Protonated CO$_2$ in massive star-forming clumps

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ABSTRACT

Interstellar CO$_2$ is an important reservoir of carbon and oxygen, and one of the major constituents of the icy mantles of dust grains, but it is not observable directly in the cold gas because has no permanent dipole moment. Its protonated form, HOCO$^+$, is believed to be a good proxy for gaseous CO$_2$. However, it has been detected in only a few star-forming regions so far, so that its interstellar chemistry is not well understood. We present new detections of HOCO$^+$ lines in 11 high-mass star-forming clumps. Our observations increase by more than three times the number of detections in star-forming regions so far. We have derived beam-averaged abundances relative to H$_2$ in between 0.3 and $3.8 \times 10^{-11}$. We have compared these values with the abundances of H$^{13}$CO$^+$, a possible gas-phase precursor of HOCO$^+$, and CH$_3$OH, a product of surface chemistry. We have found a positive correlation with H$^{13}$CO$^+$, while with CH$_3$OH there is no correlation. We suggest that the gas-phase formation route starting from HCO$^+$ plays an important role in the formation of HOCO$^+$, perhaps more relevant than protonation of CO$_2$ (upon evaporation of this latter from icy dust mantles).

Key words: Stars: formation – ISM: clouds – ISM: molecules – Radio lines: ISM

1 INTRODUCTION

Carbon dioxide (CO$_2$) is a relevant molecular species in a variety of interstellar environments. In comets, planetary atmospheres, and interstellar ices, its abundance is a significant fraction ($\sim 0.1$ – 0.5) of that of water (e.g. Bergin et al. 2005, Whittet et al. 2009, McKay et al. 2016, Hoang et al. 2017). CO$_2$ ice is one of the main constituent of the icy mantles of dust grains (Öberg et al. 2011). In the gas-phase, CO$_2$ can be observed directly through ro-vibrational transitions (e.g. van Dishoeck et al. 1996), but the lack of permanent dipole moment, and hence of a pure rotational spectrum, makes it impossible a detection in cold environments. Instead, its protonated form, HOCO$^+$, has been detected towards the Galactic center (Thaddeus et al. 1981, Minh et al. 1991, Neill et al. 2014), in diffuse and translucent clouds (Turner et al. 1999), but only in a handful of star-forming regions: in the low-mass pre-stellar core L1544 (Vastel et al. 2016), in the protostars L1527 and IRAS 16293–2422 (Salai et al. 2008, Majumdar et al. 2018), and in the protostellar shock L1157-B1 (Podio et al. 2014).

In cold and dense gas, two main chemical formation pathways have been proposed: (1) a gas-phase route from the reaction HCO$^+$ + OH $\leftrightarrow$ HOCO$^+$ + H, and (2) the protonation of CO$_2$ (mainly upon reaction with H$_2^+$) desorbed from grain mantles (see e.g. Vastel et al. 2016, Bizzocchi et al. 2016). In scenario (1), CO$_2$ would be a product of HOCO$^+$ (after dissociative recombination), while the opposite is expected in scenario (2). Due to the lack of stringent observational constraints, it is unclear yet which of these two mechanisms is dominant, and under which physical conditions. Constraining the abundance of HOCO$^+$ has important implications also for the abundance of CO$_2$ in ice. In fact, if HOCO$^+$ is formed in the cold gas and then, upon dissociative recombination, gives rise to CO$_2$, this latter could freeze-out on grain mantles and contribute to the amount of CO$_2$ ice observed in dark clouds (Bergin et al. 2005), although this cannot explain the large amount of solid CO$_2$ measured along the line of sight of background stars (Boogert et al. 2015) or deeply embedded massive young stars (van Dishoeck et al. 1996). In fact, the formation of CO$_2$ ice from surface reactions is still debated. Laboratory experiments suggested formation of CO$_2$ ice from CO + O $\rightarrow$ CO$_2$ (D’Hendecourt et al. 1986), which however needs a strong UV irradiation, and hence it is expected to be inefficient in dark clouds. Other surface reactions have been proposed, such as cosmic-ray bombardment on carbonaceous grains covered by water ice (Mennella et al. 2004), or the radical-radical reaction OH + CO $\rightarrow$ CO$_2$ + H (Garrod & Pauly 2011, Ioppolo et al. 2011, Noble et al. 2011). However, such process

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involves the diffusion of heavy radicals, difficult to happen at dust temperatures below ~ 30 K, although high precision measurements are not available yet, and new promising techniques have been proposed (e.g. Cooke et al. 2016) to shed light on this important surface chemistry process.

In this paper, we present new detections of HOCO\(^+\) in 11 high-mass star-forming regions, belonging to an evolutionary sample of 27 clumps divided into the three main evolutionary categories of the massive star formation process (Fontani et al. 2011): high-mass starless cores (HM-SCs), high-mass protostellar objects (HMPOs) and Ultra-compact HII regions (UCHIIIs). The sample has been extensively observed in several dense gas tracers, with the aim of studying the chemical evolution of these molecules during the massive star-formation process (Fontani et al. 2011, 2014, 2015a, 2015b, 2016, Colzi et al. 2018a, 2018b, Mininni et al. 2018). This work represents the first study of protonated carbon dioxide in a statistically relevant number of star forming regions.

2 OBSERVATIONS

The spectra analysed in this work are part of the dataset presented in Colzi et al. (2018a). These data were obtained with the IRAM-30m Telescope in the 3 mm band with the EMIR receiver, covering the frequency ranges 85.31 – 87.13 GHz and 88.59 – 90.41 GHz, toward 26 dense cores in massive star-forming regions divided in the 3 evolutionary categories HM-SCs, HMPOs and UCHIIIs (see Sect. 1). For details on the source selection, see Fontani et al. (2011). The atmospheric conditions were very stable, with amounts of precipitable water vapour in the range 3 – 8 mm. We observed in wobbler-switching mode (wobbler throw of 240\(^\circ\)). Pointing was checked almost every hour on nearby quasars, planets, or bright HII regions. The data were calibrated with the chopper wheel technique (see Kutner & Ulich 1981), and the calibration uncertainty is estimated to be about 10\(^\%\). More details are given in Colzi et al. (2018a). The spectra have been reduced and analysed with the software CLASS of the GILDAS package. The detected lines have been fit with a gaussian shape.

3 RESULTS

Table 1 lists the 27 observed sources: 11 HM-SCs, 9 HMPOs, and 7 UCHIIIs. We have detected clearly (signal-to-noise ratio ≥ 5) the HOCO\(^+\) 4\(^0\) - 3\(^3\) transition (HOCO\(^+\) 4 - 3 hereafter, \(E_{\text{up}}\sim 10.3\) K) at 85531.497 MHz (Bizzocchi et al. 2016) in five HM-SCs, two HMPOs and four UCHIIIs. The spectra of the detected sources are shown in Fig. 1. The relatively high detection (≥ 50\%) in the HMSCs indicates that HOCO\(^+\) is a species abundant in cold and dense gas. The detection rate decreases during the HMPO phase (≤ 22\%), and then it increases again at the UCHII stage (≥ 57\%). Since we have detected only one transition of HOCO\(^+\), to confirm that the detected line is indeed HOCO\(^+\) and rule out contamination by transitions of other molecules, we have simulated the spectrum of one of the two sources in which the line has the highest intensity peak, namely 05358-mm1 (Fig. 1), and used the software MADCUBA\(^1\) to search for emission of nearby lines potentially blended with HOCO\(^+\) 4 - 3. Belloche et al. (2013) have shown that in Sgr B2(N) the only species with lines that could contaminate HOCO\(^+\) 4 - 3 is C\(_2\)H\(_3\)CN. They found C\(_2\)H\(_3\)CN column densities above 10\(^{18}\) cm\(^{-2}\) and line widths larger than those that we have found for HOCO\(^+\). To simulate the spectrum, we have assumed as excitation temperature the kinetic temperature obtained from ammonia (39 K, Fontani et al. 2011) and the same line width obtained fitting HOCO\(^+\) 4 - 3 (4.9 km s\(^{-1}\)). As shown in Fig. 2 (top panel), even assuming a huge column density of 10\(^{18}\) cm\(^{-2}\) as in Sgr B2(N), the expected C\(_2\)H\(_3\)CN line intensities are well below the spectral r.m.s., and well separate from the HOCO\(^+\) 4 - 3 line. A second transition of HOCO\(^+\), namely the 4\(^1\)\(_3\) - 3\(^1\)\(_2\) line centred at 85852.8576 MHz (\(E_{\text{up}}\sim 48\) K), falls in our band but it is undetected. Because its line strength and Einstein coefficient are quite similar to those of the 4\(^0\)\(_4\) - 3\(^3\)\(_3\) transition (see Bizzocchi et al. 2016), we have investigated if its non-detection is due to the lack of sensitivity. Fig. 2 (bottom panel) shows that indeed the synthetic spectrum of 05358-mm1 around this line (simulated assuming the parameters described above for HOCO\(^+\)) is consistent with a non-detection. Because this source shows the highest intensity peak of HOCO\(^+\) 4 - 3, we can reasonably conclude that the non-detection of the second transition is due to a sensitivity limit in all sources.

All detected lines are well fit by a single gaussian (Fig. 1). The results of the fit performed as explained in Sect. 2, namely line integrated intensity (\(\int T_{\text{MB}} dv\)), peak velocity in the Local Standard of Rest (LSR) (\(v_p\)), and line width at half maximum (\(\Delta v\)) are shown in Table 1. The uncertainties on \(\int T_{\text{MB}} dv\) are calculated from the expression \(\sigma_{\Delta v_{\text{res}}}n\/\sqrt{\text{res}}\), obtained from the propagation of errors, where \(\sigma\) is the \(1\sigma\) root mean square noise in the spectrum, \(\Delta v_{\text{res}}\) the spectral resolution, and \(n\) the number of channels with signal. The uncertainties on \(v_p\) and \(\Delta v\) are computed by the fit procedure. The \(\Delta v\) measured towards the detected UCHII regions are always larger than ~ 3.2 \(\text{km s}^{-1}\), while they are narrower than 3 \(\text{km s}^{-1}\) in all HM-SCs (but in 05358-mm3), in agreement with the fact that the envelopes of UCHII regions are more turbulent than those of HM-SCs. The case of 05358-mm3 is peculiar because this core is likely externally heated (Fontani et al. 2011), hence its chemical composition and the emission that we observe is likely a mix between the cold and dense core nucleus and the warmer envelope. The line shapes are symmetric and do not show non-gaussian wings. This suggests that in all sources the HOCO\(^+\) emission is associated with the bulk gas. This finding is supported by the fact that the peak velocities are consistent with the systemic velocities (given in Fontani et al. 2011) within the uncertainties (see Fig. 1).

3.1 HOCO\(^+\) column densities and fractional abundances

From the line integrated intensity, we have calculated the total column density of HOCO\(^+\) assuming Local Thermody-

\(^1\) Madrid Data Cube Analysis on image is a software to visualize and analyse astronomical single spectra and datacubes (Martín et al., in prep., Rivilla et al. 2016).
Figure 1. Spectra of the HOCO$^+$ ($\nu_{0.4} - 3_{0.3}$) line in the 11 detected sources. The y-axis is in T$_{MB}$ units. The x-axis corresponds to [V$_{LSR} - V_{sys}$], i.e. the difference between the local standard of rest velocity, V$_{LSR}$, and the nominal systemic velocity, V$_{sys}$, given in Fontani et al. 2011. The red curves superimposed on the spectra represent the best gaussian fits.

The equation:

$$N = \frac{8\pi^3 g_i^2}{c^3 A_{ij}} \int T_{MB} dv \frac{Q(T_{ex}) \exp(E_i/kT_{ex})}{(T_{ex} - T_{BG})^2 + T_{ex}^2}$$

where $\nu_0$ is the frequency of the transition, $A_{ij}$ is the Einstein coefficient of spontaneous emission, $g_i$ is the statistical weight of the upper level, $E_i$ is the energy of the lower level, $c$ is the speed of light, $h$ and $k$ are the Planck and Boltzmann constants, respectively, $T_{ex}$ is the excitation temperature, $Q(T_{ex})$ is the partition function computed at temperature $T_{ex}$, $T_{BG}$ is the background temperature (assumed to be that of the cosmic microwave background, 2.7 K), and $J_p(T)$ is the equivalent Rayleigh-Jeans temperature (see also Eq. (A4) in Caselli et al. 2002). The line strength, energy of the upper level, and Einstein coefficient of spontaneous emission, are taken from the Cologne Database for Molecular Spectroscopy (CDMS$^2$, see also Bogey et al. 1986, and Bizzocchi et al. 2016), and are: $5\mu^2 \sim 29.2$ D$^2$, $E_a \sim 10.3$ K, and $A_{ij} \sim 2.36 \times 10^{-2}$ s$^{-1}$, respectively. The assumption of optically thin emission is consistent with the low abundance of the molecule and with line shapes without hints of high optical depths (like, e.g., asymmetric or flat topped profiles). The beam averaged column densities are in the range $\sim 3.5 \times 10^{11} - 4.6 \times 10^{12}$ cm$^{-2}$. For undetected lines, we have computed the upper limits on $\int T_{MB} dv$ assuming a gaussian line with intensity peak equal to the 3σ rms in the spectrum, and $\Delta v$ equal to the average value of each evolutionary group, and from this we have derived the upper limits on N(HOCO$^+$) from Eq. 1.

We have computed the HOCO$^+$ fractional abundances, X[HOCO$^+$], by dividing the HOCO$^+$ total column densities by those of H$_2$, N(H$_2$), derived from the sub-millimeter continuum emission. This latter was computed from the (sub-)millimeter dust thermal continuum emission extracted from the images of the 850 μm survey of Di Francesco et al. (2008) obtained with SCUBA at the James Clerk Maxwell Telescope (JCMT). We have used Eq. (A1) in Mininni et al. (2018) to compute N(H$_2$), which assumes optically thin emission, and a gas-to-dust ratio of 100. The sub-millimeter continuum fluxes, $F_{\text{submm}}$, used to compute N(H$_2$) have been extracted from a circular area equivalent to the IRAM-30m Half Power Beam Width (HPBW) at the frequency of the HOCO$^+$ line, i.e. $\sim 28''$. The uncertainty on $F_{\text{submm}}$ is calculated from the propagation of errors. The sub-mm fluxes, and the derived N(H$_2$) and X[HOCO$^+$] obtained as explained above, are given in Table 1. For the sources not present in the survey of Di Francesco et al. (2008), we have estimated N(H$_2$) following the same analysis from the APEX ATLASGAL continuum images (http://www3.mpifr-bonn.mpg.de/div/atlasgal/index.html) at $\sim 870$ GHz. We derive X[HOCO$^+$] in the range $0.3 - 3.8 \times 10^{-11}$. These values are intermediate between those obtained towards the pre-stellar core L1544 ($\sim 5 \times 10^{-11}$, Vastel et al. 2016) and the hot corino IRAS 16293–2422 ($\sim 1 \times 10^{-13}$, Majumdar et al. 2018).

4 DISCUSSION AND CONCLUSIONS

As discussed in Sect. 1, two main pathways have been proposed for the formation of HOCO$^+$ in dense gas: either the
Table 1. Results derived from gaussian fits to the lines. In cols. 2-6 we give: integrated intensity ($\int T_{\text{mb}} \text{d}v$), velocity in the Local Standard of Rest (LSR) at line peak ($v_p$), full width at half maximum ($\Delta v$), assumed gas excitation temperature ($T_{\text{ex}}$), and HOCO$^+$ beam-averaged total column density, $N($HOCO$^+$), calculated as explained in Sect. 3.1. The uncertainties on $N$ are obtained propagating the error on $\int T_{\text{mb}} \text{d}v$, to which we sum a 10% of calibration error on the $T_{\text{mb}}$ scale (see Sect. 2) not included in the error on $\int T_{\text{mb}} \text{d}v$. $T_{\text{ex}}$ is assumed without uncertainty. Col. 7 and 8 give the sub-millimeter flux densities, $F_{\text{submm}}$, and the $H_2$ column densities, $N(H_2)$, derived from it, respectively (see Sect. 3.1 for details). The error on $N(H_2)$ is obtained propagating the error on $F_{\text{submm}}$ to which we add a calibration error of 20% on the SCUBA absolute flux scale at 850$\mu$m (Di Francesco et al. 2008). The HOCO$^+$ fractional abundances, $X($HOCO$^+$), are shown in Col. 9. Finally, in Cols. 10, 11 and 12, we list the fractional abundances of CH$_4$, H$^{13}$CO$^+$, and N$_2$H$^+$ averaged over 28$^\circ$. 

| Source | $\int T_{\text{mb}} \text{d}v$ | $v_p$ | $\Delta v$ | $T_{\text{ex}}$ | $N($HOCO$^+$) | $F_{\text{submm}}$ | $N(H_2)$ | $X($HOCO$^+$) | $X($CH$_4$) | $X($H$^{13}$CO$^+$) | $X($N$_2$H$^+$) |
|--------|----------------|------|---------|--------------|----------------|----------------|--------|---------------|-------------|----------------|----------------|
| HMSCs |
| 00117-MM2 | $\leq 0.069$ | $-\quad -$ | $\leq 3$ | | | | | | | | |
| AGFL514-EC$^{(w)}$ | 0.17 ± 0.03 | $-2.5 ± 0.2$ | $2.4 ± 0.3$ | 39 | | | | | | | |
| 05358-mm5$^{(w)}$ | 0.37 ± 0.04 | $-17.0 ± 0.2$ | $4.9 ± 0.5$ | | | | | | | | |
| 18089-1732 | 0.11 | | $\leq 38$ | $\leq 8$ | $7.5 ± 0.4^{(s)}$ | $9.6 ± 0.2^{(s)}$ | $\leq 0.8$ | | | | |
| 18517+0437 | 0.12 | | $\leq 40$ | | $6.7 ± 0.4^{(a)}$ | $7.9 ± 1.3$ | $\leq 1.0$ | | | | |
| G75-core | 0.10 | | $\leq 96$ | | $10.0 ± 0.4^{(a)}$ | $4.4 ± 1.1$ | $\leq 3.2$ | | | | |
| I20293-MM1 | 0.10 | | $\leq 37$ | | $3.7 ± 0.2^{(a)}$ | $4.9 ± 1.2$ | $\leq 1.3$ | | | | |
| I21307 | 0.087 | | $\leq 21$ | | $1.05 ± 0.04^{(a)}$ | $2.9 ± 0.7$ | $\leq 1.4$ | $4.5 ± 1.1$ | $3.2 ± 1.1$ | $0.8 ± 0.3$ | |
| I23385 | 0.096 | | $\leq 37$ | | $1.81 ± 0.05^{(a)}$ | $2.4 ± 0.6$ | $\leq 2.6$ | $15 ± 4$ | $9.3 ± 3.3$ | $6.0 ± 0.2$ | |
| HMPs |
| 00117-MM1 | $\leq 0.11$ | | $\leq 20$ | | $\leq 5$ | | | | | | |
| AGFL514-MM | 0.15 ± 0.03 | $-2.5 ± 0.2$ | $2.4 ± 0.3$ | | | | | | | | |
| G5.89-0.39 | 0.26 ± 0.03 | $9.5 ± 0.2$ | $4.3 ± 0.6$ | 31 | | | | | | | |
| IH0355-32A | 0.20 ± 0.03 | $33.3 ± 0.4$ | $6.4 ± 0.9$ | 39 | | | | | | | |
| I23385-IR59 | $\leq 0.16$ | | | | | | | | | | |
| UCHIIs |
| G5.89-0.39 | 0.25 ± 0.03 | $9.5 ± 0.2$ | $4.3 ± 0.6$ | 31 | | | | | | | |
| IH0355-32A | 0.20 ± 0.03 | $33.3 ± 0.4$ | $6.4 ± 0.9$ | 39 | | | | | | | |
| I23385-IR59 | $\leq 0.16$ | | | | | | | | | | | (w) "warm" core having a kinetic temperature higher than 20 K, and likely externally heated (Fontani et al. 2011), (a) measured from the maps of the SCUBA survey (Di Francesco et al. 2008), (s) measured from the maps of the APEX ATLASGAL survey (http://www3.mpifr-bonn.mpg.de/div/atlasgal/index.html); (a) continuum map not available either in the survey of Di Francesco et al. 2008 (http://www3.mpifr-bonn.mpg.de/div/atlasgal/index.html); (s) continuum map not available either in the survey of Di Francesco et al. 2008 or in the ATLASGAL survey. The H$^{13}$CO$^+$ column densities used to derive $X($H$^{13}$CO$^+$) have been estimated from the integrated intensities of the H$^{13}$CO$^+$ 1–0 lines at 86754.288 MHz, serendipitously detected in the same dataset described in Sect. 2 and in Colzi et al. (2018a). We have followed the same approach used for HOCO$^+$, namely we assumed optically thin lines and LTE conditions (see Sect. 3.1). We used the excitation temperatures listed in Table 1. The beam size is almost the same of that of HOCO$^+$, hence all the fractional abundances in Table 1 are averaged over the same angular region. Figure 3 indicates a clear non-correlation between the abundances of CH$_3$OH and HOCO$^+$, while H$^{13}$CO$^+$ and HOCO$^+$ seems positively correlated. By applying simple statistical tests to the detected sources only, the correlation co-
efficiency (Pearson’s $\rho$) between X[HOCO$^+$] and X[H$^{13}$CO$^+$] is 0.7. Considering also the upper limits, the correlation remains positive (Pearson’s $\rho = 0.6$). The correlation between X[HOCO$^+$] and X[N$_2$H$^+$] is positive (Pearson’s $\rho = 0.4$ without the upper limits) but much less convincing. If we assume that both CO$_2$ and CH$_3$OH form on grain mantles, and what we find in the gas is evaporated at similar times, the lack of correlation between X[HOCO$^+$] and both X[CH$_3$OH] and X[N$_2$H$^+$] would indicate that the origin of HOCO$^+$ is likely not from CO$_2$ evaporated from ice mantles. This interpretation has two big caveats. First, the formation processes of CO$_2$ and CH$_3$OH on the surfaces of dust grains can be different. In fact, CO$_2$ is thought to form in water ice mantles of cold carbonaceous grains via cosmic-ray bombardment (Menella et al. 2004), or via the surface reaction CO + OH at dust temperatures of ~30 K (Garrod & Pauly 2011), while CH$_3$OH if formed from hydrogenation of CO at dust temperatures ~ 10 K (Vasyunin et al. 2017). Second, the main molecular ion responsible for the protonation of CO$_2$ is H$_3^+$ and not N$_2$H$^+$. Nevertheless, the positive correlation between X[H$^{13}$CO$^+$] and X[HOCO$^+$] suggests a non negligible, or even dominant, contribution from HCO$^+$ to the formation of the detected HOCO$^+$. This interpretation of our results is in agreement with the study of Majumdar et al. (2018), who proposed that the dominant (up to 85%) formation route of HOCO$^+$ in the extended and cold (T $\leq$ 30 K) envelope of the hot corino IRAS 16293–2422 is indeed from the gas-phase reaction OH + HCO$^+$. The fact that HOCO$^+$ and H$^{13}$CO$^+$ likely arise from similar gas can be understood also from the comparison of their line widths at half maximum. Fig. 4 indicates that the HOCO$^+$ line widths are correlated with those of H$^{13}$CO$^+$, but not with those of CH$_3$OH (which are always narrower). Hence, CH$_3$OH is likely not associated with the same gas.

Overall, our findings suggest a significant (perhaps dominant) role of HCO$^+$ as a gas-phase progenitor of HOCO$^+$. However, caution needs to be taken in the interpretation of our results for several reasons. First, the HOCO$^+$ column densities, and hence the fractional abundances, have been derived assuming an excitation temperature that could not be that of the molecule. To solve this problem, detection of more lines tracing different excitation conditions are absolutely required. Another caveat arises from the fact that our column densities are values averaged over large ($\sim$20$''$) angular surfaces. Our targets are known to have complex structure, and temperature (and density) gradients. Therefore, higher angular resolution observations are needed to precisely determine the HOCO$^+$ emitting region, and, from this, understand its temperatures and densities, required to properly model the chemistry.

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Figure 3. Abundance of HOCO$^+$ against that of, from top to bottom: CH$_3$OH, H$^{13}$CO$^+$, and N$_2$H$^+$. The colours indicate the different evolutionary groups as labelled in the top-left corner. The large filled symbols correspond to the detected sources, while the small triangles indicate the upper limits on the abundance of HOCO$^+$. In the panel with $X[H^{13}CO^+]$, we do not show 05358-mm3, observed and detected in CH$_3$OH, N$_2$H$^+$ and HOCO$^+$ but not in H$^{13}$CO$^+$.

Figure 4. Line widths at half maximum, $\Delta v$, of H$^{13}$CO$^+$ (left panel) and CH$_3$OH (right panel) against those of HOCO$^+$. The colours indicate the different evolutionary groups as in Fig. 3. The solid line in the left panel corresponds to a linear fit to the data.
