THE ORIGIN OF COMPLEX ORGANIC MOLECULES IN PRESTELLAR CORES

1. INTRODUCTION

Interstellar complex organic molecules (hereinafter COMs) are defined in the astrochemical literature as organic molecules containing at least six heavy atoms (Herbst & van Dishoeck 2009). Among the discovered interstellar molecules, COMs are of particular interest for their potential relation with the origin of the terrestrial life and, more prosaically, because they are a powerful diagnostic to understand matter chemical evolution during the formation of planetary systems like our own (Caselli & Ceccarelli 2012).

COMs were first detected in hot cores associated with high-mass, star-forming regions (Cummins et al. 1986; Blake et al. 1987). Since then, they have been discovered in a variety of environments such as low-mass hot corinos (Cazaux et al. 2003; Bottinelli et al. 2004; Ceccarelli 2005) and cold envelopes (Jaber 2006), and prestellar cores (¨Oberg et al. 2010; Cernicharo et al. 2014), Galactic center cold clouds (Requena-Torres et al. 2015), and recently in the circumstellar material of YSOs (Fukagawa et al. 2015). For the latter, high-resolution observations revealed the presence of these molecules in the form of extended emission (¨Oberg et al. 2010). The discovery of COMs in low-mass objects up to the very last stages of the protostellar phase is a hallmark of the astrochemical activity occurring in the interstellar medium. The formation of high-mass stars is accompanied by an increase in the amount of COMs (Herbst & van Dishoeck 2009), suggesting that the origin of COMs is closely related to the birth of massive stars. The detection of COMs in prestellar objects is important for understanding both (1) the origin of the molecules in the interstellar medium, (2) the chemical evolution of the gas and dust in the early stages of star formation, and (3) the impact of these molecules on the formation of new stars.

2. THE SOURCE

L1544 is a prototypical starless core in the Taurus molecular cloud complex (d ~ 140 pc) on the verge of gravitational collapse (Caselli et al. 2002, and references within). It is characterized by a central high-density (2 × 10^6 cm^-3), low-temperature (~7 K; Crapsi et al. 2007), and high CO depletion, accompanied by a large degree of molecular deuteration (Caselli et al. 2003; Crapsi et al. 2005; Vastel et al. 2006). Its physical and dynamical conditions make it an ideal target for studying the origin of COMs in prestellar objects.

3. Previous works have shown that water vapor is enhanced in the same environments such as low-mass hot corinos (Cazaux et al. 2003; Bottinelli et al. 2004; Ceccarelli 2005) and cold envelopes (Jaber 2006), and prestellar cores (¨Oberg et al. 2010; Cernicharo et al. 2014). Galactic center cold clouds (Requena-Torres et al. 2015), and recently in the circumstellar material of YSOs (Fukagawa et al. 2015). For the latter, high-resolution observations revealed the presence of these molecules in the form of extended emission (¨Oberg et al. 2010). The discovery of COMs in low-mass objects up to the very last stages of the protostellar phase is a hallmark of the astrochemical activity occurring in the interstellar medium. The formation of high-mass stars is accompanied by an increase in the amount of COMs (Herbst & van Dishoeck 2009), suggesting that the origin of COMs is closely related to the birth of massive stars. The detection of COMs in prestellar objects is important for understanding both (1) the origin of the molecules in the interstellar medium, (2) the chemical evolution of the gas and dust in the early stages of star formation, and (3) the impact of these molecules on the formation of new stars.

4. The non-LTE analysis of the methanol lines shows that they are likely emitted at the border of the core at a radius of ~8000 AU, where T ∼ 10 K and n_H2 ∼ 2 × 10^4 cm^-3. Previous works have shown that water vapor is enhanced in the same region because of the photodesorption of water ices. We propose that a non-thermal desorption mechanism is also responsible for the observed emission of methanol and COMs from the same layer. The desorbed oxygen and a small amount of desorbed methanol and ethene are enough to reproduce the abundances of tricarbon monoxide, methanol, acetaldehyde, and ketene measured in L1544. These new findings open the possibility that COMs in prestellar cores originate in a similar outer layer rather than in the dense inner cores, as previously assumed, and that their formation is driven by the non-thermally desorbed species.

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ABSTRACT

Complex organic molecules (COMs) have been detected in a variety of environments including cold prestellar cores. Given the low temperatures of these objects, these detections challenge existing models. We report here new observations toward the prestellar core L1544. They are based on an unbiased spectral survey of the 3 mm band at the IRAM 30 m telescope as part of the Large Program ASAI. The observations allow us to provide a full census of the oxygen-bearing COMs in this source. We detected tricarbon monoxide, methanol, acetaldehyde, formic acid, ketene, and propyne with abundances varying from 5 × 10^-11 to 6 × 10^-9. The non-LTE analysis of the methanol lines shows that they are likely emitted at the border of the core at a radius of ~8000 AU, where T ∼ 10 K and n_H2 ∼ 2 × 10^4 cm^-3. Previous works have shown that water vapor is enhanced in the same region because of the photodesorption of water ices. We propose that a non-thermal desorption mechanism is also responsible for the observed emission of methanol and COMs from the same layer. The desorbed oxygen and a small amount of desorbed methanol and ethene are enough to reproduce the abundances of tricarbon monoxide, methanol, acetaldehyde, and ketene measured in L1544. These new findings open the possibility that COMs in prestellar cores originate in a similar outer layer rather than in the dense inner cores, as previously assumed, and that their formation is driven by the non-thermally desorbed species.

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Received 2014 August 8; accepted 2014 September 23; published 2014 October 10
structure has recently been reconstructed by Caselli et al. (2012, hereinafter CKB2012) and Keto et al. (2014) using numerous existing observations toward L1544. Among them, we emphasize the recent detection of water vapor by the Herschel Space Observatory, the first water detection in a prestellar core, which provided key information for reconstructing the physical and chemical structure of L1544 (CKB2012). In fact, the observed water line shows an inverse P-Cygni profile, characteristic of gravitational contraction, confirming that L1544 is on the verge of collapse. Based on the line shape, CKB2012 predict that water is largely frozen into the grain mantles in the interior (<4000 AU) of the L1544 core, where the gaseous H2O abundance (with respect to H2) is only ~10−9. The low (but not zero) level of water vapor is believed to be caused by the photodesorption of water molecules from the icy mantles by the FUV photons created by the interaction of cosmic rays with H2 molecules. Farther away from the center (~104 AU), where the density is low enough (<109 cm−3) that the photodesorption rate is not overcome by the freeze-out rate, the gaseous H2O abundance reaches ~3 × 10−7, as predicted by previous models (Dominik et al. 2005; Hollenbach et al. 2009).

3. OBSERVATIONS AND RESULTS

The observations were performed on 2013 July 3 and 2013 September 10 toward L1544 (α2000 = 05h04m17.21s, δ2000 = 25°10′42″S). Using the 3 mm Eight Mixer Receivers (16 GHz of total instantaneous bandwidth per polarization) and the fast Fourier transform spectrometers with a spectral resolution of 50 kHz (allowing for the observation of the inner 1.82 GHz of each band), six set ups were needed to cover the full band, namely, the frequency range between 81 and 110 GHz. Two higher-energy level transitions of the C3O species, at 96.2 and 105.8 GHz, respectively, were observed during the 2014 January run to reach a better rms.

Weather conditions were averaged with 2–3 mm of precipitable water vapor. System temperatures were between 110 and 180 K, resulting in an average rms of 4–7 mK in a 50 kHz frequency bin. In order to obtain a flat baseline, observations were carried out using a nutating secondary mirror, with a throw of 3′. No contamination from the reference position was observed. Pointing was checked every 1.5 hr on the nearby continuum sources 0439+360 and 0528+134. Pointing errors were always within 3″. We adopted telescope and receiver parameters (main-beam efficiency, half power beam width, forward efficiency) from the values monitored at IRAM (http://www.iram.fr). Line intensities are expressed in units of main-beam brightness temperature.

We detected several lines from E- and A-CH3OH and 13CH3OH, CH3CHO, t-HCOOH, H2CCO, E-CH3CCH, and C3O. All lines, detected for the first time in L1544, are in emission, except the 107 GHz line of E-CH3OH, which appears in absorption. We did not detect any other oxygen-bearing COM. Important non-detections include CH3OCH3, HCOOCH3, and CH3O, which were, on the contrary, detected in other prestellar cores (Oberg et al. 2010; Cernicharo et al. 2012; Bachmann et al. 2012).

Figures 1 and 2 show the detected transitions of C3O, A- and E-CH3OH, CH3CHO, t-HCOOH, H2CCO, E-CH3CCH. Using the CASSIS software, the lines have been fitted using the Levenberg–Marquardt function. The parameters resulting from the fit are listed in Table 1.

4. DERIVATION OF THE COLUMN DENSITIES

We carried out an LTE analysis of the observed line intensities for all of the detected species (except CH3OH; see below). We assumed that the source fills the beam and we carried out a rotational diagram analysis for the species in which more than one line has been detected, namely, all the detected species except C3O and t-HCOOH. Specifically, we computed a grid of LTE models for the CH3CHO, H2CCO, and E-CH3CCH lines. Then, for each species, we found the best-fit parameters varying the linewidth, Vlsr, excitation temperature (assumed to be the same in all observed lines), and column density. In the cases of C3O and t-HCOOH, we adopted an excitation temperature equal to 10 K. The results of this analysis are reported in Table 2.

In the case of CH3OH, we carried out a non-LTE analysis, considering the A and E forms separately and assuming an abundance ratio 1:1 between them and 12C/13C equal to 75. We used the large velocity gradient (LVG) code described in Ceccarelli et al. (2003) and the collisional rates by Rabli & Flower (2010), retrieved from the BASECOL database (http://basecol.obspm.fr; Dubernet et al. 2013). We run a large grid of models varying the methanol column density from 5 × 1012 to 6 × 1013 cm−2, the density from 1 × 104 to 1 × 106 cm−3, the temperature from 7 to 16 K, and the source size from 1″ to 200″. For each methanol column density, we found the source size, temperature, and density with the minimum reduced χ2. All solutions with reduced χ2 ≤ 0.8 are considered to be good (equivalent to a probability of 1σ). With this criterion, we found that CH3OH column densities between 2.6 and 3.8 × 1013 cm−2 are consistent with the data. The observed lines are optically thick for N(CH3OH) ≥ 3.8 × 1013 cm−2 and this allows us to also constrain the emitting size to be larger than about 30″. At larger sizes, the beam-filling factor becomes unity and the lines become optically thin. The temperature and density are degenerate, as shown in Figure 3 for the two extreme methanol column densities. Note, however, that the derived density is ≤ 1014 cm−3 and the temperature is between 7 and 15 K for a

5 http://cassis.irap.omp.eu/
Figure 2. Spectra of the detected lines from t-HCOOH (top panel), H2CCO (central panel), and CH3CHO (bottom panel). The temperatures are main-beam temperatures.

Figure 3. Results from the LVG analysis of the CH3OH lines. The black lines show the $\chi^2 = 0.8$ contour plot for $N(\text{CH}_3\text{OH}) = 3.8 \times 10^{13}$ cm$^{-2}$ and a size of 30$''$ (dashed) and $N(\text{CH}_3\text{OH}) = 2.6 \times 10^{13}$ cm$^{-2}$) and size 100$''$ (solid), the two extremes of the solutions with reduced $\chi^2 \leq 0.8$. The gray line shows the densities and temperatures at different distances from the center (diameter in arcseconds are marked along the curve) predicted for the structures of L1544 by CKB2012.

The density between $10^4$ and $10^5$ cm$^{-3}$. Note also that the best-fit models correctly reproduce the absorption line at 107 GHz.

Finally, the non-detection of lines from CH3OCH3, HCOOCH3, and CH3O provide upper limits to their column density of $1 \times 10^{12}$, $6 \times 10^{12}$, and $6 \times 10^{11}$, respectively.

5. SPATIAL ORIGIN AND ABUNDANCES OF THE COMs

The analysis of the CH$_3$OH lines provides a strong constraint on the gas density, which has to be $\leq 10^5$ cm$^{-3}$. This means that the bulk of the CH$_3$OH emission does not originate in the dense interior of the L1544 core, but in a less dense, external zone. In order to constrain the location of the CH$_3$OH, we overplot the density and temperature structure derived by CKB2012 on the density--temperature $\chi^2$ contour plot of the LVG analysis. As can be seen from Figure 3, the density--temperature $\chi^2$ contours intercept the L1544 structure when the source size is between 100$''$ and 140$''$, namely, the CH$_3$OH emitting gas is at a radius between about 6800 and 9600 AU from the center. At these radii, the CKB2012 structure predicts a density of $3\,–\,1.5 \times 10^4$ cm$^{-3}$ and a temperature of $\sim 10$ K. The very recent work by Bizzocchi et al. (2014) reaches the same conclusion.

The coincidence between the CH$_3$OH-emitting region with that where the gaseous water abundance is the largest (see
Section 2) is remarkable. In other words, the LVG analysis strongly suggests that methanol has an enhanced abundance where the FUV photons desorb water molecules. It is therefore natural to conclude that methanol has the same origin, namely, it is photodesorbed from the icy mantles (Andrade et al. 2010).

The identification of the region where the CH$_3$OH lines are emitted has an obvious impact on the estimate of the methanol abundance, as, in order to obtain it, one must divide the measured column density of Table 2 by the H$_2$ column density of the emitting region, namely, $\sim 6 \times 10^{21}$ cm$^{-2}$, and not the entire L1544 core, which is $\sim 30$ times larger. Therefore, the (E + A) methanol abundance is $\sim 6 \times 10^{-9}$.

It is natural to assume that the emission from the other COMs detected comes from the same outer layer of L1544, rather than the core itself. The rotational temperatures ($\geq 10$ K) in Table 2 support this hypothesis. Therefore, we computed the COMs’ abundances following this assumption. The resulting abundances, reported in Table 2, vary from $\sim 5 \times 10^{-9}$ for the CH$_3$CCH, the most abundant COM after methanol, to $\sim 5 \times 10^{-11}$ for C$_3$O, the least abundant. Finally, the upper limits to the column density of CH$_3$OH$_3$, HCOOH$_3$, and CH$_3$O$_2$ convert into an upper limit to their abundances of $2 \times 10^{-10}$, $1.5 \times 10^{-9}$, and $1.5 \times 10^{-10}$, respectively.

### 6. CHEMICAL MODELING

In order to shed light on the formation pathways of the observed COMs, we run a simple chemical model where we first computed the steady state abundances of all the species and then studied the effect on the COMs’ abundances caused by the injection of grain mantle species with the gas phase. We do not pretend here to describe the situation with a self-consistent model, but just to understand what species from the mantles are needed to reproduce the observed COMs and in what approximate amount. To make this as simple as possible,
we considered two species: methanol, known to be present in the mantles, and ethene (C₂H₆). The latter has not been detected in the ices (with an abundance larger than \( \sim 10^{-7} \)), but it is the first step toward ethane (C₂H₆), whose oxidation leads to acetaldehyde, among other oxygen-bearing COMs (Charnley 2004). In addition, we considered the elemental oxygen (in the gas) as a parameter in order to account for the amount of oxygen trapped into the mantle ices.

We used the Nahoon gas-phase chemical model (http://kida.obs.u-bordeaux1.fr/models/; Wakelam et al. 2010), which computes the chemical evolution of a species as a function of time for a fixed temperature and density. The chemical network kida.uva.2011 (http://kida.obs.u-bordeaux1.fr/) has been updated following Loison et al. (2014) and includes 6680 reactions over 486 species. In our computations, we used the following elemental abundances (with respect to H nuclei): \( \text{He} = 0.07 \), \( \text{C} = 5 \times 10^{-8} \), \( \text{N} = 2 \times 10^{-9} \), \( \text{Si} = 8 \times 10^{-9} \), \( \text{S} = 8 \times 10^{-8} \), \( \text{Fe} = 3 \times 10^{-9} \), \( \text{Na} = 2 \times 10^{-9} \), \( \text{Mg} = 7 \times 10^{-9} \), \( \text{Cl} = 1 \times 10^{-8} \), and \( \text{P} = 2 \times 10^{-10} \). The oxygen elemental abundance was such to have the following C/O abundance ratios: 0.5, 0.6, 0.7, and 0.8. For the first step, we adopted a gas and dust temperature of 10 K, an H density of \( 2 \times 10^4 \text{ cm}^{-3} \), a visual extinction of 10 mag, and a cosmic ray ionization rate of \( 3 \times 10^{-17} \text{ s}^{-1} \). We let the chemical composition evolve until a steady state is reached. The abundances from this first step were then used as initial abundances for the second step, where we changed the abundance of methanol and ethene separately. In the following, we discuss the results for the detected species.

C₃O is the longest oxygen-bearing carbon chain observed in the interstellar medium. So far, very few detections of C₃O have been reported and only one in a cold dark cloud core, TMC-1, unusually carbon-rich (Matthews et al. 1984; Kaifu et al. 2004). Loison et al. (2014) showed that the reactions between carbon chain molecules and radicals (\( \text{C}_n, \text{C}_n\text{H}, \text{C}_n\text{H}_2, \text{C}_n\text{H}_3, \text{O} \ldots \)) with O atoms produce large enough abundances of C₃O. We therefore started modeling this species as it provides constraints on the amount of gaseous oxygen. We could reproduce the observed C₃O abundance only when the lowest C/O ratio of 0.5 is used, namely, when a large fraction of oxygen is in the gas phase. This is in remarkable agreement with the CKB2012 model, which predicts that a large fraction of water is photodesorbed from the grain mantles, making the gas oxygen-rich.

CH₃OH is known to be a grain surface product, so that it is no surprising that a pure gas-phase model does not reproduce the measured abundance. Injecting \( \sim 1 \times 10^{-8} \) methanol from the ices provides the observed amount of methanol. This is a small fraction with respect to the methanol formed on the grain surfaces during the prestellar phase (e.g., Taquet et al. 2012).

CH₃CHO and H₂CCO are overabundant with respect to the predictions of the model in step 1 by about three and one orders of magnitude, respectively. However, the injection of ethene with an abundance of \( 5 \times 10^{-9} \) is enough to reproduce the measured abundances through the following sequences (Charnley 2004):

\[
\begin{align*}
\text{C}_2\text{H}_4 & \xrightarrow{H} \text{C}_2\text{H}_6 \xrightarrow{\text{III}} \text{C}_2\text{H}_7 \xrightarrow{O} \text{C}_2\text{H}_8 \xrightarrow{\text{H}_2} \text{CH}_3\text{CHO} \quad (1) \\
\text{C}_2\text{H}_4 & \xrightarrow{\text{III}} \text{C}_2\text{H}_5 \xrightarrow{O} \text{C}_2\text{H}_3 \xrightarrow{\text{H}_2} \text{H}_2\text{CCO} \quad (2)
\end{align*}
\]

CH₃CCH is also overabundant with respect to the predictions of the model in step 1 by about five orders of magnitude. The injection of \( 5 \times 10^{-9} \) ethene increases the abundance by three orders of magnitude but it is still not enough to reproduce the measured abundance. Öberg et al. (2013) suggested that an important formation pathway in cold gas is missing for CH₃CCH in the models, as reinforced by our new measurements.

t-HCOOH is the only species underabundant with respect to the predicted value of the model in step 1 by about one order of magnitude. This suggests that, in this case, routes of destruction of this species are probably missing.

Finally, the non-detections of CH₃OCH₃, HCOOCH₃, and CH₃O are consistent with our and the Vasyunin & Herbst (2013) model predictions.

7. DISCUSSION AND CONCLUSIONS

The three major results of this work are as follows.

1. The detection of CH₃OH, CH₃CHO, t-HCOOH, H₂CCO, CH₃CCH, and C₃O. Their abundances are equal to \( \sim 1 \times 10^{-11} \) (CH₃CHO and t-HCOOH), \( \sim 5 \times 10^{-11} \) (C₃O), \( \sim 1 \times 10^{-12} \) (H₂CCO), \( \sim 5 \times 10^{-13} \) (CH₃CCH), and \( \sim 6 \times 10^{-15} \) (CH₃O). No other oxygen-bearing COM has been detected, including CH₃OCH₃, HCOOCH₃, and CH₃O, species that have been detected in other prestellar cores (Section 1). The upper limit to their abundances is \( \lesssim 10^{-9} \) to \( 10^{-10} \).

2. The gas must be oxygen-rich (C/O \( \sim 0.5 \)) and an injection of a relatively small amount of methanol (\( \sim 10^{-8} \)) and ethene (\( \sim 5 \times 10^{-7} \)) from the ices is enough to reproduce the observed abundances of CH₃OH, CH₃CHO, H₂CCO, and C₃O. On the contrary, the model overestimates the abundance of t-HCOOH and underestimates that of CH₃CCH.

3. It is likely that the most important result is the discovery that the CH₃OH emission comes from the border of the L1544 core, at \( \sim 8000 \) AU, in a region where the ices are desorbed through non-thermal processes. We suggest that it is also very likely that the other COMs detected have the same origin. The large rotational temperatures support this hypothesis.

L1544 is the third prestellar core, after B1-b and L1689B, where COMs have been detected (Öberg et al. 2010; Cernicharo et al. 2012; Bacmann et al. 2012). In the three cores, acetaldehyde, ketene, and acid formic have similar column densities (within factors of three to four). The same applies to methanol in L1544 and B1-b. Finally, the column densities of methyl formate and dimethyl ether are also similar in B1-b and L1689B, and consistent with our upper limits. This may lead to the supposition that the observed COM line emission in B1-b and L1689B also originates in an outer layer where desorption is not fully compensated by the freeze out rather than in the core. If this is the case, the COMs’ chemistry in prestellar cores may be driven by the non-thermal desorption of simple ice components, namely, hydrogenated species like methanol and ethene, and not necessarily by other processes (e.g., Cernicharo et al. 2012; Vasyunin & Herbst 2013).

In conclusion, L1544 is a core on the verge of collapsing (Caselli et al. 2002; Keto et al. 2014). The center of the core is very cold and dense, and all species are largely frozen onto the grain mantles (CKB2012). There is, however, a region, at \( \sim 8000 \) AU from the center where FUV photons (the product of the interaction of cosmic rays with the H₂ molecules, according to CKB2012) photodesorb a small fraction of the frozen water and possibly methanol and ethene. These molecules react with other species in the gas phase and produce a detectable amount of acetaldehyde, ketene, and tricarbon monoxide. It is possible, but not demonstrated, that a similar situation also occurs in the vicinity of L1544.
other prestellar cores, for example, in B1-b and L1689B, where previous observations have detected COMs with similar column densities. If this is the case, the quoted abundances may need some revision. Also, in these cases, the COMs’ chemistry may be driven by the desorption of simple hydrogenated species from the ices. Higher spatial resolution observations are necessary to settle the issue and better constrain the formation routes of COMs in prestellar cores.

We thank P. Caselli, J. C. Loison, and M. Ruaud for helpful discussions.

Facilities: IRAM:30m

REFERENCES

Andrade, D. P. P., Rocco, M. L. M., & Boechat-Roberty, H. M. 2010, MNRAS, 409, 1289
Bacmann, A., Taquet, V., Faure, A., Kahane, C., & Ceccarelli, C. 2012, A&A, 541, 12
Bizzocchi, L., Caselli, P., Spezzano, S., & Leonardo, E. 2014, A&A, 569, A27
Blake, G. A., Sutton, E. C., Masson, C. R., & Phillips, T. G. 1987, ApJ, 315, 621
Bottinelli, S., Ceccarelli, C., Lefloch, B., et al. 2004, ApJ, 615, 354
Caselli, P., & Ceccarelli, C. 2012, A&ARv, 20, 56
Caselli, P., Keto, E., Bergin, E. A., et al. 2012, ApJL, 759, L37 (CKB2012)
Caselli, P., van der Tak, F. F. S., Ceccarelli, C., & Bacmann, A. 2003, A&A, 403, 37
Caselli, P., Walmsley, C. M., Zucconi, A., et al. 2002, ApJ, 565, 331
Cazaux, S., Tielens, A. G. G. M., Ceccarelli, C., et al. 2003, ApJ, 593, 51
Ceccarelli, C. 2005, in Astrochemistry: Recent Successes and Current Challenges, ed. D. C. Lis, G. A. Blake, & E. Herbst (Cambridge: Cambridge Univ. Press), 1