THE CENSUS OF COMPLEX ORGANIC MOLECULES IN THE SOLAR-TYPE PROTOSTAR IRAS16293-2422

Ali A. Jaber1,2,3, C. Ceccarelli1,2, C. Kahane1,2, and E. Caux4,5
1 Université Grenoble Alpes, IPAG, F-38000 Grenoble, France
2 CNRS, IPAG, F-38000 Grenoble, France
3 University of AL-Muthana, AL-Muthana, Iraq
4 Université de Toulouse, UPS-OMP, IRAP, F-31400 Toulouse, France
5 CNRS, IRAP, 9 Av. Colonel Roche, BP 44346, F-31028 Toulouse Cedex 4, France

Received 2014 January 14; accepted 2014 June 23; published 2014 July 23

ABSTRACT

Complex organic molecules (COMs) are considered to be crucial molecules, since they are connected with organic chemistry, at the basis of terrestrial life. More pragmatically, they are molecules which in principle are difficult to synthesize in harsh interstellar environments and, therefore, are a crucial test for astrochemical models. Current models assume that several COMs are synthesized on lukewarm grain surfaces ($\gtrsim 30–40$ K) and released in the gas phase at dust temperatures of $\gtrsim 100$ K. However, recent detections of COMs in $\lesssim 20$ K gas demonstrate that we still need important pieces to complete the puzzle of COMs formation. Here, we present a complete census of the oxygen- and nitrogen-bearing COMs, previously detected in different Interstellar Medium (ISM) regions, toward the solar-type protostar IRAS16293-2422. The census was obtained from the millimeter–submillimeter unbiased spectral survey TIMASSS. Of the 29 COMs searched for, 6 were detected: methyl cyanide, ketene, acetalddehyde, formamide, dimethyl ether, and methyl formate. Multifrequency analysis of the last five COMs provides clear evidence that they are present in the cold ($\lesssim 30$ K) envelope of IRAS16293-2422, with abundances of $0.03–2 \times 10^{-10}$. Our data do not allow us to support the hypothesis that the COMs abundance increases with increasing dust temperature in the cold envelope, as expected if COMs were predominately formed on lukewarm grain surfaces. Finally, when also considering other ISM sources, we find a strong correlation over five orders of magnitude between methyl formate and dimethyl ether, and methyl formate and formamide abundances, which may point to a link between these two couples of species in cold and warm gas.

Key words: ISM: abundances – ISM: molecules – stars: formation

Online-only material: color figure

1. INTRODUCTION

Complex organic molecules (COMs), namely, organic molecules with more than six atoms (Herbst & van Dishoeck 2009), have been known for more than four decades (Ball et al. 1971; Rubin et al. 1971; Solomon et al. 1971; Brown et al. 1975; Blake et al. 1987). Since some COMs have a prebiotic relevance, they immediately evoke great interest and several models were developed to explain why and how these molecules are formed in space. Those models were based on a two-step process: (1) “mother” (or first generation) species were created during the cold star formation process and frozen into the grain mantles; (2) “daughter” (or second generation) species were synthesized via gas phase reactions from mother species in the warm ($\gtrsim 200$ K) regions where the grain mantles sublimate (Millar et al. 1991; Charnley et al. 1992; Caselli et al. 1993). This two-step paradigm enjoyed great success for about a decade, until new observations toward low mass hot corinos (Ceccarelli et al. 2000; Cazaux et al. 2003) and Galactic center molecular clouds (Requena-Torres et al. 2006) challenged the assumption that COMs are formed by gas phase reactions. At the same time, new laboratory experiments and theoretical computations revisited and ruled out some gas phase reactions which are crucial to those models (Horn et al. 2004; Geppert et al. 2007). Attention then moved toward the possibility that grains could act as catalysts and that COMs could form on their surfaces at lukewarm ($\gtrsim 30–40$ K) temperatures (Garrod et al. 2009). However, grain surface chemistry is even more difficult to understand than gas phase chemistry, both from theoretically and experimentally. Let us take the example of methanol, one of the simplest COMs. It is supposed to form on grain surfaces via successive hydrogenation of frozen CO (Tielens & Hagen 1982; Taquet et al. 2012). However, while laboratory experiments claim that this is the case (e.g., Watanabe & Kouchi 2002; Pirim et al. 2010), theoretical quantum chemistry computations show that the first and last steps toward CH$_3$OH formation have large (tens of KCal) energy barriers that are impossible to surmount in the cold ($\sim 10$ K) cloud conditions (Woon 2002; Marenich & Boggs 2003; Goumans et al. 2008) where CO hydrogenation is supposed to occur. To add to the confusion, recent observations have revealed that some COMs (notably acetalddehyde, methyl formate, and dimethyl ether) are found in definitively cold ($\lesssim 20$ K) regions (Oberg et al. 2010; Bacmann et al. 2012; Cornicharo et al. 2012), challenging the theory of the grain surface formation of COMs.

In this context, we examined the millimeter–submillimeter spectral survey performed toward the solar-type protostar IRAS16293-2422 (hereinafter IRAS16293; Caux et al. 2011) with the goal of extracting line emission from all oxygen- and nitrogen-bearing COMs already detected in the ISM, and to estimate their abundances across its envelope. Our emphasis here is on the abundances in the cold ($\lesssim 50$ K) region of the envelope in order to provide astrochemical modellers with the first systematic survey of COMs in cold gas.

2. SOURCE DESCRIPTION

IRAS16293 is a solar-type Class 0 protostar in the $\rho$ Ophiuchus star forming region, at a distance of 120 pc (Loinard et al. 2008). It has a bolometric luminosity of 22 $L_{\odot}$ (Crimier et al. 2010). Given its proximity and brightness, it has been the target
of numerous studies that have reconstructed its physical and chemical structure. Briefly, IRAS16293 has a large envelope that extends up to ~6000 AU and that surrounds two sources, named I16293-A and I16293-B in the literature, separated by ~5″ (~600 AU; Wootten 1989; Mundy et al. 1992). I16293-A sizes are ~1″, whereas I16293-B is unresolved at a scale of ~0′.4 (Zapata et al. 2013). I16293-A itself is composed of two sources, each one emitting a molecular outflow (Mizuno et al. 1990; Loinard et al. 2013). I16293-B possesses a very compact outflow (Loinard et al. 2013) and is surrounded by infalling gas (Pineda et al. 2012; Zapata et al. 2013). From a chemical point of view, IRAS16293 can be considered to be composed of an outer envelope, characterized by low molecular abundances, and a hot corino, where the abundance of many molecules increases by orders of magnitude (Ceccarelli et al. 2000; Schöier et al. 2002; Coutens et al. 2013). The transition between the two regions occurs at ~100 K, the sublimation temperature of the icy grain mantles. In the hot corino, several abundant COMs have been detected (Caux et al. 2003).

3. THE DATA SET
3.1. Observations

We used the data from The IRAS16293 Millimeter And Submillimeter Spectral Survey (TIMASSS9; Caux et al. 2011). Briefly, the survey covers the 80–280 and 328–366 GHz frequency intervals and was conducted with the IRAM 30 m and James Clerk Maxwell telescope 15 m telescopes. The data are publicly available on the TIMASSS Web site. Details on the data reduction and calibration can be found in Caux et al. (2011). Here, we review the major features which are relevant for this work. The telescope beam depends on the frequency and varies between 9″ and 30″. The spectral resolution varies between 0.3 and 1.25 MHz, corresponding to velocity resolutions between 0.51 and 2.25 km s\(^{-1}\). The achieved rms is between 4 and 17 mK. Note that it is given in a 1.5 km s\(^{-1}\) bin for observations taken with a velocity resolution of \(\lesssim\)1.5 km s\(^{-1}\), and in the resolution bin for larger velocity resolutions. The observations are centered on IRAS16293B at \(α(2000.0) = 16^h32^m22^s, δ(2000.0) = -24°28′33″\). Note that the A and B components are both inside the beam of observations at all frequencies.

3.2. Species Identification

We searched for the lines of all the oxygen- and nitrogen-bearing COMs already detected in the ISM (as reported in the CDMS database\(^8\); they are listed in Table 1. From this perspective, we used the list of identified lines in Caux et al. (2011) and double-checked for possible misidentifications. This was obtained via the publicly available package CASSIS\(^8\), and the CDMS (Müller et al. 2005) and JPL (Pickett et al. 1998) databases. References to the specific articles on the laboratory data of the detected species are Guarnieri & Huckauf (2003), Kleiner et al. (1996), Neustock et al. (1990), and Maeda et al. (2008). If the line identification is in doubt or if we detect the presence of important residual baseline effects, we do not consider the relevant line. Except for those few (~10%) cases, we used the line parameters (flux, linewidth, and rest velocity) from Caux et al. (2011). Using these tight criteria, we secured the detection of six COMs: ketene (\(H_2CCO\); 13 lines), acetaldehyde (\(CH_2CHO\); 130 lines), formamide (\(NH_2CHO\); 17 lines), dimethyl ether (\(CH_3OCH_3\); 65 lines), methyl formate (\(HCOOCH_3\); 121 lines), and methyl cyanide (\(CH_3CN\); 38 lines). For comparison, Cazaux et al. (2003) detected 5 \(CH_2CHO\) lines, 7 \(CH_3OCH_3\) lines, and 20 \(CH_3CHO\) lines. We do not confirm the Cazaux et al. (2003) detection of acetic acid (\(CH_3COOH\)) and formic acid (\(HCOOH\)), where these authors reported the possible detection of 1 and 2 lines, respectively, none of which are in the TIMASSS observed frequency range.

4. ANALYSIS AND RESULTS

4.1. Model Description

Our goal is to estimate the abundance of the detected COMs across the envelope of IRAS16293, with particular emphasis on the cold envelope (see the Introduction). For this purpose, we used the spectral line energy distribution (SLED) of the detected COMs, and the GRenoble Analysis of Protostellar Envelope Spectra (GRAPES) package, based on the code described in Ceccarelli et al. (1996, 2003). Briefly, (1) GRAPES computes the species SLED from a spherical infalling envelope with a given structure; (2) it solves locally the level population statistical equilibrium equations in the beta escape formalism, consistently computing the line optical depth by integrating it over the solid angle at each point of the envelope; and (3) the predicted line flux is then integrated over the whole envelope after convolution with the telescope beam. The abundance \(X\) of the considered species is assumed to vary as a function of the radius with power law in the cold part of the envelope and to jump to a new abundance in the warm part. The transition between the two regions is set by the dust temperature, to simulate the sublimation of the ice mantles, and occurs at \(T_{jump}\).

It holds:

\[
X(r) = X_{out} \left( \frac{r}{R_{max}} \right)^{\alpha} \quad T \leq T_{jump}
\]

\[
X(r) = X_{in} > T_{jump}.
\]

GRAPES allows us to run large grids of models varying the four parameters (\(X_{in}, X_{out}, \alpha, \text{ and } T_{jump}\)) and to find the best fit to the observed fluxes.

This code has disadvantages and advantages compared with other codes. The first, obvious disadvantage is that the spherical assumption only holds for the large-scale (\(\gg 10^6\): see Crimier et al. 2010) envelope of IRAS16293. At small scales, the presence of the binary system (Section 2) causes the spherical symmetry assumption to be wrong. Consequently, the GRAPES code is, by definition, unable to correctly estimate the emission from the two sources 116293-A and 116293-B separately. The derived inner envelope abundance is therefore likely a rough indication of the real abundance of the species toward 116293-A and 116293-B. The other disadvantage of GRAPES is that it relies on the analysis of the SLED and not on the line profiles. Since the majority of the TIMASSS spectra have a relatively poor spectral resolution (\(\gtrsim 1\) km s\(^{-1}\)), this is appropriate in this case. The great advantage of GRAPES, and the reason why we used it here, is that it is very fast, and so a large multi-parameter space can be explored.

In this work, we used the physical structure of the envelope of IRAS16293 as derived by Crimier et al. (2010), which is based on single-dish and interferometric continuum observations. Collisional coefficients are only available for methyl cyanide,
and not for the other five detected COMs. Since methyl cyanide is a top symmetric molecule, it represents a “particular case” with respect to the other detected COMs, so that in order to have a homogeneous data set, we decided here to analyze only the latter molecules and assume LTE for their level populations. The analysis of the CH$_3$CN molecule will be the only the latter molecules and assume LTE for their level is a top symmetric molecule, it represents a “particular case” and not for the other five detected COMs. Since methyl cyanide

| Species          | Formula          | $X_{\text{in}}$ ($10^{-8}$) | $X_{\text{out}}$ ($10^{-10}$) | $T_{\text{jump}}$ (K) | DF | $\chi^2$ | Radius (AU) | Size (″) |
|------------------|------------------|-----------------------------|-------------------------------|----------------------|----|----------|-------------|---------|
| Detected COMs    |                  |                             |                               |                      |    |          |             |         |
| Ketene           | H$_2$CCO         | 0.01 ± 0.005                | 0.3 ± 0.08                    | 20$^{+20}_{-10}$      | 10 | 0.63     | 1800        | 31      |
| Acetaldehyde     | CH$_3$CHO        | 0.3 ± 0.2                   | 1 ± 0.2                       | 70 ± 5               | 127| 0.79     | 127         | 2       |
| Formamide        | NH$_2$CHO        | 0.06 ± 0.02                 | 0.03 ± 0.02                   | 80 ± 5               | 14 | 0.69     | 100         | 2       |
| Dimethyl ether   | CH$_3$OCH$_3$    | 4 ± 1                       | 2 ± 1                         | 50 ± 10              | 62 | 0.72     | 240         | 4       |
| Methyl formate   | HCOOCH$_3$       | 0.9 ± 0.2                   | 0.3 ± 0.1                     | 50 ± 5               | 118| 0.78     | 240         | 4       |
| Vinyl alcohol    | C$_2$H$_5$OH     | ≤0.1                        | ≥3                            |                      |    |          |             |         |
| Ethanol          | C$_2$H$_5$OH     | ≤0.5                        | ≥8                            |                      |    |          |             |         |
| Formic acid      | HCOOH            | ≤0.03                       | ≥0.8                          |                      |    |          |             |         |
| Propynal         | HC$_2$CHO        | ≤0.02                       | ≥0.5                          |                      |    |          |             |         |
| Cyclopropenone   | c-H$_2$C$_2$O    | ≤0.004                      | ≥0.1                          |                      |    |          |             |         |
| Acrolein         | C$_2$H$_5$CHO    | ≤0.02                       | ≥0.6                          |                      |    |          |             |         |
| Acetone          | CH$_3$COCH$_3$   | ≤0.07                       | ≥2                            |                      |    |          |             |         |
| Propanal         | CH$_3$CH$_2$CHO  | ≤0.1                        | ≥2                            |                      |    |          |             |         |
| Glycolaldehyde   | CH$_3$(OH)CHO    | ≤0.1                        | ≥3                            |                      |    |          |             |         |
| Ethyl methyl ether | C$_2$H$_5$OCH$_3$ | ≤0.5                      | ≥9                            |                      |    |          |             |         |
| Ethyleneglycol   | (CH$_2$OH)$_2$   | ≤0.2                        | ≥5                            |                      |    |          |             |         |
| Ethyl formate    | C$_2$H$_5$OCHO   | ≤0.2                        | ≥5                            |                      |    |          |             |         |
| Methylamine      | CH$_3$NH$_2$     | ≤0.1                        | ≥3                            |                      |    |          |             |         |
| Methylisocyanide | CH$_3$NC         | ≤0.002                      | ≥0.07                         |                      |    |          |             |         |
| Etheneimine      | H$_2$CCNH        | ≤0.1                        | ≥2                            |                      |    |          |             |         |
| Cyanocacetylene+ | HC$_2$NH$^+$     | ≤0.01                       | ≥0.2                          |                      |    |          |             |         |
| Vinyl cyanide    | C$_2$H$_5$CN     | ≤0.01                       | ≥0.2                          |                      |    |          |             |         |
| Ethyl cyanide    | C$_2$H$_5$CN     | ≤0.02                       | ≥0.7                          |                      |    |          |             |         |
| Aminocetanitrite | H$_2$NCH$_2$CN   | ≤0.03                       | ≥0.7                          |                      |    |          |             |         |
| Cyanopropyne     | CH$_3$C$_2$N     | ≤0.002                      | ≥0.07                         |                      |    |          |             |         |
| n-Propyl cyanide | n-C$_3$H$_7$CN   | ≤0.05                       | ≥0.8                          |                      |    |          |             |         |
| Cyanopentadiyne  | CH$_3$C$_5$N     | ≤0.01                       | ≥0.3                          |                      |    |          |             |         |

Notes. Note that the first two columns report the species name and formula. The third, fourth, and fifth columns report the values of the inner and outer abundances $X_{\text{in}}$ and $X_{\text{out}}$ (with respect to H$_2$), and $T_{\text{jump}}$. The sixth and seventh columns report the degrees of freedom and the minimum reduced $\chi^2$. The last two columns report the radius and the sizes (diameter) at which the abundance jump occurs. The error bars are at a 2σ confidence level. The top half of the table lists the detected species, while the bottom half of the table lists the upper limit on the abundances of undetected COMs (see the text).

4.2. Results

For each of the five analyzed COMs, we run a large grid of models using the following strategy. We explored the $X_{\text{in}}$-$X_{\text{out}}$ parameter space (in general, we obtained grids of more than $20 \times 20$ for $\alpha$ equal to $-1$, $0$, and $+1$, and varied $T_{\text{jump}}$ from 10 to 120 K by steps of 10 K. Note that we first started with a 3 or 4 orders-of-magnitude range in $X_{\text{in}}$ and $X_{\text{out}}$, respectively, to find a first approximate solution and then we fine-tuned the grid around that solution. In total, therefore, we run more than $3 \times 10^6$ models for each species. The results of the best-fit procedure are reported in Table 1. Figure 1 shows the example of acetaldehyde. Note that the lines are predicted to be optically thin by the best-fit models of all five molecules. First, we did not find a significant difference in the $\chi^2$ best-fit value if $\alpha$ is $-1$, 0, or $+1$ in any of the five COMs, so that Table 1 reports the values obtained with $\alpha = 0$ only. Second, the $T_{\text{jump}}$ is different in the five COMs: it is $\sim 20$ K for ketene, $\sim 70$ to $80$ K for acetaldehyde and formamide, and $\sim 50$ K for dimethyl ether and methyl formate. Third, the abundance in the outer envelope ranges from $\sim 3 \times 10^{-12}$ to $\sim 2 \times 10^{-10}$: acetaldehyde and dimethyl ether have the largest values, formamide the lowest, and ketene and methyl formate intermediate values. Fourth, the abundance jumps by about a factor 100 in all COMs except for ketene, which remains practically constant (when the errors are considered). Note that we find warm envelope abundances of acetaldehyde, dimethyl ether, and methyl formate about 10 times smaller than those quoted by Cazaux et al. (2003). The difference mostly derives from a combination of different $T_{\text{jump}}$ (assumed to be 100 K in Cazaux et al. 2003), which implies different emitting sizes and a different H$_2$ column density. As was also emphasized by Cazaux et al. (2003), their hot corino sizes and H$_2$ column density were best guesses and, consequently, uncertain, whereas in the present work these values are self-consistently estimated from the molecular lines.
5. DISCUSSION

The analysis of outer and inner abundances of the five detected COMs leads to three major considerations and results.

1. **COMs in the Cold Envelope.** The first important result of this analysis is the presence of COMs in the cold part of the envelope, with an approximately constant abundance. This is the first time that we have unambiguous evidence that the cold outer envelope of (low mass) protostars can also host COMs. Bacmann et al. (2012) reported the detection of acetaldehyde, dimethyl ether, and methyl formate with abundances around $10^{-11}$ (with an uncertainty of about one order of magnitude) toward a cold ($\lesssim 10$ K) pre-stellar core. Oberg et al. (2010) and Cernicharo et al. (2012) reported the detection of the same molecules in B1-b, a low mass protostar where the temperature of the emitting gas is estimated to be 12–15 K (but no specific analysis to separate possible emission from warm gas has been carried out in this case) with similar abundances. In the cold envelope of IRAS16293, these COMs seem to be slightly more abundant, with abundances around $10^{-10}$, possibly because the gas is slightly warmer. If the dust surface chemistry dominated the formation of COMs in the outer envelope, then the COM abundance would increase with increasing dust temperature, namely, with decreasing radius in the cold envelope. However, our analysis does not show a definitively better $\chi^2$ for the solution corresponding to $\alpha = -1$, so that it cannot support this hypothesis. These new measurements add evidence that COMs, at least the ones studied here, may also be formed in cold conditions in addition to warm grain surfaces as predicted by current models (see the Introduction).

2. **Comparison with Other Objects.** Additional information on the formation (and destruction) routes of the detected COMs can be gained by comparing the COM abundances in galactic objects with different conditions (temperature, density, and history) and solar system comets. Here, we consider the abundances normalized to that of methyl formate, a molecule which has been detected in all of the objects that we want to compare. Figure 2 graphically shows this comparison. Ketene seems to be the most sensitive species for distinguishing two groups of objects: “cold” objects, formed by the cold and Galactic center clouds and the outer envelope of IRAS16293; and “warm” objects, constituted by the IRAS16293 hot corino (the only hot corino where the five COMs of this study have been detected so far) and the massive hot cores. In the first group, ketene has an abundance larger than $\sim 0.1$ with respect to methyl formate. In the second group, the relative abundance is lower than $\sim 0.1$. Finally, comets are definitively different from hot cores, with which they are often compared in the literature (see also the discussion in Caselli & Ceccarelli 2012).

3. **Correlations versus Methyl Formate.** Figure 3 shows the abundance of dimethyl ether, formamide, acetaldehyde, and ketene as a function of the abundance of methyl formate in different ISM sources. The linear correlation between the methyl formate and dimethyl ether is striking (with a Pearson correlation coefficient equal to 0.95 and power-law index equal to 1.0). It covers almost five orders of magnitude, so that it persists even when considering the dispersion of the measurements and the uncertainty linked to the determination of the absolute abundances mentioned.

Finally, for the undetected species, we derived upper limits to the abundance in the outer (assuming $N(H_2) = 8 \times 10^{22}$ cm$^{-2}$, diameter $= 30''$, $T = 20$ K) and inner (assuming $N(H_2) = 3 \times 10^{23}$ cm$^{-2}$, diameter $= 3''$, $T = 60$ K) envelope listed in Table 1.
Figure 2. Abundances of the five COMs analyzed in this work, normalized to the methyl formate abundance, in different objects: inner and outer envelope of IRAS16293 (this work), cold clouds (Bacmann et al. 2012; Cernicharo et al. 2012), Galactic center (GC) clouds (Requena-Torres et al. 2006, 2008), hot cores (Gibb et al. 2000; Ikeda et al. 2001; Bisschop et al. 2007; note that we did not include SgrB2 in this sample), and comets (Mumma & Charnley 2011). Error bars represent the dispersion in each group of objects, except IRAS16293, for which error bars reflect the errors in the abundance determination (Table 1).

(A color version of this figure is available in the online journal.)

Figure 3. Abundance of dimethyl ether (top left), formamide (bottom left), acetaldehyde (top right), and ketene (bottom right) as a function of the abundance of methyl formate in different ISM sources. The correlation coefficient $r$ and the power-law index are reported for each species.

above. This linear correlation, previously observed over a smaller range (e.g., Brouillet et al. 2013), gives us an important and remarkable message: the precursor of methyl formate and dimethyl ether is probably either the same (Brouillet et al. 2013) or one of the two is the precursor of the other, a hypothesis that has not been invoked previously in the literature. We cannot rule out other explanations, but they seem less likely at this stage. The bottom line is that such a link between these two species must be the same in both cold and warm gas. This does not favor a formation mechanism of these two COMs on the grain surfaces since, according to the existing models, the mechanism does not work at low temperatures. Current chemical networks do not report reactions linking the two species. Also, the recent article by Vasyunin & Herbst (2013), which proposes new reactions to explain the Bacmann et al. (2012) and Cernicharo et al. (2012) observations, does not suggest

9 For example, KIDA at http://kida.obs.u-bordeaux1.fr and UMIST at http://www.udfa.net.
a link between methyl formate and dimethyl ether. We suggest here that those networks are missing this important piece.

Similar analyses and conclusions (a Pearson correlation coefficient equal to 0.92 and a power-law index equal to 0.8) apply to the methyl formate and formamide. On the contrary, the correlation between methyl formate and acetaldehyde or ketene is poorer (a Pearson correlation coefficient equal to 0.66 and 0.62, and a power-law index equal to 0.5 and 0.4, respectively).

6. CONCLUSIONS

We searched for all oxygen- and nitrogen-bearing COMs observed in the ISM toward the envelope of IRAS16293. We detected six COMs: methyl cyanide, ketene, acetaldehyde, formamide, dimethyl ether, and methyl formate. We report the analysis of the last five species. A specific analysis of methyl cyanide emission will be presented in a subsequent paper. For each species, several lines covering a large upper-level energy range (up to 150 K) are detected. This allows us to disentangle the emission originating in the cold and warm envelope, respectively, and where the transition between the two occurs. The main results of this study can be summarized in three points.

1. The five analyzed COMs are all present in the cold envelope of IRAS16293. Acetaldehyde and dimethyl ether have the largest abundances, $10^{-10}$, slightly larger than the values found in other cold objects (Bacmann et al. 2012; Cernicharo et al. 2012). These new measurements add support to the idea that a relatively efficient formation mechanism for these COMs must exist in the cold gas phase.

2. When considering the abundance of the five analyzed COMs, the ketene abundance relative to methyl formate is different in cold and hot objects. Besides, comets are different from hot cores.

3. There is a remarkable correlation between the abundance of methyl formate and those of dimethyl ether and formamide. The correlation spans over five orders of magnitude. This may suggest that both dimethyl ether and formamide have a progenitor in common with methyl formate, and that the mechanism of their formation is gas-phase reactions. We suggest that the current chemical networks still miss important pieces.

We thank the anonymous referee for useful comments that helped to improve the article. This work has been supported by l’Agence Nationale pour la Recherche (ANR), France (project FORCOMS, contracts ANR-08-BLAN-0225). We acknowledge the financial support from the university of Al-Muthana and ministry of higher education and scientific research in Iraq.

REFERENCES

Bacmann, A., Taquet, V., Faure, A., Kahane, C., & Ceccarelli, C. 2012, A&A, 541, L12

Ball, J. A., Gottlieb, C. A., Lilley, A. E., & Radford, H. E. 1971, IAUC, 2350, 1

Bisschop, S. E., Jorgensen, J. K., van Dishoeck, E. F., & de Wachter, E. B. M. 2007, A&A, 465, 913

Blake, G. A., Sutton, E. C., Masson, C. R., & Phillips, T. G. 1987, ApJ, 315, 621

Brouillet, N., Despois, D., Baudry, A., et al. 2013, A&A, 550, A46

Brown, R. D., Crofts, J. G., Godfrey, P. D., et al. 1975, ApJL, 197, L29

Caselli, P., & Ceccarelli, C. 2012, A&ARv, 20, 56

Caselli, P., Hasegawa, T. I., & Herbst, E. 1993, ApJ, 408, 548

Caux, E., Kahane, C., Castets, A., et al. 2011, A&A, 532, A23

Cazaux, S., Tielens, A. G. M., Ceccarelli, C., et al. 2003, ApJL, 593, L51

Ceccarelli, C., Castets, A., Caux, E., et al. 2000, A&A, 355, 1129

Ceccarelli, C., Hollenbach, D. J., & Tielens, A. G. M. 1996, ApJ, 471, 400

Ceccarelli, C., Maret, S., Tielens, A. G. M., Castets, A., & Caux, E. 2003, A&A, 410, 587

Cernicharo, J., Marcelino, N., Roueff, E., et al. 2012, ApJL, 759, L43

Charnley, S. B., Tielens, A. G. M., & Millar, T. J. 1992, ApJL, 399, L71

Coutens, A., Vastel, C., Cabrit, S., et al. 2013, A&A, 560, A39

Crimier, N., Ceccarelli, C., Maret, S., et al. 2010, A&A, 519, A65

Garrod, R. T., Vasyunin, A. I., Semenov, D. A., Wiebe, D. S., & Henning, T. 2009, ApJL, 700, L43

Geppert, W. D., Vigren, E., Hamberg, M., et al. 2007, in European Planetary Science Congress 2007, Dissociative Recombination—A Key Process in Ionospheres of Giant Planets and Their Satellites, 613

Gibb, E., Nimmeln, A., Irvine, W. M., Whittet, D. C. B., & Bergman, P. 2000, ApJ, 545, 309

Goumans, T. P. M., Catlow, C. R. A., & Brown, W. A. 2008, JChPh, 128, 13

Guarnieri, A., & Hackua, A. 2003, Naturforsch, 58, 275

Herbst, E., & van Dishoeck, E. F. 2009, ARA&A, 47, 427

Horn, A., Mellendorf, H., Sekiguchi, O., et al. 2004, ApJL, 611, 605

Ikeda, M., Ohishi, M., Nimmeln, A., et al. 2001, ApJL, 560, 792

Kleiner, I., Lovas, F. J., & Godefroid, M. 1996, JPCRD, 25, 1113

Loinard, L., Torres, R. M., Mioduszewski, A. J., & Rodríguez, L. F. 2008, ApJL, 675, L29

Loinard, L., Zapata, L. A., Rodríguez, L. F., et al. 2013, MNRAS, 430, L10

Maeda, A., De Lucia, F. C., & Herbst, E. 2008, JMoSp, 251, 293

Marenich, A., & Boggis, J. 2003, JChPh, 107, 2343

Millar, T. J., Herbst, E., & Charnley, S. B. 1991, ApJL, 369, 147

Mizuno, A., Fukui, Y., Iwata, T., Nozawa, S., & Takano, T. 1990, ApJ, 356, 184

Müller, H. S. P., Schlöder, F., Stutzki, J., & Winnewisser, G. 2005, JMoSt, 742, 215

Mumma, M. J., & Charnley, S. B. 2011, ARA&A, 49, 471

Mundy, L. G., Wootten, A., Wilking, B. A., Blake, G. A., & Sargent, A. I. 1992, ApJ, 385, 306

Neustock, W., Guarnieri, A., & Gó, D. 1990, Naturforsch, 45, 702

Öberg, K. I., Bottinelli, S., Jorgensen, J. K., & van Dishoeck, E. F. 2010, ApJL, 716, 825

Picket, H. M., Poynter, R. L., Cohen, E. A., et al. 1998, JQSRT, 60, 883

Pineda, J. E., Maury, A. J., Fuller, G. A., et al. 2012, A&A, 544, L7

Piram, C., Krim, L., & Laffon, C. 2010, JChPh, 114, 3320

Requena-Torres, M. A., Martin-Pintado, J., Martin, S., & Morris, M. R. 2008, ApJ, 672, 352

Requena-Torres, M. A., Martin-Pintado, J., Rodriguez-Franco, A., et al. 2006, A&A, 455, 971

Rubin, R. H., Swenson, G. W., Jr., Benson, R. C., Tigelra, H. L., & Flygare, W. H. 1971, ApJL, 169, L39

Schoier, F. L., Jorgensen, J. K., van Dishoeck, E. F., & Blake, G. A. 2002, A&A, 390, 1001

Soderstrom, P. M., Jefferts, K. B., Penzias, A. A., & Wilson, R. W. 1971, ApJL, 169, L39

Schaerer, M., & Dittmar, T. I., van Dishoeck, E. F., & Blake, G. A. 2007, A&A, 390, 1001

Solomon, P. M., Jefferts, K. B., Penzias, A. A., & Wilson, R. W. 1971, ApJL, 168, L107

Taquet, V., Ceccarelli, C., & Kahane, C. 2012, A&A, 538, A42

Tielens, A. G. M., & Hagen, W. 1982, A&A, 114, 245

Vasyunin, A. I., & Herbst, E. 2013, ApJ, 769, 34

Watanohe, N., & Kouchi, A. 2002, ApJL, 571, L173

Woon, D. E. 2002, ApJL, 571, L177

Wootten, A. 1989, ApJL, 337, 858

Zapata, L. A., Loinard, L., Rodriguez, L. F., et al. 2013, ApJL, 764, L14