for CH. Beyond 2000, the general pattern is relatively similar for both species. Although, the long-term variations in CH and CH$^+$ seem to be loosely correlated, there is a good correspondence between the short-term ones; this is especially clear in Fig. 7 (note in particular the coincidence of the local minima in February 2007 and February 2008, $\tau_N = 0.5$ yr) and then increased by 9% to reach the last February 2008 value (see Fig. 7 for a zoom on the recent W data).

We shall now focus on the high resolution spectra of the CH $\lambda$4300 and CH$^+$ $\lambda$4232 absorption lines in order to investigate whether the observed long and short-term variations in W are accompanied by detectable changes in line profiles. Profile variations might also be present which are not necessarily reflected in appreciable W changes.

### 3.3. High resolution CH and CH$^+$ line profiles and their variations

The high resolution profiles obtained at McDonald Observatory have all been corrected for the Doppler shift due to the Earth velocity and have been brought in the LSR system. Yet, after correction, the wavelength of the $\zeta$ Per lines still show slight fluctuations in position (of at most a few mÅ) from one epoch to another (given the excellent S/N and the sharp line profiles, misalignments by only a few mÅ are sufficient to induce significant profile differences). These fluctuations are identical for both CN and CH lines to within 1 mÅ and show a good correlation with those of the HD 34078 lines. They must then be due to some inaccuracy in the LSR correction from one epoch to another. To improve the accuracy in the alignment of the HD 34078 absorption lines, we assume that $\zeta$ Per lines have been stable in position (this is confirmed by SOPHIE spectra whose wavelength scale is accurately defined) and infer the value of the relative shifts for each epoch. These are used to slightly adjust the position of HD 34078 lines.

The CH and CH$^+$ line profiles are quite similar (Fig. 10): both include a narrow component with a full width at half maximum of about 5.5 km s$^{-1}$ (corresponding to a $b$ parameter of 3.3 km s$^{-1}$) and shallow absorption extending from $-4$ up to 17 km s$^{-1}$. The CH and CH$^+$ narrow components cover the same velocity range ($\approx 2$–$11$ km s$^{-1}$) but their shapes are significantly different: CH displays a steeper blue edge, while the opposite holds for CH$^+$. This results in a shift of about $+1.6$ km s$^{-1}$ for the CH$^+$ line centre with respect to that of CH. It is
Fig. 10. Comparison of McD CH $\lambda$4300 (lower left) and CH$^+$ $\lambda$4232 (upper left) profiles observed in January 2003 and October 2005. During this 2.81 yr time interval $W$ varied by $\sim$11.7% and $\sim$0.3% respectively. Same for OHP/SOPHIE CH $\lambda$4300 (lower right) and CH$^+$ $\lambda$4232 (upper right) profiles obtained in September 2006 and February 2007 ($W$ variation of $\sim$7.1% and $\sim$6.6% over 0.43 yr). Note the good stability of the red side of the profiles.

Fig. 11. Comparison of the HD 34078 OHP spectra obtained in February 2007 (thick line) and February 2008 (thin line) for the CH $\lambda$4300 (upper left), CH$^+$ $\lambda$4232 (lower right) and CH$^+$ $\lambda$3957 (upper right) lines. Note the good consistency between the two CH$^+$ transitions. During this 1.0 yr interval, the $\zeta$ Per CH $\lambda$4300 profile remained stable.

noteworthy that the velocity range covered by the narrow CH or CH$^+$ absorption coincides quite well with the range over which CO emission is observed.

Since we are likely probing molecular gas closely associated with HD 34078 (i.e. with peculiar physical conditions), one may wonder whether the CH and CH$^+$ profiles show significant differences to those seen on other lines of sight. We note that the presence of a weak broad component is rare (Crane et al. 1995; Crawford 1995) but such shallow absorption would be difficult to detect in most spectra; one of very low amplitude ($\sim$1% instead of $\sim$5% in our spectra) is however present in the very high S/N spectrum of $\zeta$ Oph presented by Crane et al. (1991).

By comparing successive spectra, we find that fluctuations in $W$ are most often associated with changes in the blue and central part of the profiles, the red side suffering very little variation. This is apparent in Fig. 10 (left panels) in which we display CH McD profiles for the January 2003 and October 2005 epochs. During this 2.8 yr time interval $W_{4300}(\text{CH})$ decreased by 12% and the FWHM of the narrow component decreased by 5%. $W_{4232}(\text{CH}^+)$ remained nearly constant over the same period but significant profiles changes are nevertheless clearly present; the line is slightly deeper, which compensates for a decrease in FWHM comparable to that seen for CH. Another example is shown in Fig. 10 (right panels), where we compare OHP/SOPHIE CH and CH$^+$ profiles taken over a much shorter interval (0.43 yr from September 2006 to February 2007). In this case, $W_{3957}(\text{CH})$ and $W_{4232}(\text{CH}^+)$ have decreased by a comparable amount ($\sim$7%) while both profiles became slightly narrower. Thus correlated $W$ variations appear to be associated with similar profile changes. Since 2003, $W$ values show no systematic trend but rather erratic fluctuations; the same is true for profiles and generally, for two epochs with comparable $W$ values, the profiles are quite similar (the CH $\lambda$4232 January 2003 and October 2005 profiles being an exception). In Fig. 11 we display the recent February 2007 and 2008 CH and CH$^+$ profiles; the latter show a marked increase in $W$ (cf. Fig. 7), corresponding to $\sim$+26% for $N(\text{CH}^+)$ (note that during the same interval, the CH $\lambda$4300 $\zeta$ Per profile remained stable). We do not see appreciable variations of the broad shallow component, but given its weakness, the significance of this result is limited.

Unfortunately, the S/N ratio for the CN line profiles of HD 34078 is not sufficient to allow a search for variations with a sensitivity comparable to the one attained for CH and CH$^+$. Further, the strongest CN line is clearly affected by variations of blended stellar (CIV) absorption. Thus we shall not discuss variations of CN features.
Comparing the October 2004 (8th) spectrum to the previous ones, we find that it shows noticeable differences (Fig. 12): narrow lines are deeper and damped H$_2$ lines are slightly broader [as if N(H$_2$) had increased]. This brought to our attention a potential difficulty that had not been considered in B05: contamination of the HD 34078 spectrum by diffuse emission from the IC 405 nebula. Indeed, the 8th spectrum was obtained with the MDRS aperture while all others were taken using the larger LWRS aperture. Given the difference in size (MDRS: 4×20 arcsec$^2$; LWRS: 30×30 arcsec$^2$) and the intense diffuse emission detected close to the HD 34078 line of sight by France et al. (2004), the peculiarities of the 8th spectrum might just be due to a lower level of contamination of the spectrum by diffuse emission. In Appendix A, we estimate the nebular contribution to LWRS spectra and conclude that it can explain the difference between FUSE spectra 1 to 7 and the 8th MDRS one. Thus only spectra 1 to 7 will be considered below in our search for variations in H$_2$ lines.

The importance of diffuse emission contamination in LWRS spectra also implies some limitation in our search for variations: the aperture may not be located exactly at the same position on the sky at all epochs resulting in a slightly variable contribution from diffuse emission if gradients are present. Note that since the diffuse to stellar flux ratio decreases with wavelength towards HD 34078 (France et al. 2004), H$_2$ systems at longer wavelengths are best suited to minimize the contamination by diffuse emission. Regarding the study of the gas properties towards HD34078, the 8th spectrum is clearly to be preferred for two reasons: i) it should be much less affected by diffuse emission and ii) the S/N ratio is significantly higher than for previous spectra due to an integration time (22 500 s) about four times longer than at epochs 1 to 7 (≃6000 s). A redetermination of the gas properties based on the 8th spectrum (H$_2$ excitation diagram in particular) will be presented elsewhere; we simply note here that the detection of absorption lines from all excited H$_2$ levels quoted in B05 is confirmed.

### 4.2. Variations in N(H$_2$, J = 0)

As in B05, we perform a direct comparison of the LWRS spectra, after relative flux intercalibration and adjustment of the wavelength scale. This procedure is applied independently to three portions of the spectra located at about 1050, 1063 and 1078 Å, corresponding to the (4–0), (3–0), (2–0) H$_2$ Lyman bands respectively. Each of these broad features is a blend of four H$_2$ lines arising from the J = 0, 1 and 2 levels. A good relative flux calibration is easily obtained (as for spectra 1 to 5), indicating that the shape of the stellar spectrum does not vary (known stellar lines for such O9 stars are indeed weak and rare in these regions: Pellerin et al. 2002). Using narrow high J H$_2$ lines adjacent to the broad H$_2$ absorptions of interest, we get an accuracy in the wavelength alignment of about 0.01 Å for the 1050, 1063 and 1078 Å absorption systems.

We now focus on the blue edge of each broad H$_2$ system which presents good sensitivity to changes in N(H$_2$, J = 0). A zoom of this region for the 1050 Å system is shown in Fig. 13 (upper panel). All spectra, corrected in flux and wavelength as described above, are superimposed. They are all similar and an average spectrum can therefore be computed (thick line). The difference (Δ$F_i$) between one individual spectrum, i, and the
mean is displayed in the lower panel for each epoch \((i = 1, ..., 7\) from top to bottom). The 3\(\sigma\) dispersion on \(\Delta I_i\) among the seven epochs is indicated as a function of wavelength (dashed lines). Away from the \(J = 0\) line, the \(\Delta I\) profile is consistent with no variation. In the region close to the \(J = 0\) line (displayed in red) where variations in \(N(J = 0)\) would induce changes in the profiles, spectra 1 to 7 are also consistent with the mean spectrum. Similarly, B05 have adjusted the first spectra using \(\log N(J = 0) = 20.52\) and concluded that the variation among the five first spectra was lower than 5%. Indeed, an increase (decrease) of this amplitude roughly corresponds to a difference that follows the lower (upper) 3\(\sigma\) profile in Fig. 10. We conclude from our analysis that \(\Delta I(H_2)\) changed by less than 5\% at the 3\(\sigma\) level between January 2000 and February 2004 while \(\Delta I(\text{CH})\) has undergone variations as large as 20\% over the same time interval (cf. Fig. 6).

5. Observations summary

5.1. The stability of \(\zeta\) Per CH absorption

As mentioned above, \(\zeta\) Per was observed primarily to test the homogeneity of our measurements. After correction of the small offset found in the OHP/ELodie data, the whole set of \(W\) values appears remarkably consistent. The latter, and the most recent (2006–2008) data in particular, lead us to a strong twofold conclusion: i) \(W_{2300}(\text{CH})\) remains constant towards \(\zeta\) Per and ii) \(N(\text{CH})\) and \(N(\text{CH}^+)\) do vary towards HD 34078. Indeed, if variations of instrumental origin were responsible for changes in HD 34078 values, one should invoke a very unlikely “conspiracy” to explain the stability of \(\zeta\) Per lines. The fact that the same behavior is observed for distinct \(\text{CH}^+\) lines is a strong additional proof of the reality of HD 34078’s variations.

\(\zeta\) Per was observed for 5 years and over this time interval, the drift of the line of sight through the foreground cloud has been significant. The distance to the cloud is thought to be 350 pc (Hilton & Lahulla 1995) and thus the drift of the line of sight amounts to 17.8 AU. The constancy of \(N(\text{CH})\) then shows that over this scale and below, there is no marked structure in the cloud. The 3\(\sigma\) upper limit on relative variations of \(N(\text{CH})\) is about 6\%. We derive this value simply from the raw average and rms scatter of McD and OHP/SOPHIE measurements, assuming the CH \(J=4\) line is optically thin; a more detailed analysis of the \(\zeta\) Per data, including CN and \(\text{CH}^+\) lines, will be presented elsewhere.

5.2. Main observational results on HD 34078

From multiwavelength observations of the gas towards HD 34078 and in its close environment, we obtain the following results:

\(\star\) the \(^{12}\text{CO}(2–1)\) emission map of the HD 34078 field shows a pronounced peak coincident with the star’s position, clearly indicating that molecular gas seen in absorption is closely associated with HD 34078. The extent and morphology of the CO emission correlates well with the 24 \(\mu\)m dust emission arc of France et al. (2007). Presumably as a result of the interaction between HD 34078 and the ambient cloud, the \(\text{CO}(2–1)/\text{CO}(1–0)\) ratio is anomalously large, pointing towards dense \(\left(10^2–10^4\,\text{cm}^{-3}\right)\) and warm \((T > 12\,\text{K})\) emitting gas and further, a remarkable kinematical pattern with doubled-peaked profiles is observed;

\(\star\) we confirm the reality of rapid, large amplitude (typically 10\% yr\(^{-1}\)) and correlated variations of \(N(\text{CH})\) and \(N(\text{CH}^+)\) towards HD 34078. The velocity ranges covered by CH and \(\text{CH}^+\) narrow absorption coincide well with that of CO emission. Variations in CH and \(\text{CH}^+\) line profiles are unambiguously detected; these occur mainly in the blue part of the narrow absorption. A broad shallow and relatively stable component is seen for both CH and \(\text{CH}^+\) in the interval \([-4, 17\,\text{km s}^{-1}]\);

\(\star\) comparison of LWRS and MDRS FUSE spectra reveals that the 7 LWRS spectra available are significantly contaminated by diffuse light from IC 405. The absence of variations in the LWRS profiles of \(H_2\) \(J = 0\) lines yields a 3\(\sigma\) upper limit of 5\% on \(N\) values, extending the result of B05 over nearly four years (or 90 AU).

6. Discussion

Given the marked contrast between the stability of \(\zeta\) Per CH lines and the rapid, large amplitude variations seen for CH and \(\text{CH}^+\) towards HD 34078, we shall assume in the following discussion that these variations can be attributed entirely to phenomena associated with the star/cloud interaction and not to small scale structure in cold gas.

6.1. Towards a coherent picture of the close environment of HD 34078

From the broad set of observations available, a coherent scenario emerges which can be summarized as follows. HD 34078 recently encountered a molecular cloud, as originally suggested by Herbig (1958). The stellar wind impacts the ambient material resulting in a shell of compressed, highly excited gas. Modelling of both the \(H_2\) excitation (B05) and CO emission (Sect. 2.2) provides consistent estimates for the density in the shell, \(n \approx 10^4\,\text{cm}^{-3}\). Dust grains located in this region are directly exposed to the intense UV flux from the O star and strongly emit at infrared wavelengths. Thus, both the mid-IR emission detected by France et al. (2007) and the CO emission probably delineate the part of the shell seen edge-on by the observer, accounting for the good correlation between the Spitzer 8 or 24 \(\mu\)m arc and the CO map (Fig. 1).

B05 favored a two-cloud model on the basis of the dichotomy in the physical conditions derived for the highly excited \(H_2\) on the one hand and for all other molecular absorption on the other hand. They discarded a single cloud model (although it would have naturally explained the similar velocity for all absorption lines and the presence of preexisting diffuse \(H_2\) near HD 34078...) because they implicitly assumed that molecules should be photodissociated at the very small distance (a few 0.01 pc) implied by the modelling of the \(H_2\) excitation. In fact, this argument is valid only in a model that is stationary regarding the formation/destruction of molecules. Given the large space velocity \((V_s)\) of HD 34078, its arrival is so recent that probably no such steady-state equilibrium could be established. Rather, as the O star is approaching the cloud, a photoionisation and photodissociation front develops, moving at velocities of the order of a few km s\(^{-1}\) only (Bertoldi & Draine 1996), i.e. well below the star velocity. The distance between HD 34078 and these fronts then gradually decreases and the velocity of the latter becomes higher (the front velocities increase with stellar flux), up to a point where the star and front velocities equate. Moreover, the stellar wind has a strong mechanical impact on the surrounding gas and the latter is gradually set into motion.
As a result of momentum flux. When the star is close enough to the cloud, a stationary bow shock is established at a position nearly coincident with that of the photodissociation front. At this stage, the distance ($R_0 = AS$, see Fig. 14) between the star and the apex of the shock is well defined and remains constant as long as the density of the ambient cloud and the wind properties (mass loss rate and terminal velocity) do not change. In this picture (Fig. 14), whether the dynamical steady-state regime is established or not, the molecular material located beyond the front/shock surface should be little affected by the presence of the closeby star, thereby accounting for the characteristics of the molecular components that B05 assigned to the “translucent” component.

We conclude that a model involving a single cloud located very close to HD 34078 may, in fact, be consistent with all observations. A key issue remains open however: at what stage of the star-cloud interaction have we captured HD 34078 and its close environment? A stationary dynamical regime is expected to be established ultimately and in the thin-shell limit, detailed models describing the geometry and velocity structure of steady-state bow shocks are available (e.g. van Buren et al. 1990; Mac Low et al. 1991; Wilkin 1996). We thus performed a detailed comparison between the predictions of these models and observations (Appendix B). From this analysis, we conclude that the IR/CO arc does not display the properties expected for a stationary bow shock and that we are possibly observing a “nascent bow shock”, i.e. the wind/cloud interaction at an early evolutionary stage, well before the formation of a steady-state flow around the star. We also find that the geometrical constraints provided by the IR data, $h \approx R_0 \approx 0.04$ pc, are roughly consistent with the radiation field implied by the modelling of H$_2$ excitation (B05).

A variant of the above scenario is suggested by France et al. (2004), who proposed that differential extinction is present between HD 34078 and the surrounding diffuse emission, in order to explain the increase of the diffuse to stellar ratio at far-UV wavelengths. More specifically, France et al. (2004) propose that a small clump lies in front of HD 34078 (Fig. 15). With an extent no larger that about 20$''$, the latter could induce the observed HD 34078 extinction without affecting the surrounding nebular emission.

Such a picture is attractive in our context because 20$''$ is approximately the size of the area over which a “dip” is seen in the CO profiles, suggesting that the double-peaked line shapes might be due to narrow absorption rather than to velocity structure in the emitting gas. In this scenario, CO emission could originate from the ambient cloud background to HD 34078 – especially its outer boundary, compressed by the wind – accounting for the widespread emission seen over most of the field (Fig. 15). Additional emission could come from the clump itself, in particular from the region located immediately beyond the hot PDR facing the star, explaining the enhanced emission close to HD 34078 and the high excitation of the emitting material. Gas located on the cold side of the clump facing the observer should be little affected by the interaction, as in the bow-shock scenario. This region corresponds to the translucent component in B05’s model; with a small CO excitation temperature and low velocity dispersion, this gas could induce narrow absorption in the background CO emission. The close similarity of the CO dip velocity at the star position, $V \approx 6.0$ km s$^{-1}$ (this value is stable to within 0.2 km s$^{-1}$ among spectra displaying the dip), and the velocity of maximum narrow CH and CH$^+$ absorption (see Fig. 10) is consistent with absorption being responsible for the dip in CO profiles. The clump should be located at a distance from the star of about 0.1 pc (comparable to that of point L$_2$ in the bow-shock picture) so that the hot PDR facing the star is exposed to a radiation field large enough to account for the H$_2$ excitation (Appendix B, B05). In fact, the bow-shock and clump scenario are more or less equivalent, both of them involving the presence along the line of sight of a shell of dense gas illuminated by intense UV radiation; the main difference is that in the clump picture, the ambient material is not distributed in a continuous manner around HD 34078.

### 6.2. CH and CH$^+$ abundance and time variations

In the picture described above (Fig. 14), the dense shell at the wind/cloud interface is nearly static in the ambient cloud’s frame and as time elapses, the point (L$_2$) at which the line of sight...
intersects the shell drifts over the latter towards the apex (A) at a velocity $V_1/\cos \varphi$, where $V_1$ is the transverse velocity and $\varphi$ is the inclination of the shell at $L_2$. Similarly, in the clump scenario (Fig. 15), the line of sight drifts over the wind/clump interface. The rapid CH and CH$^+$ variations observed imply that a significant fraction of these species is enclosed in a very localised region (with a size of about 10 AU, corresponding to a time interval of 6 months) and in our context, it is natural to assume that time variations arise from structure over the shell of compressed gas intersected by the line of sight. Further, as already outlined by B05, the CH/H$_2$ ratio towards HD 34078 is anomalously large: for $N$(CH$^+$) $\approx 10^{14}$ cm$^{-2}$ (the largest values reached, in 2000–2003) we get a ratio of $1.6 \times 10^{-2}$, which appears to be 3.7 times larger than the value inferred from the best fit given by Sheffer et al. (2008) (a similar result is obtained by comparing HD 34078 values to those compiled by Welty et al. 2006). Since the CH–H$_2$ correlation is quite good, such a deviation is very significant and indeed, in Fig. 8 presented by Sheffer et al. (2008), HD 34078 is clearly an outlier (note that surprisingly, HD 37903, the other star showing highly excited H$_2$, has an anomalously low CH/H$_2$ ratio). The CH$^+$/H$_2$ ratio displays much more scatter among all sightlines, but nevertheless, $N$(CH$^+$) towards HD 34078 is among the largest values for $N$(H$_2$) $\approx 6 \times 10^{20}$ cm$^{-2}$ (Fig. 10 in Sheffer et al. 2008). In the end, the CH/CH$^+$ ratio in HD 34078 is well within the range observed towards other stars (cf. Fig. 10 in Welty et al. 2006). We thus apparently have a comparable relative excess of both CH and CH$^+$, and again, it is natural to assume that the overproduction of these species occurs in the compressed shell. To induce such a large deviation in the CH/H$_2$ ratio, the overproduction of CH must be quite large since molecular gas located beyond the shell probably displays a more standard ratio. Similarly, the spatial distribution of CH and CH$^+$ over the shell must be very inhomogeneous at scales of about 10 AU to induce the observed variations. Since the CH and CH$^+$ variations are strongly correlated, a single mechanism must be at work to explain the overproduction of both species.

Clearly, the CH and CH$^+$ time variations cannot be attributed to pure density structure. Indeed, no corresponding changes have been seen for $N$(H$_2$) and further, explaining CH or CH$^+$ variations by more or less spherical clumps with a size of about 10 AU would require very high volume densities, $n$(H$_2$) $\geq 10^{-16}$ cm$^{-3}$, as argued by R03. In such gas, CH$^+$ would be rapidly destroyed by reactions with H$_2$. Then, the structure is likely to be more chemical in nature.

The production of CH$^+$, which is not expected at thermal equilibrium, together with the correlated variations of CH and CH$^+$, suggest that both molecules are mainly formed in the dense shell, through a MHD shock where the drift velocity between ions and neutrals triggers the formation of both CH and CH$^+$ (Pineau des Forêts et al. 1986; Flower & Pineau des Forêts 1998). CH$^+$ could also be overproduced at the interface between the ambient cloud and warmer gas, as suggested by Dudley et al. (1992), Crawford (1995) and more recently by Lesaffre et al. (2007). In the specific conditions prevailing around HD 34078, one may imagine that Rayleigh-Taylor instabilities develop efficiently (e.g. as a result of fluctuations in the wind properties or in the ambient cloud), leading to the formation of a turbulent mixing layer with pronounced small-scale structure. HD 34078 being variable (Marchenko et al. 1998), stellar flux variations can also trigger or amplify the formation of small-scale structure at the interface and in the PDR. In regions hot enough to form significant amounts of CH$^+$ via the endoenergetic C$^+$ + H$_2$ reaction (whatever the heating mechanism, shocks or turbulent dissipation), small spatial temperature fluctuations will result in appreciable variations in the CH$^+$ formation rate and then in the relative abundance of CH$^+$ and CH (recall that CH is easily formed from CH$^+$ once the latter species is present). One can indeed estimate that since the CH$^+$ formation rate scales as $\exp(-4640/T)$, a local variation as small as 22 K around $T \approx 1000$ K is sufficient to induce a fluctuation of 10% in the local abundance. The broad, shallow CH and CH$^+$ absorption components (Fig. 10) could be a signature of the highly turbulent velocity field at the interface (note the excellent agreement in the velocity intervals [4 to 17 km s$^{-1}$] covered by the CH and CH$^+$ broad components, indicating that the species responsible for that component are cosmopial).

CH and CH$^+$ line profiles vary mainly on their blue side, at $V_{LSR} \approx 4–5$ km s$^{-1}$ (Fig. 10), suggesting this velocity for the gas lying at the interface near $L_2$. This material is therefore blueshifted with respect to the ambient cloud (at $V_{LSR} \approx 6.5$ km s$^{-1}$); this is consistent with the stellar wind pushing ambient molecular gas towards the observer. The higher excitation derived for the CO component at $V_{LSR} \approx 5$ km s$^{-1}$ also nicely fits this view. Thus, the scenario described above might, at the same time, explain in a coherent way the high abundances of CH and CH$^+$ as well as their time variations.

The amounts of excited H$_2$ ($J = 3$ to 5) and CH$^+$ are known to correlate (Lambert & Danks 1986) and is taken as an indication that the same mechanism is responsible for these species, the production of which requires an input of additional energy of yet unknown nature. Towards HD 34078, a marked excess of both excited H$_2$ and CH$^+$ is observed, in agreement with the correlation seen among more standard lines of sight. We note that in our scenario, the large amount of excited H$_2$ and CH$^+$ is a direct consequence of the proximity of HD 34078, through its wind and UV flux.

### 6.3. Small scale structure in quiescent H$_2$ gas

In the picture that we propose, H$_2$ gas located beyond the photodissociation front and shocked region is essentially unaffected by the presence of the star (dust grains should be somewhat warmer due to the proximity of the star, but at densities of a few $10^5$ cm$^{-3}$, this has little impact on the gas temperature). This part of the cloud gives by far the dominant contribution to the H$_2$ column density in the J $\geq 0$ level (in B05’s model, the hot PDR represents less than 1% of the total $N$ value); it should also contain a significant fraction of the CO responsible for the UV absorption, about 1/4 of CH molecules (cf above) and most of the CN. Thus, the lack of variation in $N$(H$_2$, J = 0) at a level better than 5% implies that no marked small-scale density structure is present within the fraction of the ambient cloud probed by the drift of the line of sight between 2000 and 2004. If this region is representative of quiescent diffuse molecular material in general, the structure seen elsewhere for other tracers like H$_2$CO, HCO$^+$, and OH would be mainly “chemical” structure, possibly reflecting the specific formation/destruction processes relevant to these species.

We further note that the lack of structure in quiescent H$_2$ gas is consistent with the stability of CH absorption lines towards ζ Per, provided the CH/H$_2$ abundance ratio is uniform at scales of about 10 AU within this quiescent cloud.

### 7. Conclusions and prospects

- By mapping $^{12}$CO(2–1) emission around HD 34078, we have unambiguously shown that the molecular material seen in the...
foreground is closely associated with the star, supporting the suggestion by Herbig (1958) that HD 34078 is currently encountering a molecular cloud. Repeated CH and CH$^+$ observations, performed using the star $\zeta$ Per as reference, confirm the reality of rapid and large amplitude variations of $N$(CH) and $N$(CH$^+$) along the line of sight.

- The results altogether strongly suggest that the recent arrival of HD 34078 near the southern edge of a molecular cloud has given rise to a shell of dense gas at the interface between the stellar wind and H$_2$ gas, the latter material belonging either to the distorted boundary of the ambient cloud or to a small foreground clump, as suggested by France et al. (2004). The location of this shell relative to the star is consistent with constraints derived from earlier modelling of H$_2$ excitation.

By comparing the geometrical characteristics of the IR arc detected by France et al. (2007) and the velocity field inferred from our CO or optical observations to predictions of steady-state bow shock models, we find that the latter are inconsistent with the observed properties. Therefore, we may be seeing this region at an early phase of the wind/cloud interaction, with a dense layer formed at the interface but no stationary flow yet established.

- We propose that the large relative CH and CH$^+$ abundances originate from significant overproduction of CH$^+$ in the dense shell, due to the presence of a strong C-shock and/or of mixing of warm ionised gas and highly excited molecular material at the wind/cloud interface. The pronounced, correlated CH and CH$^+$ variations would then reflect marked chemical structure in the dense shell, possibly resulting from instabilities occurring at the interface.

- No variations of $N$(H$_2$, $J=0$) have been found at a level of 5% ($3\sigma$ limit), extending the result obtained in B05 to a time interval of 4 years, or 110 AU. In the scenario that we propose, $J=0$ H$_2$ molecules are mainly located beyond the dense shell. This indicates that beyond the photodissociation and photoionisation fronts, where the molecular material is not yet affected by the interaction with HD 34078, no marked small-scale structure is present and that the bulk of the mass is distributed relatively uniformly within the cloud.

Let us now discuss some prospects concerning the time evolution of HD 34078’s environment, assuming the scenario sketched in this paper is roughly correct. One may in particular wonder whether the future evolution can induce significant observable changes in the coming years. Using the estimates for the observed standoff distance and its expected steady-state value given in Appendix B, one can get a lower limit for the time needed for a stationary flow to establish, $(R_{\text{obs}} - R_{\text{sh})}/V_s \approx R_{\text{obs}}/V_s \approx 350$ yr. We therefore expect very little change in the morphology of the mid-IR or CO emission. The only appreciable evolution would involve the motion of the star relative to the IR or CO peak (1" in 23 yrs), since the shell is supposed to remain nearly static in the near future.

However, during its evolution towards a stationary dynamical regime, the velocity field must undergo a drastic variation to reach the steady-state solution. CO mm observations, which provide excellent spectral resolution, might thus reveal significant velocity changes. A higher spatial resolution map of CO emission would be useful in this regard and of great help to better understand the kinematics underlying the remarkable pattern observed for line profiles in Fig. 1. In the next decade, ALMA will offer excellent opportunities for such observations. Numerical simulations of the time evolution of the wind/cloud interface (which, to our knowledge are not available) would also be very useful to indicate how the evolution of the velocity field will proceed in the early phase.

In the above reasoning, we implicitly assumed that the dense shell will smoothly evolve towards the steady-state solution but this is in no way evident. If indeed instabilities develop efficiently at the interface (as suggested by CH and CH$^+$ variations), the cloud may simply be gradually destroyed as the star moves. Such a picture would be consistent with the suggestion by Herbig (1958) that the absence of IS material south of the star is due to “clearing” along the path followed by HD 34078 in the past (the clump involved in the second scenario might then simply be a fragment of the initial cloud in the process of photoevaporation). Focusing now on the present state of HD 34078’s environment, we note that it represents a remarkable PDR and shock for which many observational constraints are or might be available, thanks to the presence of a background UV-bright star. Geometrical parameters are now well determined and physical conditions in the ambient cloud relatively well constrained (sensitive CO emission observations further away from HD 34078 would allow us to better characterize them and verify that the peculiar excitation conditions determined in Sect. 2.2 are specific to the immediate vicinity of the star). Then, the HD 34078 PDR may be used as a reference to test our understanding of various physical and chemical processes occurring elsewhere at cloud interfaces subject to less extreme conditions.

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Appendix A: The contribution of the IC 405 nebula to HD 34078 spectra

France et al. (2004) observed the diffuse emission from IC 405 at four positions (their Pos1 to Pos4), two of which (Pos1 and Pos2) are located close to the HD 34078 position (75° offset, E and W respectively). Thus, diffuse emission is certainly present towards HD 34078 itself and may contribute significantly to the flux collected in the FUSE apertures. To estimate this contribution, we retrieved from the FUSE database the spectra obtained at Pos1 to Pos4 (cf. Fig. 1 from France et al. 2004). Pos2 is the brightest region; around 1050 Å, the surface brightness is about 30% larger than at Pos1, indicating spatial variations of this emission. Since Pos1 and Pos2 are symmetrically located with respect to HD 34078, a first order estimate of the diffuse flux towards the star is the average of Pos1 and Pos2 spectra. We thus estimate that the diffuse flux received in the LWRS aperture is about 7% of the HD 34078 flux around $\lambda = 1050$ Å (this fraction decreases with wavelength since the diffuse to stellar flux ratio gets lower at longer wavelengths, as discussed by France et al. 2004). If the surface brightness is locally uniform over the LWRS aperture centred on HD 34078’s position, the contribution of diffuse emission scales linearly with aperture size and should be about 11 times lower in MDRS spectra. Thus, while LWRS spectra of HD 34078 are significantly affected by diffuse emission, the MDRS spectrum should be essentially free of such “pollution”, except possibly at the shortest wavelengths.

To estimate the impact on HD 34078’s LWRS spectra of the contamination by diffuse emission, one needs to examine the
spectrum of the latter (the Pos1 spectrum is displayed in Fig. 7 from France et al. 2004). Although its S/N ratio is limited, it is clear that it differs from that of HD 34078 in two respects. First, narrow lines appear to be fainter and shallower (only the strongest lines are detected); this is due, at least in part, to the lower effective resolution implied by the extented nature of the source. Second, broad H2 lines are narrower, indicating that the average pathlength of scattered photons through the molecular gas is shorter than that followed by direct HD 34078 photons. These two properties of diffuse emission qualitatively explain the peculiarities of the 8th spectrum and indeed, one finds that by combining it and our estimate of the diffuse emission spectrum towards HD 34078, it is possible to reproduce spectra 1 to 7 fairly well. We conclude that the apparent changes in the 8th spectrum can be attributed mainly to a smaller contribution of diffuse emission due to the use of MRDS instead of LWRS in the earlier spectra.

Appendix B: The steady-state bow shock model compared to observations

Extensive work has been performed to describe the geometry and velocity structure of steady-state bow shocks (e.g. van Buren et al. 1990; Mac Low et al. 1991; Wilkin 1996) and in the thin-shell limit, there are simple analytical predictions that can be directly compared to observations.

B.1. Shape and radius of the shell

Assuming that the IR arc detected by France et al. (2007) corresponds to a steady-state bow shock viewed in projection onto the sky, we can first check whether the apparent geometrical properties are consistent with the predicted ones. At first sight, the distance between the star and the apex of the bow shock looks too small compared to its radius of curvature on the Spitzer image but we have to account for projection effects which somewhat influence the appearance of the arc. HD 34078's tangential and radial components (Vt and Vr respectively) are well constrained by observations; we adopt Vt = 100 km s⁻¹ and Vr = +59 km s⁻¹ (in the LSR system; we remeasured the latter value from our own visible spectra). The velocity vector is then inclined by an angle θ = 30° with respect to the plane of the sky (Fig. 14).

To estimate the impact of projection effects on the h/Rp ratio, where h is the apparent standoff distance (h/D = 10–20″ after France et al. 2007, we adopt h/D = 15″ with D = 530 pc, the distance to HD 34078) and Rp is the radius of curvature of the arc as seen in projection on the sky (Rp/D = 37″), we approximate the bow shock geometry by a paraboloid (van Buren et al. 1990; Wilkin 1996) and find after some algebra that

\[
\frac{\sin^2 \theta}{4 \cos \theta} R_0 = h
\]

and

\[
R_p = \frac{3}{2 \cos \theta} R_0,
\]

where Rp is the distance between the star (S) and the apex (A) of the shock. With θ = 30°, we get h = 1.08R0 and h/Rp = 0.62 while the estimate inferred from the IR map is h/Rp = 0.40 (the upper limit is 0.54 for h = 20″). Thus, projection effects appear to be insufficient to explain the relatively large radius of curvature of the arc. Moreover, it seems difficult to explain in this model why the arc does not extend further southward (cf. Fig. 5 in France et al. 2007). Given that projection effects are in the end very limited, the standoff distance can be estimated to be about 0.04 pc.

Although the observed arc shape is not well fitted by the model prediction, the IR data can nevertheless be used to get a rough estimate of the distance between the star and the point where the line of sight intersects the shell (L2 in Fig. 14), by making the reasonable assumption that the latter is axially symmetric. From the 24 μm map, we estimate that d(S, L2)/D > 40″, implying d = 0.10 pc. Is this value compatible with the UV flux necessary to explain the amount of highly excited H2? B05 found that a radiation field about 10^12 larger than that in the local ISM is required, which is obtained at 0.2 pc from the HD 34078, a value in reasonable agreement with our estimate for d(S, L2).

B.2. Momentum balance and ambient density

In steady-state, the standoff distance, R0, is set by a momentum balance equation (Eq. (2) in van Buren et al. 1990; Eq. (1) in Wilkin 1996) which is

\[
R_0 = \sqrt{\frac{m_\star V_0}{4 \pi \rho_\star V_\star}}
\]

where m_\star is the mass loss rate, V_0 the terminal wind velocity (10^{-9.5} M_\odot yr^{-1} and 800 km s^{-1} respectively after Martins et al. 2005), \rho_\star the mass density of the ambient medium and V_\star the star velocity (116 km s^{-1} with the above values for Vt and Vr). The ambient H number density can be estimated either from CIV (n = 700 cm^{-2}; B05) or C2 absorption lines (n = 300 cm^{-3}; Federman et al. 1994), assuming the latter are not significantly contaminated by the dense shell. Adopting n = 500 cm^{-3}, we get a “theoretical” value of R0 = 3.5×10^{-3} pc while observations indicate R0 = 0.04 pc, in marked disagreement. In other words, an ambient density as low as of a few 10^{-2} cm^{-3} would be required for a steady-state bow shock to be at the observed distance, which is highly unrealistic for molecule-rich gas. Radiative pressure from stellar photons might help to maintain the shell at a distance larger than expected on the basis of the wind pressure alone. One can obtain easily an upper limit for the radiative to wind pressure ratio, P_rad/P_w, by assuming that all photons impinging on the shell are absorbed: P_rad/P_w = L/(m_\star c V_w). This ratio is of the order of 10^{-4} for HD 34078; radiation pressure is therefore negligible here.

Since P_{rad} scales linearly with m_\star, one may wonder whether the mass loss rate has been underestimated. Prior to the study by Martins et al. (2005), the adopted value for HD 34078 was 10^{-6.6} M_\odot yr^{-1} (i.e. larger by a factor of 800 than the present estimate) and even with this much higher rate, the required ambient density would amount only to n = 20 cm^{-3}. The much lower recent mass loss estimate is based on the availability of UV lines (CIV, A1550 mainly) which better probe weak winds; the uncertainty on the revised value is estimated to be of a factor of about 3 (F. Martins; private communication). Then, m_\star cannot have been underestimated by a factor large enough to explain the discrepancy between the observed and theoretical steady-state R0 values.

Stationary bow shock models also provide specific predictions for the mass surface density or equivalently the column density N(H) of swept-up material trapped in the bow shock (cf. Eq. (7) from van Buren et al. 1990; or Eq. (12) from Wilkin 1996). N(H) scales as \( m_\star^{1/2} V_0^{1/2} V_\star^{-1} \) and with the values quoted above, we get N(H) = 6.0×10^{22} cm^{-2}. This prediction is
to be compared to the \( H \) column density in the hot PDR component of B05: \( 2.7 \times 10^{19} \text{ cm}^{-2} \), including \( \text{H}_2 \) only (their Table 4). Note that their exceedingly large predicted value for the \( \text{H}_1 \) column density was due to the assumption of steady-state equilibrium for the photodissociation of \( \text{H}_2 \); in our scenario, this assumption is no longer realistic. The observed value corresponds to the dense material along the line of sight to HD 34078 (i.e. located at \( L_2 \) in Fig. 14) while the “theoretical” one refers to the apex position (A in Fig. 14). This does not make a large difference however since Wilkin’s results (his Fig. 4) indicate that the surface density normal to the bow shock varies slowly with position away from the apex. One should also consider that in the geometry of Fig. 14, the shell is not crossed normally by the line of sight but with an inclination angle \( \varphi \). But this involves a factor of at most a few. Obviously, this cannot explain the large discrepancy between the two values above.

In the 24 \( \mu \)m map, the arc defines a roughly hemispherical cavity (with a radius of about \( R_{\text{c}} \)) and one can easily get another estimate for the column density in the compressed shell by simply assuming that material from the ambient cloud (i.e. with \( n = 500 \text{ cm}^{-3} \)) initially filling this cavity has been swept by the stellar wind to form the present shell. This leads to a column density of \( N = n R_c/\varphi \) and interestingly, this expression provides a value, \( N \approx 5 \times 10^{19} \text{ cm}^{-2} \), comparable to the estimate of B05 for the hot PDR component.

### B.3. Velocity field of the compressed gas

Another way to assess whether a steady-state bow-shock model is consistent with our data is to compare the observed and predicted velocity fields. Since \( ^{13}\text{CO}(2–1) \) emission traces dense gas within the shell of compressed gas, our CO data can be used to constrain the velocity field around HD 34078. One may wonder in particular, whether the double-peaked profiles with their remarkable symmetry properties (Fig. 1) simply arise from the fact that the IRAM beam intersects the paraboloidal wind/cloud interface twice. To compute a “synthetic” \( ^{12}\text{CO}(2–1) \) emission map, we adapted the model developed by Pety et al. (2006) to describe the outflow around HH30. We rely on the analytical expressions provided by Wilkin (1996) for the geometry, velocity field and mass surface density (see also van Buren & Mac Low 1992), with the parameter values considered above. For practical reasons, the thickness of the boundary layer has been assumed to be \( R_{\text{b}}/20 \) (while it is zero in Wilkin’s model) and the absolute surface mass density has been scaled so as to reproduce the observed intensity. The underlying assumption is that the medium is optically thin which is reasonable given the strength of the CO emission. The resulting signal model was convolved with the IRAM-30 m 230 GHz beam, an important step given the beam size relative to the source extent. Finally, in order to assess whether a specific model is acceptable or not, we compared the synthetized and observed maps of spectra as well as position–velocity and channel maps.

Several difficulties arise when comparing the model to observations. First, the extent of the \( ^{12}\text{CO}(2–1) \) emission tends to be too limited if one adopts \( R_{\text{b}}/D = 15 \) arcsec. This is related to the fact that the expected radius of curvature is too small for such a \( R_0 \) value, as compared to the observed one (cf. above). Since here we are mainly interested in the velocity field, we simply adjusted \( R_0 \) so as to match the observed extent of the emission. Second, the velocity range over which \( ^{12}\text{CO}(2–1) \) emission appears in the model is much larger than the observed one. Indeed, the velocity field of the gas scales linearly with \( V_c \); in particular, the typical separation \( \Delta V \) between the two CO emission peaks near HD 34078’s position should be of the order of 0.7 \( V_c \) while we observe only 0.02 \( V_c \) (corresponding to about 2 km s\(^{-1}\)). Artificially modifying the star’s velocity to the former value allows us to qualitatively reproduce the emission properties close to the star. However, the double-peeked character of the model profiles tend to be less pronounced that in the observed ones. Other velocity/density distributions might be considered to get a better fit, but clearly, only higher spatial resolution observations would allow us to obtain unambiguous constraints on such models.

Another constraint can be obtained from optical absorption lines arising towards HD 34078. With the parameters quoted above, the expected velocity of the gas from the shell along the sightline to HD 34078 (i.e. at \( L_2 \)) is \( V_{\text{LSR}} \approx -15 \text{ km s}^{-1} \). Such a shift between highly excited \( \text{H}_2 \) lines (tracing the dense layer) and absorption from species located beyond the shell would be easily detectable, but B05 failed to find any significant velocity difference between the two components.

To summarize, the dense shell at the stellar wind/molecular cloud interface (with a density of about \( n \approx 10^4 \text{ cm}^{-3} \) and column density \( N(H) \approx 3 \times 10^{19} \text{ cm}^{-2} \), thus corresponding to a thickness of \( \approx 10^{-3} \text{ pc} \)) is located at a distance of the star that is consistent with the excitation of \( \text{H}_2 \) but it does not display the properties expected for a steady-state bow shock: i) the arc is not curved enough; ii) the shell is too far from the star for the momentum balance to be satisfied; iii) the amount of material swept up by the wind is too large and iv) the velocity field shows very little deviation from the ambient value. The limited extent and somewhat irregular geometry of the arc are additional indications against a steady-state bow shock.

### References

Herbig, G. H. 1958, PASP, 70, 468