HCO mapping of the Horsehead: tracing the illuminated dense molecular cloud surfaces*,**

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ABSTRACT

Context. Far-UV photons (FUV) strongly affect the physical and chemical state of molecular gas in the vicinity of young massive stars.

Aims. Finding molecular tracers of the presence of FUV radiation fields in the millimeter wavelength domain is desirable because IR diagnostics (for instance PAHs) are not easily accessible along high extinction line-of-sights. Furthermore, gas phase diagnostics provide information on the velocity fields.

Methods. We have obtained maps of the HCO and H13CO+ ground state lines towards the Horsehead edge at 5” angular resolution with a combination of Plateau de Bure Interferometer (PdBI) and the IRAM-30-m telescope observations. These maps have been complemented with IRAM-30-m observations of several excited transitions at two different positions.

Results. Bright formyl radical emission delineates the illuminated edge of the nebula, with a faint emission remaining towards the shielded molecular core. Viewed from the illuminated star, the HCO emission almost coincides with the PAH and CCH emission. HCO reaches a similar abundance to HCO+ in the photon dissociation region (PDR), ≃1–2×10^5 with respect to H₂. To our knowledge, this is the highest HCO abundance ever measured. Pure gas-phase chemistry models fail to reproduce the observed HCO abundance by ∼2 orders of magnitude, except if reactions of atomic oxygen with carbon radicals abundant in the PDR (i.e., CH₂) play a significant role in the HCO formation. Alternatively, HCO could be produced in the PDR by non-thermal processes such as photo-processing of ice mantles and subsequent photo-desorption of either HCO or H2CO, and further gas phase photodissociation.

Conclusions. The measured HCO/H²CO+ abundance ratio is large towards the PDR (≥50), and much lower toward the gas shielded from FUV radiation (≤1). We propose that high HCO abundances (≥10^16) together with large HCO/H²CO+ abundance ratios (≥1) are sensitive diagnostics of the presence of active photochemistry induced by FUV radiation.

Key words. astrochemistry – ISM: clouds – ISM: molecules – ISM: individual objects: Horsehead nebula – radiative transfer – radio lines: ISM

1. Introduction

Photodissociation region (PDR) models are used to understand the evolution of far-UV (FUV; hv < 13.6 eV) illuminated matter both in our Galaxy and in external galaxies. These sophisticated models have been benchmarked Röllig et al. (2007) and are continuously upgraded (e.g., Goicoechea & Le Bourlot 2007; González-García et al. 2008). Given the large number of physical and chemical processes included in such models, it is necessary to build reference data sets that can be used to test the predictive accuracy of models. Our team has contributed to this goal by providing a series of high resolution interferometric observations of the Horsehead nebula (see Pety et al. 2007b, for a summary). Indeed, this source is particularly well suited because of its favorable orientation and geometry, and its moderate distance (∼400 pc; Habart et al. 2005). We have previously studied the carbon (Teyssier et al. 2004; Pety et al. 2005) and sulfur chemistry (Goicoechea et al. 2006) of the nebula, and detected the presence of a cold dense core, with active deuterium fractionation (Pety et al. 2007a).

The formyl radical, HCO, is known to be present in the interstellar medium since the late 1970’s Snyder et al. (1976). Snyder et al. (1985) give a detailed description of the HCO structure and discuss the energy diagram for the lowest energy levels. HCO is a bent tritatomic asymmetric top with an unpaired electron. a-type and b-type transitions are allowed, with a stronger dipole moment (1.36 Debye) for the a-type transitions Landsberg et al. (1977), which are therefore more easily detectable. The strongest HCO ground state transitions lie at 86.670, 86.708, 86.777 and 86.805 GHz, very close to the ground state transition of H²CO+ and to the first rotationally excited SiO line. Therefore HCO can be observed simultaneously with SiO and H²CO+. HCO ground state lines have been detected in the Orion Bar as well as in the dense PDRs NGC 2023, NGC 7023 and S 140 Schilke et al. (2001). From limited mapping, they have shown that HCO is
Table 1. Observation parameters for the maps shown in Figs. 1 and 5. The projection center of all the maps is $\alpha_{2000} = 05^h40^m54.27^s$, $\delta_{2000} = -02^\circ28'00''$.

| Molecule | Transition | Frequency GHz | Instrument | Config. | Beam arcsec | PA $^\circ$ | Vel. Resol. km s$^{-1}$ | Int. Time $^a$ h | $T_{sys}^b$ K | Noise $^a$ mK | Obs. date |
|----------|------------|---------------|------------|---------|-------------|-----------|-----------------|----------------|-------------|------------|----------|
| H$^13$CO$^+$ | 1–0 | 86.754288 | PdBI | C & D | 6.76 x 4.65 | 13 | 0.2 | 6.5 | 150 | 0.10 | 2006–2007 |
| HCO | 1,0/1, 2–0,0 | 86.670760 | PdBI | C & D | 6.69 x 4.39 | 16 | 0.2 | 6.5 | 150 | 0.09 | 2006–2007 |
| CCH | 1,3/2–0,1/2/1 | 87.316925 | PdBI | C & D | 7.24 x 4.99 | 54 | 0.2 | 6.9 | 130 | 0.07 | 2002–2003 |

$^a$ On-source time computed as if the source were always observed with 6 antennas. $^b$ The noise values quoted here are the values at the mosaic phase center (Mosaic noise is inhomogeneous due to primary beam correction; it steeply increases at the mosaic edges).

Table 2. Observation parameters for the HCO deep integrations shown in Fig. 1. Associated transitions can be found in Table 3. The RA and Dec offsets are computed with reference to $\alpha_{2000} = 05^h40^m54.27^s$, $\delta_{2000} = -02^\circ28'00''$. The positions are also given in the coordinate system used to display the maps in Figs. 1 and 5. In this coordinate system, maps are rotated by $14^\circ$ counter-clockwise around the projection center, located at $(\delta_x, \delta_y) = (20^\circ, 0^\circ)$, to bring the illuminated star direction in the horizontal direction and the horizontal zero has been set at the PDR edge.

| Position | Frequency GHz | Line area$^a$ K km s$^{-1}$ | Instrument | $F_{\text{eff}}$ | $B_{\text{eff}}$ | Resol. arcsec | Resol. km s$^{-1}$ | Int. Time$^c$ h | $T_{\text{sys}}^b$ K | Noise mK | Obs. date |
|----------|---------------|-----------------|------------|-------------|------------|----------------|-----------------|----------------|-------------|-----------|----------|
| “DCO$^+$ peak” | 86.670760 | 0.23 ± 0.009 | 30 m/AB100 | 0.95 | 0.78 | 28.4 | 0.27 | 0.75/1.5 | 134 | 11 | 2008 |
| “HCO peak” | 86.670760 | 0.12 ± 0.009 | 30 m/AB100 | 0.95 | 0.78 | 28.4 | 0.27 | 0.75/1.5 | 134 | 11 | 2008 |
| “HCO peak” | 86.708360 | 0.52 ± 0.008 | 30 m/AB100 | 0.95 | 0.78 | 28.4 | 0.27 | 0.75/1.5 | 127 | 10 | 2008 |
| “HCO peak” | 173.377770 | 0.47 ± 0.023 | 30 m/C150 | 0.93 | 0.65 | 14.2 | 0.067 | 2.0/4.0 | 667 | 66 | 2008 |
| “HCO peak” | 173.4060816 | 0.26 ± 0.018 | 30 m/C150 | 0.93 | 0.65 | 14.2 | 0.067 | 2.0/4.0 | 667 | 66 | 2008 |
| “HCO peak” | 173.4406648 | 0.23 ± 0.020 | 30 m/C150 | 0.93 | 0.65 | 14.2 | 0.067 | 2.0/4.0 | 667 | 66 | 2008 |
| “HCO peak” | 260.063290 | 0.16 ± 0.019 | 30 m/C270 | 0.88 | 0.46 | 9.5 | 0.18 | 3.0/6.0 | 740 | 59 | 2008 |
| “HCO peak” | 260.0821920 | 0.14 ± 0.020 | 30 m/C270 | 0.88 | 0.46 | 9.5 | 0.18 | 3.0/6.0 | 740 | 59 | 2008 |
| “HCO peak” | 260.1358580 | 0.12 ± 0.017 | 30 m/C270 | 0.88 | 0.46 | 9.5 | 0.18 | 3.0/6.0 | 740 | 59 | 2008 |
| “HCO peak” | 260.1557690 | 0.06 ± 0.016 | 30 m/C270 | 0.88 | 0.46 | 9.5 | 0.18 | 3.0/6.0 | 740 | 59 | 2008 |

$^a$ Values obtained from Gaussian fits performed on the spectra using the main beam temperature scale. $^b$ Two values are given for the integration time: the on-source time and the telescope time.

The noise values quoted here are the values at the mosaic phase center (Mosaic noise is inhomogeneous due to primary beam correction; it steeply increases at the mosaic edges).

Table 2. Observation parameters for the HCO deep integrations shown in Fig. 1. Associated transitions can be found in Table 3. The RA and Dec offsets are computed with reference to $\alpha_{2000} = 05^h40^m54.27^s$, $\delta_{2000} = -02^\circ28'00''$. The positions are also given in the coordinate system used to display the maps in Figs. 1 and 5. In this coordinate system, maps are rotated by $14^\circ$ counter-clockwise around the projection center, located at $(\delta_x, \delta_y) = (20^\circ, 0^\circ)$, to bring the illuminated star direction in the horizontal direction and the horizontal zero has been set at the PDR edge.

2. Observations and data reduction
Tables 1 and 2 summarize the observation parameters for the data obtained with the IRAM PdBI and 30 m telescopes. The HCO ground state lines were observed simultaneously with H$^13$CO$^+$ and SiO. Frequency-switched, on-the-fly maps of the H$^13$CO$^+$ $J = 1–0$ and HCO ground state lines (see Fig. 5), obtained at the IRAM-30m using the A100 and B100 3 mm receivers (~7 mm of water vapor) were used to produce the short-splittings needed to complement a 7-field mosaic acquired with the 6 PdBI antennas in the CD configuration (baseline lengths from 24 to 176 m). The whole PdBI data set will be comprehensively described in a forthcoming paper studying the
fractional ionization across the Horsehead edge (Goicoechea et al. 2009). The CCH data shown in Fig. 1 have been extensively described in Pety et al. (2005). The high resolution HCO $1_{0,1-0,0}$ data are complemented by observations of the $2_{0,2-1_{0,1}}$ and $3_{0,3-2_{0,2}}$ multiplets with the IRAM 30 m telescope centered on the PDR and the dense core. To obtain those deep integration spectra, we used the position switching observing mode. The on-off cycle duration was 1 min and the off-position offsets were $(\delta RA, \delta Dec) = (-100'', 0'')$, i.e. the H II region ionized by $\sigma$Ori and free of molecular emission. Position accuracy is estimated to be about $3''$ for the 30 m data and less than $0.5''$ for the PdBI data.

The data processing was done with the GILDAS$^1$ softwares (Pety 2005b). The IRAM-30 m data were first calibrated to the $T_A^*$ scale using the chopper wheel method (Penzias & Burrus 1973), and finally converted to main beam temperatures ($T_{mb}$) using the forward and main beam efficiencies ($F_{off}$ & $B_{mb}$) displayed in Table 2. The resulting amplitude accuracy is $\sim10\%$. Frequency-switched spectra were folded using the standard shift-and-add method, after baseline subtraction. The resulting spectra were finally gridded through convolution by a Gaussian. Position-switched spectra were co-added before baseline subtraction. Interferometric data and short-spacing data were merged before imaging and deconvolution of the mosaic, using standard techniques of GILDAS (see e.g. Pety et al. 2005, for details).

3. Results and discussion

3.1. Spatial distribution

Figure 1 shows a map of the integrated intensity of the strongest HCO line at 86.671 GHz, of the $\text{H}^{13}\text{C}^+ \text{O}^*$ $J = 1-0$ line and of the strongest CCH line at 87.317 GHz. Figure 2 displays high signal-to-noise ratio spectra of several hyperfine components of three HCO rotational transitions towards the HCO and the DCO$^+$ emission peaks.

Most of the formyl radical emission is concentrated in a narrow structure, delineating the edge of the Horsehead nebula.

Low level emission is however detected throughout the nebula, including towards the dense core identified by its strong DCO$^+$ and H$^{13}\text{C}^+\text{O}^*$ emission (Pety et al. 2007a). The HCO emission is resolved by our PdBI observations. From 2-dimensional Gaussian fits of the image, we estimate that the emission width is $\sim 13 \pm 4''$ in the plane of the sky. The $\text{H}^{13}\text{C}^+\text{O}^*$ emission shows a different pattern: most of the signal is associated with the dense core behind the photodissociation front, and faint $\text{H}^{13}\text{C}^+\text{O}^*$ emission detected in the illuminated edge. The CCH emission pattern is less extreme than HCO, but shows a similar enhancement in the PDR.

In summary, the morphology of the HCO emission is reminiscent of the emission of the PDR tracers, either the PAH emission (Abergel et al. 2002) or the emission of small hydrocarbons, which is strongly enhanced towards the PDR (Teyssier et al. 2004; Pety et al. 2005). In contrast, the HCO emission becomes very faint where the gas is dense and shielded from FUV radiation. These regions are associated with bright DCO$^+$ and H$^{13}\text{C}^+\text{O}^*$ emission (Pety et al. 2007a). Our maps therefore confirm that HCO is a PDR species.

3.2. Column densities and abundances

3.2.1. Radiative transfer models of HCO and $\text{H}^{13}\text{C}^+\text{O}^*$

Einstein coefficients and upper level energies of the studied HCO and $\text{H}^{13}\text{C}^+\text{O}^*$ lines are given in Table 3. As no collisional sections with H$_2$ nor He have been calculated for HCO so far, we have computed the HCO column densities assuming a single excitation temperature $T_{ex}$ for all transitions. Nevertheless our calculation takes into account thermal, turbulent and opacity broadening as well as the cosmic microwave background and line opacity (Goicoechea et al. 2006). For $\text{H}^{13}\text{C}^+\text{O}^*$, detailed non-local and non-LTE excitation and radiative transfer calculations have been performed using the same approach as in our previous PdBI CS and C$^{18}$O line analysis (see Appendix in Goicoechea et al. 2006). $\text{H}^{13}\text{C}^+\text{O}^*$-H$_2$ collisional rate coefficients were adapted from those of Flower (1999) for HCO$^*$, and specific $\text{H}^{13}\text{C}^+\text{O}^*$-electron rates where kindly provided by Faure & Tennyson (in prep.).
Table 3. Einstein coefficients and upper level energies.

| Molecule | Transition | Frequency (GHz) | $A_{ij}$ (s$^{-1}$) | $E_{up}$ (K) |
|----------|------------|----------------|-------------------|--------------|
| HCO      | $J_{101-000}$ | 3/2, 2–1/2, 1 | 86.670760          | 4.69 × 10$^{-6}$ | 4.2           |
|          |            | 3/2, 1–1/2, 0 | 86.708360          | 4.60 × 10$^{-6}$ | 4.2           |
|          |            | 1/2, 1–2/0     | 86.777460          | 4.61 × 10$^{-6}$ | 4.2           |
|          |            | 1/2, 0–1/2, 1  | 86.805780          | 4.71 × 10$^{-6}$ | 4.2           |
|          | $J_{202-101}$ | 5/2, 3–3/2, 2  | 173.377370         | 4.51 × 10$^{-3}$ | 12.5          |
|          |            | 5/2, 2–3/2, 1  | 173.406816         | 4.43 × 10$^{-3}$ | 12.5          |
|          |            | 3/2, 2–1/2, 1  | 173.443064         | 3.39 × 10$^{-3}$ | 12.5          |
|          | $J_{303-202}$ | 7/2, 4–5/2, 3  | 260.0603290        | 1.63 × 10$^{-4}$ | 25.0          |
|          |            | 7/2, 3–5/2, 2  | 260.0821920        | 1.61 × 10$^{-4}$ | 25.0          |
|          |            | 5/2, 3–3/2, 1  | 260.133860         | 1.45 × 10$^{-4}$ | 25.0          |
|          |            | 5/2, 2–3/2, 1  | 260.157690         | 1.37 × 10$^{-4}$ | 25.0          |
| H$^{13}$CO$^+$ | $J = 1$ | 93/2         | 86.754288         | 3.2 × 10$^{-5}$ | 4.2           |
|          | $J = 3$   | 260.2553390  | 1.3 × 10$^{-5}$   | 25.0          |

The line frequencies and intensities were extracted from the JPL Pickett et al. (1998) and CDMS Müller et al. 2001, 2005 molecular spectroscopy data bases for HCO and H$^{13}$CO$^+$ respectively.

3.2.2. Structure of the PDR in HCO and H$^{13}$CO$^+$

For more insight into the spatial variation of the HCO and H$^{13}$CO$^+$ column densities and abundances, we have analyzed a cut through the PDR, centered on the “HCO peak” at δy = 0′′ (see Fig. 3). The cut clearly shows that HCO is brighter than H$^{13}$CO$^+$ in the PDR and vice-versa in the dense core. Taking into account the different level degeneracies of both transitions (a factor of 2.4) and the fact that the associated Einstein coefficients $A_{ij}$ differ by a factor ∼8 (due to the different permanent dipole moments, see Table 3), $N$(H$^{13}$CO$^+$) must be significantly lower than $N$(HCO) towards the PDR.

We modeled the PDR as an edge-on cloud inclined by ∼5° relative to the line-of-sight. We have chosen a cloud depth...
of ~0.1 pc, which implies an extinction of $A_V \approx 20$ mag for the considered densities towards the "HCO peak". These parameters are the best geometrical description of the Horsehead PDR-edge (e.g., Habart et al. 2005) and also reproduce the observed 1.2 mm continuum emission intensity. The details of this modeling will be presented in Goicoechea et al. (2009). In the following, we describe in detail the determination of the column densities and abundances for two particular positions, namely the "HCO peak" and the "DCO peak" (offsets relative to the map center can be found in Table 2).

3.2.3. HCO column densities

We used the three detected rotational transitions of HCO (each with several hyperfine components, see Fig. 2) to estimate the HCO column densities in the direction of the "HCO peak". We have taken into account the varying beam dilution factors of the HCO emission at the "HCO peak" by modeling the HCO emission as a Gaussian filament of ~12'' width in the $\delta \theta$ direction, and infinite in the $\delta \phi$ direction. The filling factors at 260, 173 and 87 GHz are thus ~0.8, 0.6 and 0.4, respectively.

A satisfactory fit of the IRAM-30 m data towards the "HCO peak" is obtained for $T_{\text{ex}} \approx 5$ K and a turbulent velocity dispersion of $\sigma = 0.225$ km s$^{-1}$ (FWHM = 2.355 $\times$ $\sigma$). Line profiles are reproduced for $N($HCO$) = 3.2 \times 10^{13}$ cm$^{-2}$ (see red solid curves in Fig. 2). The most intense HCO lines at 86.67 and 173.38 GHz become marginally optically thick at this column density ($\tau \gtrsim 1$). Therefore, opacity corrections need to be taken into account. We checked that the low value of $T_{\text{ex}}$ (subthermal excitation as $T_{\text{ex}} \approx 60$ K) is consistent with detailed excitation calculations carried out for H$^{13}$CO$^+$ in the PDR which are described below.

Because the HCO signals are weaker towards the "DCO peak", we only detected 2 hyperfine components of the $1_{01}\rightarrow 0_{00}$ transition. Assuming extended emission and the same excitation temperature as for the "HCO peak", 5 K, we fit the observed lines with a column density of $4.6 \times 10^{12}$ cm$^{-2}$ (blue solid lines in Fig. 2). Both HCO lines are optically thin at this position. This simple analysis shows that the HCO column density is ~7 times larger at the "HCO peak" in the PDR, than towards the dense cold core.

3.2.4. H$^{13}$CO$^+$ column densities

Both the H$^{13}$CO$^+$ $J = 3\rightarrow 2$ and $1\rightarrow 0$ line profiles at the "HCO peak" are fitted with $N($H$^{13}$CO$^+)$ $\approx 5 \times 10^4$ cm$^{-3}$, $T_{\text{ex}} \approx 60$ K and e$^{-}/H \approx 5 \times 10^{-5}$ (as predicted by the PDR models below). The required column density is $N($H$^{13}$CO$^+)$ $\approx 5.8 \times 10^{11}$ cm$^{-2}$. For those conditions, the excitation temperature, $T_{\text{ex}}$, of the $J = 3\rightarrow 2$ transition varies from $\approx 4$ to 6 K, which supports the single-$T_{\text{ex}}$ models of HCO. Both H$^{13}$CO$^+$ lines are optically thin towards the "HCO peak".

The H$^{13}$CO$^+$ line emission towards the "DCO peak" has been studied by Petry et al. (2007a). Both H$^{13}$CO$^+$ lines are moderately optically thick towards the core, and the H$^{13}$CO$^+$ column density is $N($H$^{13}$CO$^+)$ $\approx 5.0 \times 10^{12}$ cm$^{-2}$, which represents an enhancement of nearly one order of magnitude relative to the PDR. According to our 1.2 mm continuum map, the extinction towards the core is $A_V \approx 30$ mag compared to 20 mag in the PDR. The H$^{13}$CO$^+$ column density enhancement therefore corresponds to a true abundance enhancement.

### Table 4. Inferred column densities and abundances with respect to molecular hydrogen, e.g. $\chi(X) = N(X)/N(H_2)$.

| Molecule | Method | HCO peak | DCO peak |
|----------|--------|----------|----------|
| $N(H_2)$ [cm$^{-2}$] | $T_{\text{ex}} = 5$ K | 3.2 $\times$ 10$^{13}$ | 4.6 $\times$ 10$^{12}$ |
| $N($HCO$)$ [cm$^{-2}$] | Full excitation | 5.8 $\times$ 10$^{11}$ | 5.0 $\times$ 10$^{12}$ |
| $N($H$^{13}$CO$^+)$ [cm$^{-2}$] | $^{12}$C/$^{13}$C = 60 | 3.5 $\times$ 10$^{13}$ | 5.0 $\times$ 10$^{13}$ |
| $\chi($HCO$)$ | | 1.7 $\times$ 10$^{-9}$ | 1.6 $\times$ 10$^{-10}$ |
| $\chi($H$^{13}$CO$^+)$ | | 3.1 $\times$ 10$^{-11}$ | 1.7 $\times$ 10$^{-10}$ |
| $\chi($DCO$^+$) | | 1.8 $\times$ 10$^{-9}$ | 1.0 $\times$ 10$^{-8}$ |

Petry et al. (2007a). * 1.7 $\times$ 10$^{-9}$ if HCO arises only from the cloud surface ($A_V \approx 3$).

3.2.5. Comparison of HCO and H$^{13}$CO$^+$ abundances

Table 4 summarizes the inferred HCO and H$^{13}$CO$^+$ column densities and abundances towards the 2 selected positions: the "HCO peak" in the PDR and the "DCO peak" in the FUV-shielded core. Both species exhibit strong variations of their column densities and abundances relative to H$_2$ between the PDR and the shielded region. In the PDR, we found that the HCO abundance relative to H$_2$ ($\chi($HCO$) \approx 1$–$2 \times 10^{-9}$) and the HCO/H$^{13}$CO$^+$ column density ratio ($\approx 50$) are high. These figures are higher than all previously published measurements (at lower angular resolution). Besides, the formyl radical and HCO$^+$ reach similar abundances in the PDR.

The situation is reversed towards the "DCO peak", i.e. the observed HCO/H$^{13}$CO$^+$ column density ratio is lower ($\approx 1$) than towards the "HCO peak". Nevertheless, while the bulk of the observed H$^{13}$CO$^+$ emission arises from cold and shielded gas, the origin of HCO emission is less clear. HCO could either (i) co-exist with H$^{13}$CO$^+$ or (ii) arise predominantly from the line-of-sight cloud surface. In the former case, our observations show that the HCO abundance drops by one order of magnitude between the PDR and the dense core environment. However, it is possible that the abundance variation is even more pronounced, if the detected HCO emission arises from the line of sight surface. We have estimated the depth of the cloud layer, assuming that HCO keeps the "PDR abundance" in this foreground layer: a cloud surface layer of $A_V \approx 3$ (illuminated by the mean FUV radiation field around the region) also reproduces the observed HCO lines towards the cold and dense core (blue solid lines in Fig. 2).

In this case, both the HCO abundance and the HCO/H$^{13}$CO$^+$ abundance ratio in the dense core itself will be even lower than listed in Table 4. We have tried to discriminate between the scenarios by comparing the HCO $1_{01}\rightarrow 0_{00}$ ($J = 3\rightarrow 2$, $F = 2\rightarrow 1$) and H$^{13}$CO$^+$ $J = 1\rightarrow 0$ line profiles towards this position. Both lines have been observed simultaneously with the IRAM-30 m telescope. Because of their very similar frequencies (~86.7 GHz), the beam profile and angular resolution is effectively the same. In this situation, any difference in the measured linewidths reflects real differences in the gas kinematics and turbulence of the regions where the line profiles are formed. Gaussian fits of the HCO and H$^{13}$CO$^+$ lines towards the "DCO peak" provides line widths of $\Delta v($HCO$) = 0.81 \pm 0.06$ km s$^{-1}$ and $\Delta v($H$^{13}$CO$^+)$ = 0.60 $\pm 0.01$ km s$^{-1}$. Therefore, even if the H$^{13}$CO$^+$ $J = 1\rightarrow 0$ lines are slightly broadened by opacity and do not represent the true line of sight velocity dispersion, HCO lines are broader at the 3$\sigma$ level of confidence. This remarkable difference supports the scenario (ii) where the H$^{13}$CO$^+$ line...
emission towards the “DCO+ peak” arises from the quiescent, cold and dense core, whereas HCO, in the same line of sight, arises predominantly from the warmer and more turbulent outer cloud layers. We note that the presence of a foreground layer of more diffuse material (ΔV ~ 2 mag) was already introduced by Goicoechea et al. (2006) to fit the CS J = 2−1 scattered line emission. The analysis of CO J = 4−3 and CI J = 1−0 maps led Philipp et al. (2006) to propose the presence of a diffuse envelope, with ΔV ~ 2 mag, and which contributes to about half the mass of the dense filament traced by C18O and the dust continuum emission. The hypothesis of a surface layer of HCO is therefore consistent with previous modeling of molecular emission of the Horsehead.

We conclude 1) that HCO and HCO+ have similar abundances in the PDR; and 2) that the HCO abundance drops by at least one order of magnitude between the dense and warm PDR region and the cold and shielded DCO+ core.

4. HCO chemistry

4.1. Gas-phase formation: PDR models

In order to understand the HCO and H13CO+ abundances and HCO/H13CO+ column density ratio inferred from observations, we have modeled the steady state gas phase chemistry at the Horsehead edge. The density distribution in the PDR is well represented by a density gradient nH(Δx) ∝ Δx^2, where Δx is the distance from the edge towards the cloud interior and nH = n(H) + 2n(H2) (see the top panels of Fig. 4). The density reaches a constant nH value of 2 × 10^5 cm^-3 in an equivalent length of ~10". Habart et al. (2005); Goicoechea et al. (2006). The cloud edge is illuminated by a FUV field 60 times the mean interstellar radiation field (G0 ~ 60 in Draine units). We used the Neudorner PDR code2, a photochemical model of a unidimensional PDR (see Le Bourlot et al. 1993; Le Petit et al. 2006; Goicoechea & Le Bourlot 2007, for a detailed description). Our standard chemical network is based on a modified version of the Ohio State University (osu) gas-phase network, updated for photochemical studies (see Goicoechea et al. 2006). It also includes 13C fractionation reactions Graedel et al. (1982) and specific computation of the H13CO photodissociation reaction as a function of depth. The ionization rate due to cosmic rays in the models is ζ = 5 × 10^{-17} s^{-1}. Following our previous work, we chose the following elemental gas phase abundances: He/H = 0.1, O/H = 3 × 10^{-4}, C/H = 1.4 × 10^{-4}, N/H = 8 × 10^{-5}, S/H = 3.5 × 10^{-6}, 13C/H = 2.3 × 10^{-6}, Si/H = 1.7 × 10^{-8} and Fe/H = 1.0 × 10^{-9}.

In Fig. 4, we investigate the main gas-phase formation routes for HCO in a series of models “testing” different pathways leading to the formation of HCO. HCO and H13CO+ predictions are shown in Fig. 4 (middle panels). In all models the HCO abundance peaks near the cloud surface at AV ≈ 1.5 (dx ≈ 14") where the ionization fraction is high (e^-/H ~ 5 × 10^{-5}). Due to the low abundance of metals in the model (as represented by the low abundance of Fe), the ionization fraction in the shielded

Fig. 4. Photochemical models of a unidimensional PDR. Upper panels show the density gradient (nH = n(H) + 2n(H2) in cm^-3) used in the calculation. Middle panels show the predicted HCO and H13CO+ abundances (relative to nH). The H13CO+ abundance inferred from observations in the cold core (“the DCO+ peak”, see the offsets in Table 2) is shown with blue lines. The HCO abundance inferred from observations in the PDR (“the HCO peak”, see the offsets in Table 2) is shown with red lines. Lower panels show the HCO/H13CO+ abundance ratio predicted by the models whereas the HCO/H13CO+ column density ratio inferred from observations is shown as blue arrows and red lines (for the cold core and PDR respectively). Each panel compares two different models: left-side models show a standard chemistry (dashed curves) versus the same network upgraded with the addition of the H2CO + photon → HCO + H photodissociation (solid curves). Right-side models show the previous upgraded standard model (solid curves) versus a chemistry that adds the O + CH2 reaction has almost no effect on H13CO+ for the physical conditions prevailing in the Horsehead, but triggers an increases of the HCO abundance in the PDR by two orders of magnitude.

2 Publicly available at http://aristote.obspm.fr/MIS/
regions is low ($e^-/H \lesssim 10^{-8}$), and therefore the H$^{13}$CO$^+$ predictions matches the observed values (Goicoechea et al. 2009). Besides, a low metalicity reduces the efficiency of charge exchange reactions of HCO with metals, e.g.,

$$\text{Fe} + \text{HCO}^+ \rightarrow \text{HCO} + \text{Fe}^+ \quad \text{(1)}$$

which are the main gas-phase formation route of HCO in the FUV-shielded gas in our models. Hence, the HCO abundance remains low inside the core. Nevertheless, even though such models do reproduce the observed HCO distribution, which clearly peaks at the PDR position, the predicted absolute HCO abundances can vary by orders of magnitude depending of the dominant formation route.

In our standard model (left-side models: dashed curves), the formation of HCO in the PDR is dominated by the dissociative recombination of H$_2$CO, while its destruction is dominated by photodissociation. Even if the predicted HCO/H$^{13}$CO$^+$ abundance ratio satisfactorily reproduces the value inferred from observations, the predicted HCO abundance peak is $\sim$3 orders of magnitude lower than observed. In order to increase the gas-phase formation of the HCO in the PDR we have added a new channel in the photodissociation of formaldehyde, the production HCO, in addition to the normal channel producing CO:

$$\text{H}_2\text{CO} + \text{photon} \rightarrow \text{HCO} + \text{H} \quad \text{(2)}$$

This channel is generally not included in standard chemical networks but very likely exists Troe (2007); Yin et al. (2007). We included this process with an unattenuated photodissociation rate of $k_{\text{diss}}(\text{H}_2\text{CO}) = 10^{-9}$ s$^{-1}$ and a depth dependence given by $\exp(-1.74A_V)$. This is the same rate as the one given by van Dishoeck (1988) for the photodissociation of H$_2$CO producing CO, which is explicitly calculated for the Draine (1978) radiation field. Model results are shown in Fig. 4 (left-side models: solid curves). The inclusion of Reaction 2, which becomes the dominant HCO formation route, increases the HCO abundance in the PDR by a factor of $\sim$5. But the HCO production rate is still too low to reproduce the abundance determined from observations.

Another plausible possibility to increase the HCO abundance in the PDR by pure gas-phase processes is to include additional reactions of atomic oxygen with carbon radicals that reach high abundances only in the PDR. Among the investigated reactions, the most critical one,

$$\text{O} + \text{CH}_2 \rightarrow \text{HCO} + \text{H} \quad \text{(3)}$$

is known to proceed with a relatively fast rate at high temperatures ($5.01 \times 10^{-11}$ cm$^3$ s$^{-1}$ at $T_k = 1200–1800$ K; Tsuibo & Hashimoto 1981). This is the rate recommended by NIST Mallard et al. (1994) and UMIST2006 Woodall et al. (2007) and that we adopt for our lower temperature domain (10–200 K). Model predictions are shown in Fig. 4 (right-side models: dotted curves). While the predicted HCO abundance in the shielded gas remains almost the same, the HCO abundance is dramatically increased in the PDR (by a factor of $\sim$125) and the O + CH$_2$ reaction becomes the HCO dominant production reaction. Therefore, such a pure gas-phase model adding reactions 2 and 3 not only reproduces the H$^{13}$CO$^+$ abundance in the shielded core,
but also reproduces the observed HCO absolute abundances in the PDR. In this picture, the enhanced HCO abundance that we observe in the Horsehead PDR edge would be fully determined by the gas-phase chemical path:

\[ \text{C}^+ + \text{CH}_2 \rightarrow \text{CH}_2^+ \rightarrow \text{CH}_2 \rightarrow \text{HCO}. \]  

(4)

The validity of the rate of Reaction 3 used in our PDR model remains, of course, to be confirmed theoretically or experimentally at the typical ISM temperatures (10 to 200 K).

4.2. Other routes for HCO formation: Grain photodesorption

If Reaction 3 is not included in the chemical network, the predicted HCO abundance is ~2 orders of magnitude below the observed value towards the PDR. As a consequence, the presence of HCO in the gas-phase should be linked to grain mantle formation routes, and subsequent desorption processes (not taken into account in our modeling). In particular, Schilke et al. (2001) proposed that HCO could result from H2CO photodissociation, if large quantities of formaldehyde are formed on grain mantles and then released in the gas phase. Even with this assumption, their model could not reproduce the observed HCO abundance in highly illuminated PDRs such as the Orion Bar. The weaker FUV-radiation field in the Horsehead, but high density, prevent dust grains from acquiring high temperatures over large spatial scales. In fact, both gas and grains cool down below ~30 K in ~10°−20° (or AV = 1−2) as the FUV-radiation field is attenuated. Therefore, thermal desorption of dust ice-mantles (presumably formed before σ-Orionis initiated and started to illuminate the nebula) should play a negligible role. Hence a non-thermal desorption mechanism should be considered to produce the high abundance of HCO observed in the gas phase. This mechanism could either produce HCO directly or a precursor molecule such as formaldehyde.

Since high HCO abundances are only observed in the PDR, FUV induced ice-mantle photo-desorption (with rates that roughly scale with the FUV-radiation field strength) seems the best candidate (e.g., Willacy & Williams 1993; Bergin et al. 1995). Laboratory experiments have shown that HCO radicals are produced in irradiated, methanol containing, ice mantles Bernstein et al. (1995); Moore et al. (2001); Bennett & Kaiser (2007). The formyl radical could be formed through the hydrogenation of CO in the solid phase. It is an important intermediate radical in the synthesis of more complex organic molecules such as methyl formate or glycolaldehyde Bennett & Kaiser (2007). However, the efficiency of the production of radicals in FUV irradiated ices remains uncertain, and very likely depends on the ice-mantle composition. The formation of species like formaldehyde and methanol in CO-ice exposed to H-atom bombardment has been reported by different groups Hiraoka et al. (1994); Watanabe et al. (2002); Linnartz et al. (2007), further confirming the importance of HCO as an intermediate product in the synthesis of organic molecules in ices. Indeed, hydrogenation reactions of CO-ice, which form HCO, H2CO, CH3O and CH3OH in grain mantles (e.g., Tielens & Whittet 1997; Charnley et al. 1997), are one important path which warrants further studies.

To compare with our observations, we further need to understand how the radicals are released in the gas phase, either directly during the photo-processing, or following FUV induced photo-desorption. Recent laboratory measurements have started to shed light on the efficiency of photo-desorption, which depends on the ice composition and molecule to be desorbed. For species such as CO, the rate of photo-desorbed molecules per FUV photon is much higher than previously thought (e.g., Öberg et al. 2007). Similar experiments are required to constrain the formation rate of the various species that can form in interstellar ices and to determine their photo-desorption rates.

We can use the measured gas phase abundance of HCO to constrain the efficiency of photo-desorption. We assume that the PDR is at steady state, and that the main HCO formation mechanism is non thermal photo-desorption from grain mantles (with a Fν(HCO) rate), while the main destruction mechanism is gas-phase photodissociation (with a Dν(HCO) rate), therefore:

\[ D_{\text{HCO}} = G_0 \kappa_{\text{diss}}(\text{HCO}) \chi(\text{HCO}) n(\text{H}_2) \text{ [cm}^{-3}\text{s}^{-1}] \]  

(5)

\[ F_{\text{HCO}} = G_0 \kappa_{\text{pd}}(\text{HCO}) \chi(\text{HCO}_\text{ice}) \frac{n(\text{H}_2\text{O}_\text{ice})}{n(\text{H}_2)} n(\text{H}_2) \text{ [cm}^{-3}\text{s}^{-1}] \]  

(6)

where \( \chi(\text{HCO}) \) is the gas phase abundance of HCO relative to H2, \( \chi(\text{HCO}_\text{ice}) \) is the solid phase abundance relative to water ice, and \( n(\text{H}_2\text{O}_\text{ice})/n(\text{H}_2) \) is the fraction of water in the solid phase relative to the total gas density. \( \kappa_{\text{diss}}(\text{HCO}) \) and \( \kappa_{\text{pd}}(\text{HCO}) \) are the HCO photodissociation and photo-desorption rates respectively.

By equaling the formation and destruction rates, we get:

\[ \kappa_{\text{pd}}(\text{HCO}) = \kappa_{\text{diss}}(\text{HCO}) \frac{\chi(\text{HCO})}{\chi(\text{HCO}_\text{ice})} \frac{n(\text{H}_2)}{n(\text{H}_2\text{O}_\text{ice})} \text{ [cm}^{-3}\text{s}^{-1}] \]  

(7)

or

\[ \frac{\kappa_{\text{pd}}(\text{HCO})}{s^{-1}} \approx 10^{-12} \frac{\kappa_{\text{diss}}(\text{HCO})}{10^{-9}} \frac{\chi(\text{HCO})/10^{-9}}{\chi(\text{HCO}_\text{ice})/10^{-2}} \frac{10^{-4}n(\text{H}_2)}{n(\text{H}_2\text{O}_\text{ice})} \]  

(8)

where we have used typical figures for the HCO abundance in the gas phase (~10^{-9}, see above) and solid phase (~10^{-2} see e.g. Bennet & Kaiser 2007) and for the amount of oxygen present as water ice in grain mantles.

Assuming standard ISM grains with a radius of 0.1 μm the required photodesorption efficiency (or yield) \( Y_{\text{pd}}(\text{HCO}) \):

\[ Y_{\text{pd}}(\text{HCO}) \approx \frac{\kappa_{\text{pd}}(\text{HCO})}{G_0 \exp(-2A_V) \pi a^2} \text{ [molecules photon}^{-1}] \]  

(9)

(see e.g., d’Hendecourt et al. 1985; Bergin et al. 1995) converts to \( Y_{\text{pd}}(\text{HCO}) \approx 10^{-4} \) molecules per photon (for the FUV radiation field in the Horsehead and \( A_V \approx 1.5 \), where HCO peaks). Therefore, the production of HO in the gas phase from photo-desorption of formyl radicals could be a valid alternative to gas phase production, if the photo-desorption efficiency is high and HCO abundant in the ice mantles. This mechanism also requires further laboratory and theoretical studies.

Because the formyl radical is closely related to formaldehyde and methanol and the three species are likely to coexist in the ice mantles, a combined analysis of the H2CO, CH3OH and HCO line emissions towards the Horsehead nebula (PDR and cores) is needed to provide more information on the relative efficiencies of gas-phase and solid-phase routes in the formation of complex organic molecules in environments dominated by FUV-radiation. This will be the subject of a future paper.

5. Summary and conclusions

We have presented interferometric and single-dish data showing the spatial distribution of the formyl radical rotational lines in the Horsehead PDR and associated dense core. The HCO emission delineates the illuminated edge of the nebula and coincides with the PAH and hydrocarbon emission. HCO and HCO* reach similar abundances (≃1−2 × 10^{-9}) in these PDR regions
where the chemistry is dominated by the presence of FUV photons. For the physical conditions prevailing in the Horsehead edge, pure gas-phase chemistry is able to reproduce the observed HCO abundances (high in the PDR, low in the shielded core) if the \( \text{O} + \text{CH}_2 \rightarrow \text{HCO} + \text{H} \) reaction is included in the models. This reaction connects the high abundance of HCO, through its formation from carbon radicals, with the availability of \( \text{C}^+ \) in the PDR.

The different linewidths of HCO and \( \text{H}^{13}\text{C}^+ \) in the line of sight towards the “DCO\(^+\)” peak suggest that the \( \text{H}^{13}\text{C}^+ \) line emission arises from the quiescent, cold and dense gas completely shielded from the FUV radiation, whereas HCO predominantly arises from the outer surface of the cloud (its illuminated skin). As a result we propose the HCO/\( \text{H}^{13}\text{C}^+ \) abundance ratio, and the HCO abundance itself (if \( \geq 10^{-10} \)), as sensitive diagnostics of the presence of FUV radiation fields. In particular, regions where the HCO/\( \text{H}^{13}\text{C}^+ \) abundance ratio (or intensity ratio if lines are optically thin) is greater than \( \approx 1 \) should reflect ongoing FUV-photochemistry.

Given the rich HCO spectrum and the possibility of mapping its bright millimeter line emission with interferometers, we propose HCO-H\(_2\) as a very interesting molecular system for calculating the ab initio inelastic collision rates.

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