



Publication Year	2018
Acceptance in OA @INAF	2020-10-14T14:18:09Z
Title	Protonated CO ₂ in massive star-forming clumps
Authors	FONTANI, FRANCESCO; Vagnoli, A.; Padovani, Marco; Colzi, L.; Caselli, P.; et al.
DOI	10.1093/mnras/sly160
Handle	http://hdl.handle.net/20.500.12386/27810
Journal	MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY
Number	481

Protonated CO₂ in massive star-forming clumps

F. Fontani,¹[★] A. Vagnoli,² M. Padovani,¹ L. Colzi,^{1,2} P. Caselli,³ and V.M. Rivilla¹

¹*INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125, Florence, Italy*

²*Dipartimento di Fisica e Astronomia, Università degli Studi di Firenze, I-50125 Firenze, Italy*

³*Centre for Astrochemical Studies, Max-Planck-Institute for Extraterrestrial Physics, Giessenbachstrasse 1, 85748 Garching, Germany*

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

Interstellar CO₂ 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 CO₂. 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 H₂ in between 0.3 and 3.8×10^{-11} . We have compared these values with the abundances of H¹³CO⁺, a possible gas-phase precursor of HOCO⁺, and CH₃OH, a product of surface chemistry. We have found a positive correlation with H¹³CO⁺, while with CH₃OH 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 CO₂ (upon evaporation of this latter from icy dust mantles).

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

1 INTRODUCTION

Carbon dioxide (CO₂) 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). CO₂ ice is one of the main constituent of the icy mantles of dust grains (Öberg et al. 2011). In the gas-phase, CO₂ 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 (Sakai 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 $\text{HCO}^+ + \text{OH} \leftrightarrow \text{HOCO}^+ + \text{H}$, and (2) the pro-

tonation of CO₂ (mainly upon reaction with H₃⁺) desorbed from grain mantles (see e.g. Vastel et al. 2016, Bizzocchi et al. 2016). In scenario (1), CO₂ 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 CO₂ in ice. In fact, if HOCO⁺ is formed in the cold gas and then, upon dissociative recombination, gives rise to CO₂, this latter could freeze-out on grain mantles and contribute to the amount of CO₂ ice observed in dark clouds (Bergin et al. 2005), although this cannot explain the large amount of solid CO₂ 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 CO₂ ice from surface reactions is still debated. Laboratory experiments suggested formation of CO₂ ice from $\text{CO} + \text{O} \rightarrow \text{CO}_2$ (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 $\text{OH} + \text{CO} \rightarrow \text{CO}_2 + \text{H}$ (Garrod & Pauly 2011, Ioppolo et al. 2011, Noble et al. 2011). However, such process

[★] E-mail: fontani@arcetri.astro.it

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 (UCHIIs). 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 HMSCs, HMPOs and UCHIIs (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 $240''$). 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 HMSCs, 9 HMPOs, and 7 UCHIIs. We have detected clearly (signal-to-noise ratio ≥ 5) the HOCO^+ $4_{0,4} - 3_{0,3}$ transition (HOCO^+ 4–3 hereafter, $E_{\text{up}} \sim 10.3$ K) at 85531.497 MHz (Bizzocchi et al. 2016) in five HMSCs, two HMPOs and four UCHIIs. The spectra of the detected sources are shown in Fig. 1. The relatively high detection ($\sim 50\%$) in the HMSCs indicates that HOCO^+ is a species abundant in cold and dense gas. The detection rate decreases during the HMPO phase ($\sim 22\%$), and then it increases again at the UCHII stage ($\sim 57\%$). 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 MADCUBA¹ 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 $\text{C}_2\text{H}_3\text{CN}$. They found $\text{C}_2\text{H}_3\text{CN}$ 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 $\text{C}_2\text{H}_3\text{CN}$ line intensities are well below the spectral rms, and well separate from the HOCO^+ 4–3 line. Another transition of HOCO^+ , namely the $4_{1,3} - 3_{1,2}$ line centred at 85852.8576 MHz ($E_{\text{u}} \sim 48$ K), falls in our band but it is undetected. Because its line strength and Einstein coefficient are quite similar to those of the $4_{0,4} - 3_{0,3}$ 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 (Δv) are shown in Table 1. The uncertainties on $\int T_{\text{MB}} dv$ are calculated from the expression $\sigma \Delta v_{\text{res}} \sqrt{n}$, obtained from the propagation of errors, where σ is the 1σ root mean square noise in the spectrum, Δv_{res} the spectral resolution, and n the number of channels with signal. The uncertainties on v_{p} and Δv are computed by the fit procedure. The Δv measured towards the detected UCHII regions are always larger than $\sim 3.2 \text{ km s}^{-1}$, while they are narrower than 3 km s^{-1} in all HMSCs (but in 05358-mm3), in agreement with the fact that the envelopes of UCHII regions are more turbulent than those of HMSCs. 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).

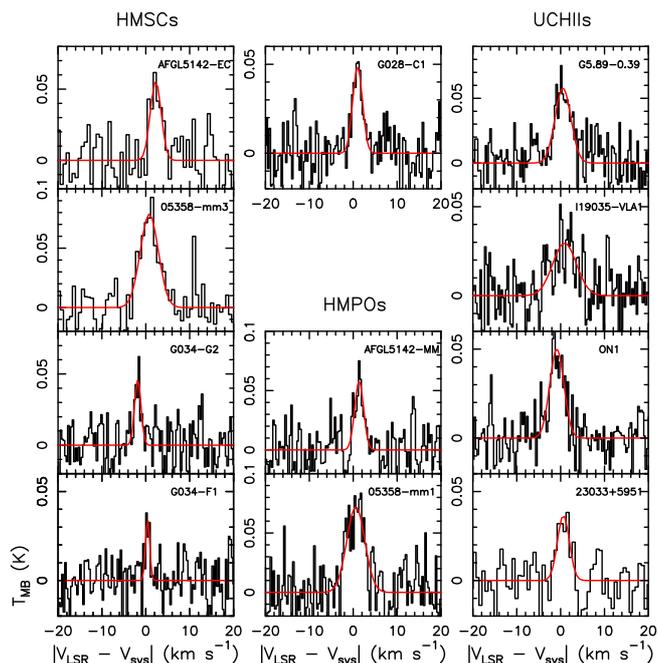


Figure 1. Spectra of the HOCO⁺ ($4_{0,4} - 3_{0,3}$) line in the 11 detected sources. The y-axis is in T_{MB} units. The x-axis corresponds to $|V_{\text{LSR}} - V_{\text{sys}}|$, i.e. the difference between the local standard of rest velocity, V_{LSR} , and the nominal systemic velocity, V_{sys} , given in Fontani et al. 2011. The red curves superimposed on the spectra represent the best gaussian fits.

dynamic Equilibrium (LTE) and optically thin conditions from the equation:

$$N = \frac{8\pi\nu_{ij}^3}{c^3 A_{ij} g_i [J_\nu(T_{\text{ex}}) - J_\nu(T_{\text{BG}})]} \frac{Q(T_{\text{ex}}) \exp(E_j/kT_{\text{ex}})}{1 - \exp(-h\nu_{ij}/kT_{\text{ex}})}, \quad (1)$$

where ν_{ij} 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_j 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, $Q(T_{\text{ex}})$ 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 $J_\nu(T)$ 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 (CDMS², see also Bogey et al. 1986, and Bizzocchi et al. 2016), and are: $S\mu^2 \sim 29.2 \text{ D}^2$, $E_u \sim 10.3 \text{ K}$, and $A_{ij} \sim 2.36 \times 10^{-5} \text{ s}^{-1}$, 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 $\sim 3.5 \times 10^{11} - 4.6 \times 10^{12} \text{ cm}^{-2}$. For undetected lines, we have computed the upper limits on $\int T_{\text{MB}} d\nu$ assuming a gaussian

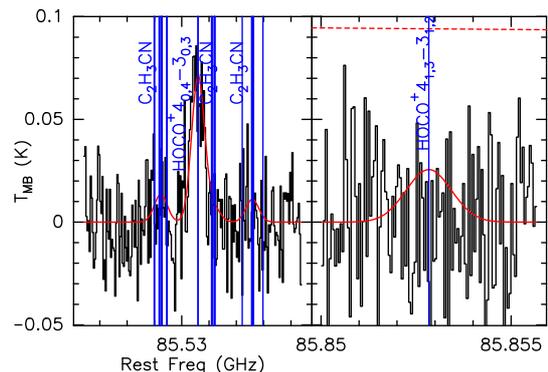


Figure 2. Left panel: spectrum of the HOCO⁺ $4_{0,4} - 3_{0,3}$ line towards 05358-mm1 superimposed on the synthetic spectrum (in red) calculated with MADCUBA. The synthetic spectrum is calculated for a HOCO⁺ column density of $4.3 \times 10^{12} \text{ cm}^{-2}$ and a C₂H₃CN column density of 10^{18} cm^{-2} , which is the value measured towards Sgr B2(N) (see Sect. 3). The rest frequencies of the nearby C₂H₃CN transitions are indicated by vertical lines. Right panel: spectrum of 05358-mm1 centred on the rest frequency of HOCO⁺ $4_{1,3} - 3_{1,2}$, superimposed on the synthetic spectrum created with the same parameters used in Left panel: the expected peak of the line is well under the 3σ rms noise (shown by the red dashed horizontal line).

line with intensity peak equal to the 3σ rms in the spectrum, and $\Delta\nu$ equal to the average value of each evolutionary group, and from this we have derived the upper limits on $N(\text{HOCO}^+)$ from Eq. 1.

We have computed the HOCO⁺ fractional abundances, $X[\text{HOCO}^+]$, by dividing the HOCO⁺ total column densities by those of H₂, $N(\text{H}_2)$, 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 $N(\text{H}_2)$, which assumes optically thin emission, and a gas-to-dust ratio of 100. The sub-millimeter continuum fluxes, F_{submm} , used to compute $N(\text{H}_2)$ 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_{submm} is calculated from the propagation of errors. The sub-mm fluxes, and the derived $N(\text{H}_2)$ and $X[\text{HOCO}^+]$ 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 $N(\text{H}_2)$ following the same analysis from the APEX ATLASGAL continuum images (<http://www3.mpifr-bonn.mpg.de/div/atlasgal/index.html>) at $\sim 870 \text{ GHz}$. We derive $X[\text{HOCO}^+]$ 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

² <https://www.astro.uni-koeln.de/cdms>

Table 1. Results derived from gaussian fits to the lines. In cols. 2–6 we give: integrated intensity ($\int T_{\text{MB}} dv$), velocity in the Local Standard of Rest (LSR) at line peak (v_p), full width at half maximum (Δv), assumed gas excitation temperature (T_{ex}), and HOCO⁺ beam-averaged total column density, $N(\text{HOCO}^+)$, calculated as explained in Sect. 3.1. The uncertainties on N are obtained propagating the error on $\int T_{\text{MB}} dv$, to which we sum a 10% of calibration error on the T_{MB} scale (see Sect. 2) not included in the error on $\int T_{\text{MB}} dv$. T_{ex} is assumed without uncertainty. Col. 7 and 8 give the sub-millimeter flux densities, F_{submm} , and the H₂ column densities, $N(\text{H}_2)$, derived from it, respectively (see Sect. 3.1 for details). The error on $N(\text{H}_2)$ is obtained propagating the error on F_{submm} , to which we add a calibration error of 20% on the SCUBA absolute flux scale at 850 μm (Di Francesco et al. 2008). The HOCO⁺ fractional abundances, $X[\text{HOCO}^+]$, are shown in Col. 9. Finally, in Cols. 10, 11 and 12, we list the fractional abundances of CH₃OH, H¹³CO⁺, and N₂H⁺ averaged over 28".

Source	$\int T_{\text{MB}} dv$ K km s ⁻¹	v_p km s ⁻¹	Δv km s ⁻¹	T_{ex} K	$N(\text{HOCO}^+)$ $\times 10^{11}$ cm ⁻²	F_{submm} Jy	$N(\text{H}_2)$ $\times 10^{22}$ cm ⁻²	$X[\text{HOCO}^+]$ $\times 10^{-11}$	$X[\text{CH}_3\text{OH}]$ $\times 10^{-10}$	$X[\text{H}^{13}\text{CO}^+]$ $\times 10^{-11}$	$X[\text{N}_2\text{H}^+]$ $\times 10^{-9}$
HMSCs											
00117-MM2	≤ 0.069	–	–	14	≤ 3	– ^(u)	–	–	–	–	–
AFGL5142-EC ^(w)	0.17 ± 0.03	-1.6 ± 0.3	2.9 ± 0.6	25	9 ± 2	$5.1 \pm 0.5^{(s)}$	11.3 ± 3.4	0.8 ± 0.4	28 ± 8	7.4 ± 3.1	2.5 ± 1.4
05358-mm3 ^(w)	0.41 ± 0.05	-16.8 ± 0.3	4.8 ± 0.6	30	23 ± 5	$6.1 \pm 0.2^{(s)}$	10.6 ± 2.4	2.2 ± 1.0	12 ± 3	–	0.6 ± 0.2
G034-G2	0.08 ± 0.02	41.8 ± 0.2	1.7 ± 0.5	20	4 ± 1	$0.88 \pm 0.04^{(a)}$	4.1 ± 1.0	0.9 ± 0.5	2.2 ± 0.5	2.0 ± 0.8	1.5 ± 0.4
G034-F2	≤ 0.081	–	–	20	≤ 4	$0.36 \pm 0.02^{(s)}$	1.6 ± 0.4	≤ 2.5	3.1 ± 0.8	1.1 ± 0.4	1.0 ± 0.3
G034-F1	0.04 ± 0.01	58.1 ± 0.2	1.2 ± 0.4	20	1.9 ± 0.4	$0.27 \pm 0.02^{(s)}$	1.2 ± 0.3	1.6 ± 1.0	9.8 ± 2.5	6.7 ± 2.7	3.4 ± 1.1
G028-C1	0.14 ± 0.02	79.3 ± 0.2	2.6 ± 0.4	17	6 ± 1	$0.93 \pm 0.03^{(s)}$	3.6 ± 0.8	1.7 ± 0.8	3.8 ± 0.9	6 ± 2	2.3 ± 0.6
G028-C3	≤ 0.084	–	–	17	≤ 4	$0.56 \pm 0.03^{(a)}$	2.4 ± 0.6	≤ 3.5	–	–	–
I20293-WC	≤ 0.074	–	–	17	≤ 3	$1.9 \pm 0.1^{(s)}$	7.4 ± 1.9	≤ 0.4	2.4 ± 0.6	4.9 ± 1.9	1.5 ± 0.5
22134-G ^(w)	≤ 0.076	–	–	25	≤ 4	$1.6 \pm 0.1^{(s)}$	3.6 ± 0.9	≤ 1.1	4 ± 1	8.7 ± 3.3	0.4 ± 0.1
22134-B	≤ 0.071	–	–	17	≤ 3	$0.52 \pm 0.05^{(s)}$	2.0 ± 0.6	≤ 1.6	0.9 ± 0.3	4.8 ± 2.0	0.9 ± 0.4
HMPOs											
00117-MM1	≤ 0.11	–	–	20	≤ 5	– ^(u)	–	–	–	–	–
AFGL5142-MM	0.15 ± 0.03	-2.5 ± 0.2	2.4 ± 0.4	34	9 ± 3	$6.8 \pm 0.3^{(s)}$	10.1 ± 2.4	0.9 ± 0.5	53 ± 13	10 ± 4	2.4 ± 0.7
05358-mm1	0.37 ± 0.04	-17.0 ± 0.2	4.9 ± 0.5	39	25 ± 5	$6.1 \pm 0.3^{(s)}$	8.4 ± 2.1	3.0 ± 1.4	30 ± 8	1.0 ± 0.4	1.4 ± 0.04
18089-1732	≤ 0.13	–	–	38	≤ 8	$7.5 \pm 0.4^{(s)}$	9.6 ± 2.4	≤ 0.8	67 ± 17	14 ± 5	2.2 ± 0.8
18517+0437	≤ 0.12	–	–	40	≤ 8	$6.7 \pm 0.4^{(a)}$	7.9 ± 1.3	≤ 1.0	54 ± 9	21 ± 6	1.1 ± 0.2
G75-core	≤ 0.10	–	–	96	≤ 14	$10.0 \pm 0.4^{(s)}$	4.4 ± 1.1	≤ 3.2	69 ± 17	38 ± 14	1.0 ± 0.3
I20293-MM1	≤ 0.10	–	–	37	≤ 7	$3.7 \pm 0.2^{(s)}$	4.9 ± 1.2	≤ 1.3	11 ± 3	13 ± 5	9 ± 2
I21307	≤ 0.087	–	–	21	≤ 4	$1.03 \pm 0.04^{(s)}$	2.9 ± 0.7	≤ 1.4	4.5 ± 1.1	3.2 ± 1.1	0.8 ± 0.3
I23385	≤ 0.096	–	–	37	≤ 6	$1.81 \pm 0.05^{(s)}$	2.4 ± 0.6	≤ 2.6	15 ± 4	9.3 ± 3.3	0.6 ± 0.2
UCHIIs											
G5.89-0.39	0.26 ± 0.03	9.5 ± 0.2	4.3 ± 0.6	31	15 ± 3	$18 \pm 1^{(s)}$	55 ± 14	0.3 ± 0.1	8.5 ± 2	4.2 ± 1.7	0.5 ± 0.1
I19035-VLA1	0.20 ± 0.03	33.3 ± 0.4	6.4 ± 0.9	39	14 ± 3	$2.9 \pm 0.1^{(s)}$	3.6 ± 0.9	3.8 ± 1.9	17 ± 4	15 ± 5	5.0 ± 1.5
19410+2336	≤ 0.15	–	–	21	≤ 7	$4.8 \pm 0.1^{(a)}$	13.6 ± 3.0	≤ 0.5	5.4 ± 1.2	3.6 ± 1.2	3.2 ± 1.0
ON1	0.20 ± 0.02	11.2 ± 0.2	3.8 ± 0.5	26	10 ± 2	– ^(u)	–	–	–	–	–
I22134-VLA1	≤ 0.11	–	–	47	≤ 9	$2.1 \pm 0.1^{(s)}$	2.1 ± 0.5	≤ 4.2	2.9 ± 0.7	2.0 ± 0.7	0.9 ± 0.3
23033+5951	0.12 ± 0.02	-52.4 ± 0.3	3.2 ± 0.5	25	7 ± 2	$3.5 \pm 0.1^{(s)}$	7.8 ± 1.8	0.8 ± 0.4	5.7 ± 1.3	9.2 ± 3.1	2.6 ± 1.4
NGC7538-IRS9	≤ 0.16	–	–	31	≤ 10	$3.9 \pm 0.1^{(s)}$	11.9 ± 2.7	≤ 0.8	5.4 ± 1.2	4.1 ± 1.4	0.5 ± 0.1

^(w) "warm" core having a kinetic temperature higher than 20 K, and likely externally heated (Fontani et al. 2011); ^(s) measured from the maps of the SCUBA survey (Di Francesco et al. 2008); ^(a) measured from the maps of the APEX ATLASGAL survey (<http://www3.mpifr-bonn.mpg.de/div/atlasgal/index.html>); ^(u) continuum map not available either in the survey of Di Francesco et al. (2008) or in the ATLASGAL survey.

gas-phase reaction $\text{HCO}^+ + \text{OH} \leftrightarrow \text{HOCO}^+ + \text{H}$, or the protonation of desorbed CO₂, mainly upon reaction with H₃⁺ (Vastel et al. 2016, Bizzocchi et al. 2016). To investigate if and how our observational results can put constraints on these alternative pathways, in Fig. 3 we show the fractional abundance of HOCO⁺ (calculated as explained in Sect. 3.1) against that of H¹³CO⁺, the main precursor of HOCO⁺ in the gas phase, and CH₃OH, a tracer of surface chemistry. For completeness, we also plot $X[\text{HOCO}^+]$ against $X[\text{N}_2\text{H}^+]$, because protonation of CO₂ may occur also via reaction with N₂H⁺. The CH₃OH and N₂H⁺ column densities used to compute $X[\text{CH}_3\text{OH}]$ and $X[\text{N}_2\text{H}^+]$ have been taken from Fontani et al. (2015a) and Fontani et al. (2015b), respectively, and rescaled to the beam of the HOCO⁺ observations.

The H¹³CO⁺ column densities used to derive $X[\text{H}^{13}\text{CO}^+]$ have been estimated from the integrated intensities of the H¹³CO⁺ 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 CH₃OH and HOCO⁺, while H¹³CO⁺ and HOCO⁺ seems positively correlated. By applying simple statistical tests to the detected sources only, the correlation co-

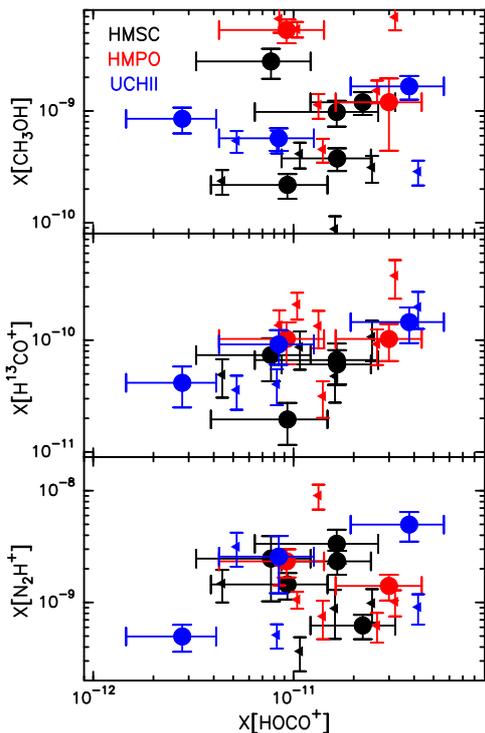


Figure 3. Abundance of HOCO⁺ against that of, from top to bottom: CH₃OH, H¹³CO⁺, and N₂H⁺. The colours indicate the different evolutionary groups as labelled in the top-left corner. The large filled symbols correspond to the detected sources, while the small triangles indicate the upper limits on the abundance of HOCO⁺. In the panel with X[H¹³CO⁺], we do not show 05358-mm3, observed and detected in CH₃OH, N₂H⁺ and HOCO⁺ but not in H¹³CO⁺.

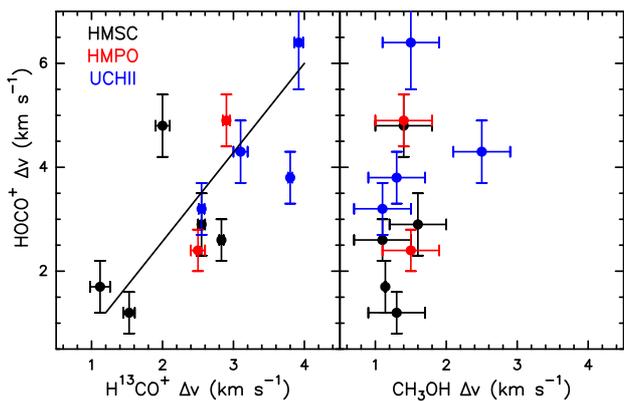


Figure 4. Line widths at half maximum, Δv , of H¹³CO⁺ (left panel) and CH₃OH (right panel) against those of HOCO⁺. The colours indicate the different evolutionary groups as in Fig. 3. The solid line in the left panel corresponds to a linear fit to the data.

efficient (Pearson’s ρ) between X[HOCO⁺] and X[H¹³CO⁺] is 0.7. Considering also the upper limits, the correlation remains positive (Pearson’s $\rho = 0.6$). The correlation between X[HOCO⁺] and X[N₂H⁺] is positive (Pearson’s $\rho = 0.4$ without the upper limits) but much less convincing. If we assume that both CO₂ and CH₃OH 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[CH₃OH] and X[N₂H⁺] would indicate that the origin of HOCO⁺ is likely not from CO₂ evaporated from ice mantles. This interpretation has two big caveats. First, the formation processes of CO₂ and CH₃OH on the surfaces of dust grains can be different. In fact, CO₂ is thought to form in water ice mantles of cold carbonaceous grains via cosmic-ray bombardment (Mennella et al. 2004), or via the surface reaction CO + OH at dust temperatures of ~30 K (Garrod & Pauly 2011), while CH₃OH 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 CO₂ is H₃⁺ and not N₂H⁺. Nevertheless, the positive correlation between X[H¹³CO⁺] 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 H¹³CO⁺ 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 H¹³CO⁺, but not with those of CH₃OH (which are always narrower). Hence, CH₃OH 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 (28'') 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.

Acknowledgments. We thank the IRAM-30m staff for the precious help during the observations. We thank the anonymous referee for his/her constructive comments. V.M.R. and M.P. acknowledge the financial support received from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 664931. L.C. acknowledges support from the Italian Ministero dell’Istruzione, Università e Ricerca through the grant Progetti Premiali 2012 - iALMA (CUP C52I13000140001). P.C. acknowledges support from the European Research Council (ERC project PALs 320620).

REFERENCES

Belloche, A., Müller, H.S.P., Menten, K.M., Schilke, P., Comito, C. 2013, *A&A*, 559, 47
 Bergin, E.A., Melnick, G.J., Gerakines, P.A., Neufeld, D.A., Whittet, D.C.B. 2005, *ApJ*, 627, L33

- Bizzocchi, L., Lattanzi, V., Laas, J., Spezzano, S., Giuliano, B.M., Prudenzeno, D., Endres, C. et al. 2017, *A&A*, 602, 34
- Bogey, M., Demuynck, C., Destombes, J.-L. 1986, *JChPh*, 84, 10
- Boogert, A.C.A., Gerakines, P.A., Whittet, D.C.B. 2015, *ARA&A*, 53, 541
- Caselli, P., Walmsley, C.M., Zucconi, A., et al. 2002, *ApJ*, 565, 344
- Colzi, L., Fontani, F., Caselli, P., Ceccarelli, C., Hily-Blant, P., Bizzocchi, L. 2018a, *A&A*, 609, 129
- Colzi, L., Fontani, F., Rivilla, V.M., Sánchez-Monge, A., Testi, L., Beltrán, M.T., Caselli, P. 2018b, *MNRAS*, 478, 3693
- Cooke, I.R., Fayolle, E.C., Öberg, K.I. 2016, *ApJ*, 832, 5
- D'Hendecourt, L.B., Allamandola, L.J., Grim, R.J.A., Greenberg, J.M. 1986, *A&A*, 158, 119
- Di Francesco, J., Johnstone, D. Kirk, H., MacKenzie, T., Ledwosinska, E. 2008, *ApJS*, 175, 277
- Fontani, F., Palau, A., Caselli, P., Sánchez-Monge, Á., Butler, M. J. 2011, *A&A*, 529, L7
- Fontani, F., Sakai, T., Furuya, K., Sakai, N., Aikawa, Y., Yamamoto, S. 2014, *MNRAS*, 440, 448
- Fontani, F., Busquet, G., Palau, Aina, Caselli, P., Sánchez-Monge, Á., Tan, J.C., Audard, M. 2015a, *A&A*, 575, 87
- Fontani, F., Caselli, P., Palau, A., Bizzocchi, L., Ceccarelli, C. 2015b, *ApJ*, 808, L46
- Fontani, F., Rivilla, V.M., Caselli, P., Vasyunin, A., Palau, A. 2016, *ApJ*, 822, L30
- Garrod, R.T & Pauly, T. 2011, *ApJ*, 735, 15
- Hoang, M., Altwegg, K., Balsiger, H., Beth, A., Bieler, A. et al. 2017, *A&A*, 600, 77
- Ioppolo, S., van Boheemen, Y., Cuppen, H.M., van Dishoeck, E.F., Linnartz, H. 2011, *MNRAS*, 413, 2281
- Kutner, M.L. & Ulich, B.L. 1981, *ApJ*, 250, 341
- Majumdar, L., Gratier, P., Wakelam, V., Caux, E., Willacy, K., Ressler, M.E. 2018, *MNRAS*, 477, 525
- McKay, A.J., Kelley, M.S.P., Cochran, A.L., Bodewits, D., DiSanti, M.A., Russo, N.D., Lisse, C.M. 2016, *Icarus*, 266, 249
- Mennella, V., Palumbo, M.E., Baratta, G.A. 2004, *ApJ*, 615, 1073
- Minh, Y.C., Brewer, M.K., Irvine, W.M., Friberg, P., Johansson, L.E.B. 1991, *A&A*, 244, 470
- Mininni, C., Fontani, F., Rivilla, V.M., Beltrán, M.T., Caselli, P., Vasyunin, A. 2018, *arXiv:180200623*
- Neill, J. L., Bergin, E. A., Lis, D. C., et al. 2014, *ApJ*, 789, 8
- Noble, J.A., Dulieu, F., Congiu, E., Fraser, H.J. 2011, *ApJ*, 735, 121
- Öberg, K.I., Boogert, A.C.A., Pontoppidan, K.M., van den Broek, S., van Dishoeck, E.F., et al. 2011, *ApJ*, 740, 109
- Podio, L., Lefloch, B., Ceccarelli, C., Codella, C., Bachiller, R. 2014, *A&A*, 565, 64
- Rivilla, V.M., Fontani, F., Beltrán, M.T., Vasyunin, A., Caselli, P., Martín-Pintado, J., Cesaroni, R. 2016, *ApJ*, 826, 161
- Sakai, N., Sakai, T., Aikawa, Y., Yamamoto, S. 2008, *ApJ*, 675, L89
- Thaddeus, P., Guelin, M., & Linke, R. A. 1981, *ApJ*, 246, L41
- Turner, B. E., Terzieva, R., & Herbst, E. 1999, *ApJ*, 518, 699
- van Dishoeck, E.F., Helmich, F.P., de Graauw, T., Black, J.H., Boogert, A.C.A., et al. 1996, *A&A*, 315, L349
- Vastel, C., Ceccarelli, C., Lefloch, B., Bachiller, R. 2016, *A&A*, 591, L2
- Vasyunin, A.I., Caselli, P., Dulieu, F., Jiménez-Serra, I. 2017, *ApJ*, 842, 33
- Whittet, D.C.B., Cook, A.M., Chiar, J.E., Pendleton, Y.J., Shenoy, S.S., Gerakines, P. A. 2009, *ApJ*, 695, 94