

COMPLEX MOLECULES IN THE HOT CORE OF THE LOW-MASS PROTOSTAR NGC 1333 IRAS 4A

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ABSTRACT

We report the detection of complex molecules (HCOOCH_3 , HCOOH , and CH_3CN), signposts of a hot core-like region, toward the low-mass Class 0 source NGC 1333 IRAS 4A. This is the second low-mass protostar in which such complex molecules have been searched for and reported, the other source being IRAS 16293–2422. It is therefore likely that compact (a few tens of AU) regions of dense and warm gas, where the chemistry is dominated by the evaporation of grain mantles and where complex molecules are found, are common in low-mass Class 0 sources. Given that the chemical formation timescale is much shorter than the gas hot-core crossing time, it is not clear whether the reported complex molecules are formed on the grain surfaces (first-generation molecules) or in the warm gas by reactions involving the evaporated mantle constituents (second-generation molecules). We do not find evidence for large differences in the molecular abundances, normalized to the formaldehyde abundance, between the two solar-type protostars, suggesting perhaps a common origin.

Subject headings: ISM: abundances — ISM: individual (NGC 1333 IRAS 4A) — ISM: molecules — stars: formation

1. INTRODUCTION

There is strong support from the composition of cometary and meteoritic materials for the notion that the solar nebula, from which the planets formed, passed through a phase of warm, dense gas with a rich chemistry. While much observational effort has been dedicated to the study of such hot cores around massive protostars, hot cores around low-mass protostars have received little attention. Only very recently has the first hot core around a solar-type protostar been discovered, toward the typical Class 0 source IRAS 16293–2422 (hereafter IRAS 16293), exhibiting all characteristics of such regions: warm temperature (>100 K) and high density ($>10^7$ cm^{-3} ; Ceccarelli et al. 2000a), high abundance of hydrides (CH_3OH , H_2CO , H_2O ; Ceccarelli et al. 2000a, 2000b; Schöier et al. 2002), high deuteration levels ($>10\%$; Ceccarelli et al. 1998, 2001; Parise et al. 2002; Roberts et al. 2002), and complex molecules (HCOOCH_3 , HCOOH , CH_3OCH_3 , CH_3CN , $\text{C}_2\text{H}_5\text{CN}$; Cazaux et al. 2003). The definition of “hot core” used for massive protostars implies the presence of a relatively large amount of warm and dense gas, along with a complex chemistry triggered by the grain mantle evaporation (e.g., Walmsley et al. 1992). In order to make clear that hot cores of low- and high-mass protostars are, however, substantially different in the amount of material involved, we use hereafter the term “hot

corino” to identify the warm inner regions of the envelope surrounding the low-mass protostars.

The chemical composition of the (massive) hot cores is thought to reflect a variety of sequential processes (Walmsley et al. 1992; Charnley et al. 1992; Caselli et al. 1993; Charnley 1995; Rodgers & Charnley 2001, 2003). Specifically, in the precollapse cold cloud phase, simple molecules form on grain surfaces by hydrogenation of CO and other heavy elements (notable examples are H_2CO , CH_3OH , and H_2S). Upon heating by a newly formed star, these molecules, called “first-generation” or “parent” molecules, evaporate into the gas and undergo fast neutral-neutral and ion-neutral reactions producing complex organic molecules, i.e., “second-generation” or “daughter” molecules. The first part of this sequence (the formation of fully hydrogenated molecules on the grain surfaces) has been demonstrated to occur around low-mass protostars by studies of the multiply deuterated molecules formaldehyde (Ceccarelli et al. 1998; Bacmann et al. 2003), methanol (Parise et al. 2002, 2004), and sulfide (Vastel et al. 2003). Evaporation from grain mantles of these first-generation species (in particular H_2CO and CH_3OH) has been observed in IRAS 16293 (Ceccarelli et al. 2000b; Schöier et al. 2002) and in about a dozen low-mass protostars (Maret et al. 2004). However, since the timescale necessary to convert first-generation molecules into complex, second-generation molecules (around 10^4 – 10^5 yr; e.g., Charnley et al. 1992, 2001) is much longer than the transit time of the gas in the hot corinos (a few hundred years; e.g., Schöier et al. 2002), the formation in the gas of second-generation molecules seems improbable (e.g., Schöier et al. 2002). The detection of a high abundance of complex molecules in the hot core of IRAS 16293 (Cazaux et al. 2003) has evidently been a challenge to the simple theoretical sequence described above. The key question has shifted from “Is a hot core present in low-mass protostars?” to “What is the origin of the molecular complexity in these sources?” In particular, there may well be chemical pathways to complex molecules involving grain surface networks (e.g., Charnley 1995). In order to answer this question, more

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observations of other low-mass protostars are necessary. This will allow the development of a solid observational framework within which we might search for clues to the formation of second-generation molecules. As remarked in previous studies, the question is far from being academic, since the molecules in the hot corinos constitute the material that will eventually form the protoplanetary disk and possibly the planets of the forming Sun-like star.

In this paper we present the first results of a survey we are carrying out on the sample of Class 0 sources studied by Maret et al. (2004). Here we report the detection of complex, second-generation molecules in NGC 1333 IRAS 4A (hereafter IRAS 4A), a well-known Class 0 protostar and a target of several studies of molecular emission (e.g., Blake et al. 1995). IRAS 4A is part of the binary system IRAS 4, located in the NGC 1333 reflection nebula in the Perseus cloud. It is separated by $31''$ from the other component, IRAS 4B, and was itself resolved into two components with a separation of $2''$ by Lay et al. (1995). The distance to the NGC 1333 cloud is uncertain (see, e.g., Maret et al. 2002), but assuming a value of 220 pc (derived by Černis 1990, for consistency with previous work), IRAS 4A has a luminosity of $6 L_{\odot}$ and an envelope mass of $3.5 M_{\odot}$ (Sandell et al. 1991). IRAS 4A is associated with a very highly collimated outflow detected in CO, CS, and SiO (Blake et al. 1995; Lefloch et al. 1998). Infall motion was detected by Di Francesco et al. (2001) and Choi et al. (1999) with an estimated accretion rate of $1.1 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$, an inner mass of $0.7 M_{\odot}$, and an age of ~ 6500 yr (see also Maret et al. 2002).

2. OBSERVATIONS AND RESULTS

The observations were carried out in 2003 June with the IRAM 30 m telescope. The position used for pointing was $\alpha(2000) = 03^{\text{h}}29^{\text{m}}10^{\text{s}}.3$ and $\delta(2000) = 31^{\circ}13'31''$. Based on the observations of IRAS 16293 by Cazaux et al. (2003), we targeted the following complex molecules: methyl formate, HCOOCH_3 (A and E); formic acid, HCOOH ; dimethyl ether, CH_3OCH_3 ; methyl cyanide, CH_3CN ; and ethyl cyanide, $\text{C}_2\text{H}_5\text{CN}$. Different telescope settings were used in order to include as many transitions as possible for each molecule. All lines were observed with a low-resolution, 1 MHz filter bank of 4×256 channels split between different receivers, providing a velocity resolution of $\sim 3, 2,$ and 1 km s^{-1} at 3, 2, and 1 mm, respectively. Each receiver was simultaneously connected to a unit of the autocorrelator, with spectral resolutions of 20, 80, or 320 kHz and bandwidths between 40 and 240 MHz, equivalent to an (unsmoothed) velocity resolution range of $0.1\text{--}0.4 \text{ km s}^{-1}$. Typical system temperatures were 100–200 K, 180–250 K, and 500–1500 K, at 3, 2, and 1 mm, respectively.

Two observation modes were used: position switching with the off position at an offset of $\Delta\alpha = -100$, $\Delta\delta = +300$, and wobbler switching with a $110''$ throw in azimuth. Pointing and focus were regularly checked using planets or strong quasars, providing a pointing accuracy of $3''$. All intensities reported in this paper are expressed in units of main-beam brightness temperature. At 3, 2, and 1 mm, the angular resolution is $24''$, $16''$, and $10''$, and the main-beam efficiency is 76%, 69%, and 50%, respectively.

Figure 1 shows two examples of the low-resolution spectra we obtained. Detected transitions have been identified using the JPL molecular line catalog (Pickett et al. 1998) and are reported in Table 1. We considered as good identifications only lines with a 3σ detection and a $V_{\text{LSR}} = 6.8 \pm 0.3 \text{ km s}^{-1}$. We detected three of the five targeted molecules: 10 transitions for HCOOCH_3 (A and E), 2 for HCOOH , and 9 for CH_3CN . We

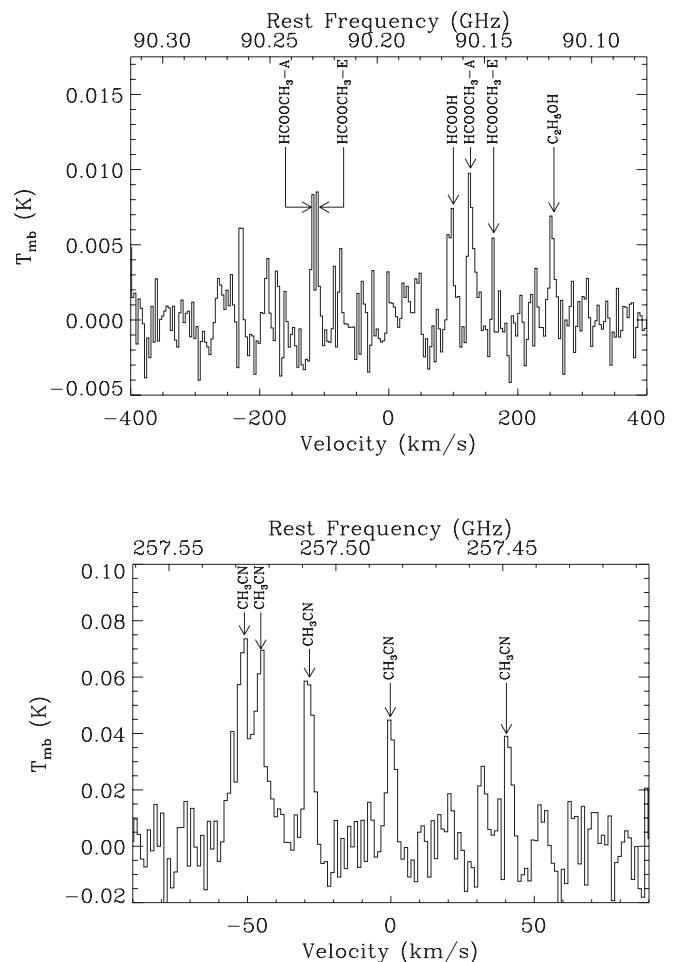


FIG. 1.—Two low-resolution spectra obtained during our observations of IRAS 4A. Lines that are not labeled are unidentified. The rms noise level is 2 mK (*top spectrum*) and 12 mK (*bottom spectrum*). The spectral resolution is 3.3 km s^{-1} (*top*) and 1.2 km s^{-1} (*bottom*). The V_{LSR} is 7.0 km s^{-1} . Known transitions are indicated but not all of them are detections, e.g., HCOOCH_3 at 90.145 GHz is not considered as such, but the upper limit derived from it is consistent with the rotational diagram of Fig. 2.

also have a possible detection for $\text{C}_2\text{H}_5\text{OH}$ at 90.118 GHz; unfortunately, no other transition with a low enough energy and high enough Einstein coefficient was contained within the frequency ranges we observed to confirm the correct identification. No transitions of CH_3OCH_3 and $\text{C}_2\text{H}_5\text{CN}$ were detected to a noise limit of 6 and 2 mK, respectively. All detected lines, with a few exceptions, have line widths $\sim 2\text{--}3 \text{ km s}^{-1}$, likely due to the presence of unresolved triplets or to the contamination of unidentified lines. In order to derive the rotational temperature and column density, we built rotational diagrams (Fig. 2) in which the observed fluxes were corrected for beam dilution, assuming a source size of $0''.5$ (derived from a hot core radius of 53 AU and a distance of 220 pc, as found by Maret et al. 2004). The assumption that the complex molecules are confined to the hot corino is supported by a Plateau de Bure interferometric study of IRAS 16293, which shows localized emission in a region $\sim 1''.4$ around the protostar (Bottinelli et al. 2004).

The rotational temperatures, total column densities, and abundances for the detected molecules are presented in Table 2. Note that the large errors in the HCOOH (this work) and CH_3OCH_3 (Cazaux et al. 2003) abundances are due to a poor constraint of the rotational temperature, and hence column

TABLE 1
MOLECULAR LINES DETECTED TOWARD IRAS 4A

Molecule	Transition Line	Frequency (MHz)	E_u^a (cm $^{-1}$)	δV^b (km s $^{-1}$)	ΔV^c (km s $^{-1}$)	T_{mb} (mK)	$\int T_{mb} dV$ (K km s $^{-1}$)	rms d (mK)
HCOOCH $_3$ -A	7 $_2$, 5-6 $_2$, 4	90156.5	13.7	0.5	1.5	22	0.036	5
	8 $_0$, 8-7 $_0$, 7	90229.7	13.9	0.5	2.5	16	0.041	5
	8 $_3$, 6-7 $_3$, 5	98611.1	18.9	0.2	1.2	28	0.036	7
	8 $_4$, 5-7 $_4$, 4	98682.8	22.2	1.9	4.2	95	0.042	2
HCOOCH $_3$ -E	7 $_2$, 5-6 $_2$, 4	90145.7	13.7	0.5	1.3	14	0.019	5
	8 $_0$, 8-7 $_0$, 7	90227.8	14.0	0.5	3.1	16	0.055	5
	8 $_3$, 6-7 $_3$, 5	98607.8	18.9	0.9	3.8	13	0.054	4
	8 $_4$, 5-7 $_4$, 4	98711.7	22.2	0.2	1.4	22	0.034	7
	20 $_2$, 18-19 $_2$, 18	226713.1	83.6	0.8	1.0	89	0.099	26
HCOOH	20 $_3$, 18-19 $_3$, 17	226773.3	83.6	0.8	2.1	54	0.121	19
	4 $_2$, 2-3 $_2$, 1	90164.5	16.4	0.5	0.8	16	0.015	5
HCOOH	6 $_2$, 4-5 $_2$, 3	135737.7	24.6	1.4	1.8	15	0.029	5
	CH $_3$ CN c	6 $_3$, 0-5 $_3$, 0	110364.6	57.6	0.8	5.1	20	0.110	6
6 $_2$, 0-5 $_2$, 0		110375.1	32.8	0.8	2.3	46	0.112	6
6 $_1$, 0-5 $_1$, 0		110381.5	17.9	0.8	3.4	67	0.241	6
6 $_0$, 0-5 $_0$, 0		110383.6	12.9	0.8	4.3	76	0.347	6
14 $_4$, 0-13 $_4$, 0		257448.9	143.9	1.2	3.3	40	0.141	12
14 $_3$, 0-13 $_3$, 0		257482.7	109.1	0.4	2.6	53	0.150	19
14 $_2$, 0-13 $_2$, 0		257507.9	84.3	0.4	3.1	59	0.195	19
14 $_1$, 0-13 $_1$, 0		257522.5	69.4	0.4	2.2	74	0.172	19
14 $_0$, 0-13 $_0$, 0		257527.4	64.4	1.2	3.8	68	0.274	12

^a Energy of the upper level of the transition.

^b Spectral resolution of the observation (when possible, the integrated intensity was derived from the high-resolution data).

^c Width of the observed line.

^d Computed over the line width.

^e All the CH $_3$ CN lines are (unresolved) triplets. The quoted signal is the integral over each triplet. Larger line widths could be due to the larger spacing between the components of the triplets.

density, of these two molecules, even though each molecule is clearly detected in each case.

3. DISCUSSION AND CONCLUSION

The most important result of the present work is the detection of complex molecules in the hot corino of IRAS 4A, the second Class 0 protostar in which those molecules have been searched for, after IRAS 16293 (Cazaux et al. 2003). This result demonstrates that as soon as a warm region is created in the center of the envelope of low-mass protostars, complex molecules are readily formed and/or injected on timescales lower than the estimated Class 0 source ages ($\sim 5 \times 10^4$ yr in IRAS 16293 and ~ 6500 yr in IRAS 4A; e.g., Maret et al. 2002) and, most importantly, shorter than the transit time in the hot corinos. The latter is ~ 400 and ~ 120 yr in IRAS 16293 and IRAS 4A, respectively, based on the hot corino sizes quoted in Maret et al. (2004) and assuming free-falling gas.

We compare the measured composition of the hot corino of IRAS 4A to IRAS 16293 (Cazaux et al. 2003) and the massive hot core of OMC-1 (Sutton et al. 1995) in Table 2. Note that the latter abundances are derived from single-dish measurements with a 14'' beam, which encompasses several hot cores (Wright et al. 1996). Unfortunately, not all the molecules considered here have interferometric measurements available, so we can only use these 14'' beam-averaged estimates of the abundances.

The first remark is that the absolute abundances of the observed molecules are 1 order of magnitude smaller in IRAS 4A than in IRAS 16293, but their relative abundances with respect to H $_2$ CO are quite similar, with the exception of methanol, which is underabundant with respect to H $_2$ CO by about a factor of 10 in IRAS 4A (Fig. 3). There are two reasons to consider abundances with respect to formaldehyde. The first one is

observational: while the IRAS 16293 hot core has now been imaged with the Plateau de Bure Interferometer (Bottinelli et al. 2004) and its size confirmed to be $\sim 1''.4$, the IRAS 4A core size is only indirectly estimated from dust continuum single-dish (12'') observations to be $0''.5$, and no interferometric observations are available yet with such a high resolution. So the IRAS 4A core size might be wrong by up to a factor of 3 (Maret et al. 2004) and the abundances by up to a factor of 10, i.e., the absolute abundances of IRAS 4A could be comparable to those of IRAS 16293. Using abundance ratios allows us to remove this size uncertainty. The second reason is theoretical: "standard" hot-core models predict that molecules like methyl formate or methyl cyanide are second-generation molecules formed in the warm gas from the evaporated grain mantle constituents (formaldehyde, ammonia, and methanol; e.g., Charnley et al. 1992; Caselli et al. 1993; Rodgers & Charnley 2003). It is therefore interesting to compare the abundances of the complex molecules to those of one of these supposed parent molecules. Formaldehyde was chosen because we only have an upper limit on the methanol abundance (S. Maret et al. 2004, in preparation), and no measurements of the ammonia abundance are available.

A possible interpretation for the similarity in the complex molecules' relative abundances, with respect to H $_2$ CO and not with respect to CH $_3$ OH, is that the former is the mother molecule of the observed O-bearing species, e.g., likely the case of HCOOCH $_3$ (Charnley et al. 1992), and that the chemical evolution timescale is shorter than the age of the youngest source. Charnley et al. (1992) also predict that methanol is the mother molecule of CH $_3$ OCH $_3$, but we cannot say whether the available data confirm this hypothesis, since we only have an upper limit on the abundance of this molecule in IRAS 4A and

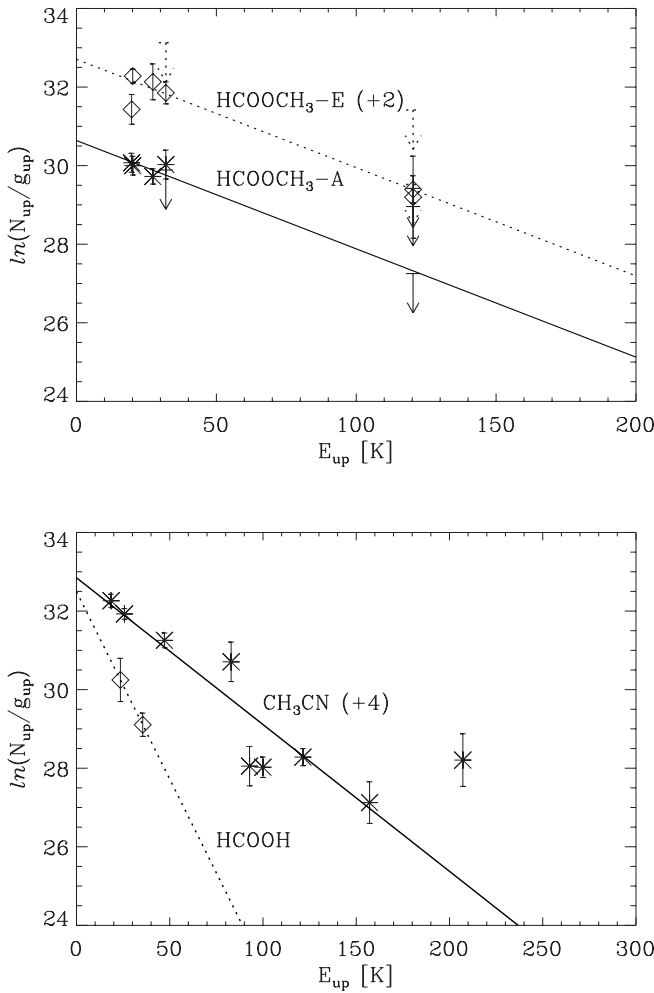


FIG. 2.—Rotational diagrams of the detected molecules, corrected for beam dilution. Arrows show the upper limits for the transitions that have not been detected, and lines represent the best fit to the data. *Top*: Asterisks and solid lines are associated with HCOOCH₃-A and diamonds and dotted lines with HCOOCH₃-E. *Bottom*: Asterisks and solid lines are associated with CH₃CN and diamonds and dotted lines with HCOOH. Error bars are derived assuming a calibration uncertainty of 10% on top of the statistical error. The excess of emission of the CH₃CN transition at 210 K is probably due to contamination from unknown line(s).

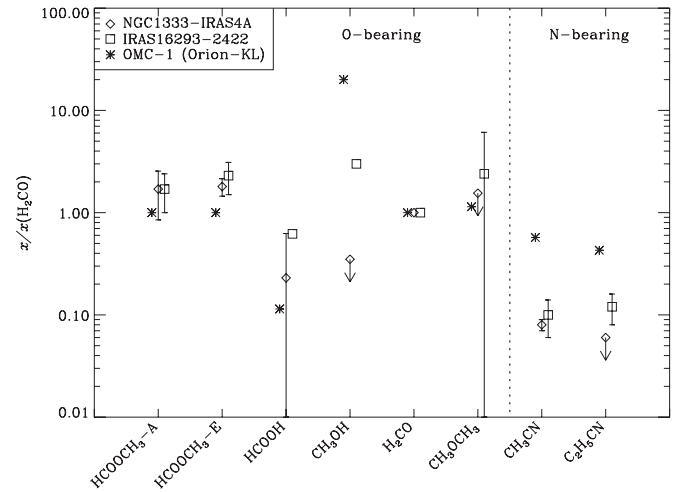


FIG. 3.—Abundances of the observed species (reported on the x-axis) normalized to the H₂CO abundances. Asterisks refer to the OMC-1 hot core, squares to the hot corino of IRAS 16293, and diamonds to the corino of IRAS 4A. Arrows represent upper limits in IRAS 4A derived from our observations. No errors were quoted by Cazaux et al. (2003) for the HCOOH abundance, which was determined from two transitions only and is rather uncertain.

a large error in IRAS 16293. Similarly, the N-bearing molecules CH₃CN and C₂H₅CN could both be daughters of the same mother molecule, probably ammonia. This would imply that the two sources have a similar ammonia mantle abundance. Alternatively, some or all of the reported molecules are possible mantle constituents themselves. This may be the case for formic acid, as predicted by Tielens & Hagen (1982) and suggested by the observational study by Liu et al. (2001). Moreover, the analysis of *Infrared Space Observatory (ISO)* absorption spectra toward the massive hot core W33A (e.g., Schutte et al. 1997) is consistent with the presence of solid formic acid and would also support the idea of this species being a mantle constituent. However, these considerations do not take into account the evolutionary state of the objects, and the fundamental question is: does the abundance of any of these complex molecules have anything to do with the age

TABLE 2
RESULTS FROM THE ROTATIONAL DIAGRAMS FOR IRAS 4A, IN COMPARISON WITH IRAS 16293 AND THE MASSIVE HOT CORE OMC-1

MOLECULE	IRAS 4A			IRAS 16293 ^b <i>X</i>	OMC-1 ^c <i>X</i>
	<i>T</i> _{rot} (K)	<i>N</i> _{total} (cm ⁻²)	<i>X</i> ^a		
HCOOCH ₃ -A.....	36 ^d	5.5 ± 2.7 E16	3.4 ± 1.7 E-8	1.7 ± 0.7 E-7	1 E-8
HCOOCH ₃ -E.....	36 ± 5	5.8 ± 1.1 E16	3.6 ± 0.7 E-8	2.3 ± 0.8 E-7	1 E-8
HCOOH.....	10 ± 6	7.3 ± 13.0 E15	4.6 ± 7.9 E-9	~6.2 E-8	8 E-10
CH ₃ CN.....	27 ± 1	2.6 ± 0.3 E15	1.6 ± 0.2 E-9	1.0 ± 0.4 E-8	4 E-9
CH ₃ OH.....	...	...	≤7 E-9 ^e	3 E-7	1 E-7
H ₂ CO.....	...	...	2 E-8 ^f	1 E-7 ^g	7 E-9
Upper Limits					
CH ₃ OCH ₃	36 ^d	≤4.5 E16	≤2.8 E-8	2.4 ± 3.7 E-7	8 E-9
C ₂ H ₅ CN.....	27 ^h	≤1.9 E15	≤1.2E-9	1.2 ± 0.4 E-8	3 E-9

^a Assuming an H₂ column density in the hot corino of $N(\text{H}_2) = 1.6 \times 10^{24} \text{ cm}^{-2}$ (from Maret et al. 2004).
^b From Cazaux et al. (2003).
^c From Sutton et al. (1995).
^d *T*_{rot} assumed to be similar to the one derived for HCOOCH₃-E.
^e From S. Maret et al. (in preparation).
^f From Maret et al. (2004).
^g From Ceccarelli et al. (2000b).
^h *T*_{rot} assumed to be similar to the one derived for CH₃CN.

and/or evolutionary stage of the protostar, or is it dominated by the initial mantle composition? Evidently, two sources are not enough to answer this question, and observations of more low-mass sources are required.

Regarding the comparison with the massive hot core(s) in Orion, Figure 3 would suggest that, with respect to formaldehyde, there is a deficiency of methanol and of N-bearing complex molecules in the low-mass hot corinos. It is possible that these differences are mostly due to a different grain mantle composition, i.e., to a different precollapse density. However, recall that the abundance ratios of CH₃CN and CH₃OH in Figure 3 refer to the 14'' beam-averaged values around the OMC-1 hot core, which in fact includes several smaller cores (Wright et al. 1996). Therefore, in order to make precise comparisons, higher resolution observations of the OMC-1 hot core are needed. It is also worth noting that if we consider, for example, the measurements by Wright et al. (1996) in the compact ridge component (a region about 10'' away from the

hot core central position, which is also a site of mantle evaporation and of active gas-phase chemistry; e.g., Charnley et al. 1992), the CH₃CN and CH₃OH abundance ratios with respect to H₂CO are (surprisingly) close to those found for the hot corinos of IRAS 16293 and IRAS 4A. Hence, interferometric observations of a larger number of massive hot cores are necessary to provide a significant comparison of the hot corinos with their high-mass counterparts.

In summary, although the present observations do not allow us to determine why and how complex molecules are formed, they do show that hot corinos, in the wide definition of chemically enriched regions, are a common property of solar-type protostars in the early stages. The evidence is that the types of complex molecules that are formed are determined primarily by the composition of the grain mantles. At this stage, it is not clear whether the evolutionary stage of the protostar plays any role at all, other than governing the presence and size of the mantle evaporation region.

REFERENCES

- Bacmann, A., Lefloch, B., Ceccarelli, C., Steinacker, J., Castets, A., & Loinard, L. 2003, *ApJ*, 585, L55
- Blake, G. A., Sandell, G., van Dishoeck, E. F., Groesbeck, T. D., Mundy, L. G., & Aspin, C. 1995, *ApJ*, 441, 689
- Bottinelli, S., et al. 2004, *ApJL*, submitted
- Caselli, P., Hasegawa, T. I., & Herbst, E. 1993, *ApJ*, 408, 548
- Cazaux, S., Tielens, A. G. G. M., Ceccarelli, C., Castets, C., Wakelam, V., Caux, E., Parise, B., & Teyssier, D. 2003, *ApJ*, 593, L51
- Ceccarelli, C., Castets, A., Caux, E., Hollenbach, D., Loinard, L., Molinari, S., & Tielens, A. G. G. M. 2000a, *A&A*, 355, 1129
- Ceccarelli, C., Castets, A., Loinard, L., Caux, E., & Tielens, A. G. G. M. 1998, *A&A*, 338, L43
- Ceccarelli, C., Loinard, L., Castets, A., Tielens, A. G. G. M., & Caux, E. 2000b, *A&A*, 357, L9
- Ceccarelli, C., Loinard, L., Castets, A., Tielens, A. G. G. M., Caux, E., Lefloch, B., & Vastel, C. 2001, *A&A*, 372, 998
- Černis, K. 1990, *Ap&SS*, 166, 315
- Charnley, S. B. 1995, *Ap&SS*, 224, 251
- Charnley, S. B., Rodgers, S. D., & Ehrenfreund, P. 2001, *A&A*, 378, 1024
- Charnley, S. B., Tielens, A. G. G. M., & Millar, T. J. 1992, *ApJ*, 399, L71
- Choi, M., Panis, J.-F., & Evans, N. J. 1999, *ApJS*, 122, 519
- Di Francesco, J., Myers, P. C., Wilner, D. J., Ohashi, N., & Mardones, D. 2001, *ApJ*, 562, 770
- Lay, O. P., Carlstrom, J. E., & Hills, R. E. 1995, *ApJ*, 452, L73
- Lefloch, B., Castets, A., Cernicharo, J., & Loinard, L. 1998, *ApJ*, 504, L109
- Liu, S.-Y., Mehringer, D. M., & Lewis, E. S. 2001, *ApJ*, 552, 654
- Maret, S., Ceccarelli, C., Caux, E., Tielens, A. G. G. M., & Castets, A. 2002, *A&A*, 395, 573
- Maret, S., et al. 2004, *A&A*, 416, 577
- Parise, B., Castets, A., Herbst, E., Caux, E., Ceccarelli, C., Mukhopadhyay, I., & Tielens, A. G. G. M. 2004, *A&A*, 416, 159
- Parise, B., et al. 2002, *A&A*, 393, L49
- Pickett, H. M., Poynter, R. L., Cohen, E. A., Delitsky, M. L., Pearson, J. C., & Muller, H. S. P. 1998, *J. Quant. Spectrosc. Radiat. Transfer*, 60, 883
- Roberts, H., Fuller, G. A., Millar, T. J., Hatchell, J., & Breckle, J. V. 2002, *A&A*, 381, 1026
- Rodgers, S. D., & Charnley, S. B. 2001, *ApJ*, 546, 324
- . 2003, *ApJ*, 585, 355
- Sandell, G., Aspin, C., Duncan, W. D., Russell, A. P. G., & Robson, E. I. 1991, *ApJ*, 376, L17
- Schöier, F. L., Jørgensen, J. K., van Dishoeck, E. F., & Blake, G. A. 2002, *A&A*, 390, 1001
- Schutte, W. A., Greenberg, J. M., van Dishoeck, E. F., Tielens, A. G. G. M., Boogert, A. C. A., & Whittet, D. C. B. 1997, *Ap&SS*, 255, 61
- Sutton, E. C., Peng, R., Danchi, W. C., Jaminet, P. A., Sandell, G., & Russell, A. P. G. 1995, *ApJS*, 97, 455
- Tielens, A. G. G. M., & Hagen, W. 1982, *A&A*, 114, 245
- Vastel, C., Phillips, T. G., Ceccarelli, C., & Pearson, J. 2003, *ApJ*, 593, L97
- Walmsley, C. M., Cesaroni, R., Churchwell, E., & Hofner, P. 1992, *Astron. Gesellschaft Abstract Ser.*, 7, 93
- Wright, M. C. H., Plambeck, R. L., & Wilner, D. J. 1996, *ApJ*, 469, 216