The Chemical Nature of Orion Protostars: Are ORANGES Different from PEACHES? ORANGES II.

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Abstract

Understanding the chemical past of our Sun and how life appeared on Earth is one of the holy grails in science. From an astrophysical point of view, as the Sun’s birth environment, the OMC-2/3 filament. In this context, we investigated the chemical nature of 19 solar-mass protostars and found that 26% of our sample sources show warm methanol emission indicative of hot corinos. Compared to the Perseus low-mass star-forming region, where the PErseus ALMA CHEmistry Survey detected hot corinos in ~60% of the sources, the hot corinos seem to be relatively scarce in the OMC-2/3 filament. While this suggests that the chemical nature of protostars in Orion and Perseus is different, improved statistics is needed in order to consolidate this result. If the two regions are truly different, this would indicate that the environment is likely playing a role in shaping the chemical composition of protostars.

Unified Astronomy Thesaurus concepts: Astrochemistry (75); Protostars (1302); Star formation (1569); Chemical abundances (224)

1. Introduction

Understanding how life appeared on Earth is one of the holy grails in science. From an astrophysical point of view, as the Sun’s birth environment being long dissipated, we cannot see what happened in its youth. We can, however, study solar-mass protostars that are currently forming in other regions of our Galaxy to understand the full story of our planetary system formation.

The discovery of two chemically distinct types of solar-mass protostars—hot corinos and warm carbon-chain chemistry (WCCC) sources—shows that the story might not be the same for every solar-mass protostar. While hot corinos are compact (≤100 au), hot (≥100 K), and dense (≥10^7 cm^-3) regions (Ceccarelli et al. 2004; Ceccarelli et al. 2007), enriched in interstellar complex organic molecules (iCOMs; Herbst & Van Dishoeck 2009; Ceccarelli et al. 2017), WCCC objects are deficient in iCOMs but show a larger zone (~2000 au) enriched in unsaturated carbon-chain molecules (Sakai et al. 2008; Sakai & Yamamoto 2013). In between these two extreme cases, there exist objects called hybrids that present both hot corino and WCCC features (e.g., L483, B335; Imai et al. 2016; Oya et al. 2017; Jacobsen et al. 2019).

Until recently, only a dozen hot corinos were discovered, but thanks to the arrival of powerful (sub)millimeter interferometers such as ALMA, more hot corinos have been identified. In particular, the recent Perseus ALMA Chemistry Survey (PEACHES; Yang et al. 2021) targeted 50 solar-mass protostars in the Perseus Molecular Cloud, a region forming only low-mass stars. They found that ~56% of their source sample show warm methanol emission, indicating that hot corinos are likely prevailing in this region. The Perseus Molecular Cloud is, however, different from the solar birth environment. The latter was most likely a dense protocluster with high-mass stars in its vicinity (e.g., Adams 2010; Pfalzner et al. 2015). Are hot corinos also abundant in an environment analog to that where our Sun was born? Recent studies showed similarities between the abundances of iCOMs found in hot corinos compared to those found in comets (Bianchi et al. 2019; Drozdovskaya et al. 2019; Rivilla et al. 2020). Did our Sun experience a hot corino phase? We need to target low-mass protostars belonging to massive star-forming regions (SFRs).

The closest and best analog of our Sun’s birth environment is the OMC-2/3 filament, located in the Orion A molecular cloud. Very recently, three hot corinos were detected in this region, the intermediate-mass protostars HOPS-87 (also known as MMS6) and HOPS-370 (also known as OMC-2-FIR3) (Tobin et al. 2019; Hsu et al. 2020) and the solar-type protostar HOPS-108 located in the OMC-2 FIR4 protocluster (Tobin et al. 2019; Chahine et al. 2022). Although hot corinos are present in massive SFRs (Codella et al. 2016; Hsu et al. 2020; Chahine et al. 2022), the statistics is too poor to draw any conclusion on the chemical past of our Sun. We, therefore, need more systematic studies of hot corinos in massive SFRs. The ORion ALMA New GEneration Survey (ORANGES) is a project aiming to study the chemical nature of the solar-type
protostars located in the OMC-2/3 filament, (393 ± 25) pc from the Sun (Großschedl et al. 2018), with an angular resolution of 0.025 (∼100 au). ORANES is analogous to PEACHES because the two studies have been designed to have the same sensitivity (corrected for the distance), spatial resolution, and spectral setup. It allows a direct comparison of the two environments, i.e., the OMC-2/3 filament and the Perseus Molecular Cloud. One of the goals of ORANES is to assess the number of hot corinos in the OMC-2/3 region and provide a first answer concerning the chemical past of our Sun.

In ORANES, we targeted the same protostars targeted by Bouvier et al. (2021). These were initially nine chosen protostellar sources based on single-dish studies (e.g., Chini et al. 1997; Lis et al. 1998; Nielbock et al. 2003) satisfying the following three criteria: (1) detection in the (sub)millimeter continuum emission; (2) estimated envelope mass ≤ 12 $M_\odot$; and (3) bona fide Class 0 and I protostars (see Bouvier et al. 2020). Recent interferometric studies showed that most of these systems are in fact multiple systems (Tobin et al. 2020; Bouvier et al. 2021), which led to a total number of 19 studied targets.

The results of a previous single-dish study (Bouvier et al. 2020) toward the same targets showed that the large-scale ($≤ 10^3$ au) line emission is dominated by the photodissociation region or by the molecular cloud, rather than the protostellar envelopes. Interferometric observations are thus essential to detect hot corinos in this highly illuminated region. In this study, we investigated the most common tracer of hot corinos, CH$_3$OH, in a sample of 19 embedded solar-type protostars. Table A1 lists the targeted protostars and their coordinates.

2. Observations

The observations were performed between 2016 October 25 and 2017 May 5 during Cycle 4, under ALMA project 2016.1.00376.S. The observations were performed in Band 6 using two different spectral setups. The ranges of frequencies covering the methanol transitions relevant for this work are 243.88–243.97 GHz and 261.77–261.88 GHz for setup 1, and 218.38–218.50 GHz, 230.33–234.08 GHz, and 234.64–234.76 GHz for setup 2. For setup 1, a total of 41 antennas of the 12 m array were used with a baseline length range of 18.6–1100 m. The integration time is ∼20 minutes per source. For setup 2, a total of 45 antennas of the 12 m array were used with a baseline range of 18.6–1400 m. The integration time is ∼8 minutes per source. The ALMA correlator was configured to have both narrow and wide spectral windows (spws), with 480 and 1920 channels, respectively. Narrow spws have a bandwidth of 58.59 MHz with a channel spacing of 122 kHz (∼0.15–0.17 km s$^{-1}$), while the wide spws have a bandwidth of 1875 MHz with a channel spacing of 0.977 MHz (∼1.2–1.3 km s$^{-1}$). The bandpass and flux calibrators were J0510 + 1800 and J0522–3627, and the phase calibrators were J0607–0834 and J0501–0159. The flux calibration error is estimated to be better than 10%. The precipitable water vapor (PWV) was typically less than 1 mm and the phase rms noise less than 60°. In the context of the ORANES project, several molecular species were targeted but we focus here in particular on methanol (CH$_3$OH), the typical tracer of hot corinos. The methanol lines were found in six (both narrow and wide) spws. The rest frequencies of the methanol transition lines and the associated primary beam sizes are shown in Table A2.

We used the Common Astronomy Software Application (CASA; McMullin et al. 2007) for the data calibration. We then exported the calibrated visibility tables to GILDAS format and performed the imaging in MAPPING. We first produced a continuum image by averaging line-free channels in the visibility plane using an automatic procedure. We then subtracted the continuum from the line emission directly in the visibility plane. We cleaned the cubes using natural weighting (with the CLEAN procedure) down to ∼24 mJy beam$^{-1}$ on average. The phase self-calibration performed on the continuum of the sources (see Bouvier et al. 2021) has been applied to the cubes. The narrow spws were resampled to a channel spacing of 0.5 km s$^{-1}$. The maps shown in this paper are not corrected for the primary beam attenuation but we took into account the correction to measure the line intensities. The resulting synthesized beam and rms for each source and each spectral window are presented in Table B1.

3. Results

3.1. Methanol Lines

Methanol is detected toward the center of 5 out of the 19 protostars: CSO33-b-a, FIR6c-a, MMS9-a, MMS5, and SIMBA-a. In these sources, the line spectra were extracted from the pixel corresponding to the position of the methanol peak, which often corresponds to the continuum emission peak. The coordinates of the position where the spectra have been extracted are indicated in Table A1. The line detection threshold is set to 3σ at the line emission peak. Figures 1 and 2 show the moment 0 map of the two CH$_3$OH lines at 243915 MHz and 234698 MHz, which have different upper-level energies $E_u$, overlaid on the 1.5mm dust continuum emission of each source. We note that for CSO33-b-a and SIMBA-a, the methanol transition at 234698 MHz ($E_u = 122.7$ K) is considered undetected as the emission is shown only by a 3σ contour, which is not centered on the source’s continuum peak. We found that while the emission of methanol lines with low upper-level energy, such as the 243915 MHz transition, is resolved and extended in most sources, the emission of methanol lines with high upper-level energy, such as the 234,698 MHz transition, is compact. Methanol emission is seen near other sources of the sample but not at the position of the protostars. As we are interested in detecting hot corinos, we will focus in this letter only on the five sources cited above.

We detected up to 11 CH$_3$OH lines with upper-level energies $E_u$ from 28 to 537 K and Einstein coefficients $A_i$ between $6.3 \times 10^{-6}$ and $1 \times 10^{-4}$ s$^{-1}$. The extracted spectra of methanol lines for each source are shown in Figure 3. We performed a Gaussian line fitting to each source in order to extract the line width (FWHM) and the peak velocity ($V_{peak}$). To extract the integrated intensity, we did a Gaussian fit ($\int T_{A}\text{dv}$) and G. We also measured it by direct integration of the channel intensities ($\int T_{R}\text{dv}$ D). Only MMS5 has lines with Gaussian profiles so we used the Gaussian fit results for this source and the results of the direct integration for the other sources. The line-fitting results, as well as the rms computed for each spw, are reported in Table B1. Line widths range between ∼2 and 7 km s$^{-1}$.

Methanol lines can be very optically thick toward hot corinos (Bianchi et al. 2020). We therefore looked for the isotopologue CH$_3^{18}$O, which is usually optically thin, in order to derive the methanol column density more accurately. Among the seven CH$_3^{18}$O lines expected to be the most intense, we

\footnote{http://www.iram.fr/IRAMFR/GILDAS}
detected and used only one line. The other lines are either undetected (3σ) or contaminated by lines from other molecules such as C2H5OH, C2H5CN, or CH2DOH. The spectral parameters and Gaussian fit results of the transition used in this work, which is the 5_0,5−4_0,4 A transition at 231758 MHz, are reported in Table B1. The frequencies of the seven CH3OH spectral lines expected to be the most intense are indicated in Figure B1.

3.2. Non-LTE LVG Analysis

To derive the physical properties of the gas where methanol is emitted, we performed a non-LTE analysis using the large velocity gradient (LVG) code grelg, originally developed by Ceccarelli et al. (2003). We used the CH2OH–H2 collisional rates from Flower et al. (2010) between 10 and 200 K for the first 256 levels, provided by the BASECOL database8 (Dubernet et al. 2013). We assumed a spherical geometry to compute the line escape probability (de Jong et al. 1980), a ratio CH3OH-E/CH3OH-A equal to 1, and an H2 ortho-to-para ratio of 3. The assumed line widths are those measured from the spectral lines toward each source (see Table B1), and we included the calibration error of 10% in the observed intensities.

8 https://basecol.vamdc.eu/
The detected methanol transitions span a large range of $E_{up}$. First, methanol lines with $E_{up}$ higher than 400 K have been excluded from the analysis as the collisional coefficients are not computed at these energies. Second, low-energy transitions can eventually trace a different region than the higher-energy-level transitions. Indeed, the low upper-energy-level transitions eventually trace a different region than the higher-energy-level transitions. Additionally, the line at 234698 MHz is likely contaminated by a $^{33}$SO$_2$ line falling at the same frequency. We do not have enough information on this line to evaluate the possible contribution of this line. We thus excluded this line from the LVG analysis as well.

In the case of MMS5, we also included the detected line of CH$_3$OH-A with the $^{16}$O/$^{17}$O ratio equal to 560 (Wilson & Rood 1994) to better constrain the derived total CH$_3$OH column density for this source. For each source, the lines that are not used for the LVG analysis are shown in italics in Table B1. In most cases, we ran the LVG radiative transfer code with only three lines so that the accuracy of the fit is not very elevated.

For each source, we ran a large grid of models varying the total (CH$_3$OH-E + CH$_3$OH-A) column density from $2 \times 10^{14}$ to $3 \times 10^{19}$ cm$^{-2}$, the gas temperature from 20 to 200 K, and the H$_2$ density from $3 \times 10^5$ to $1 \times 10^{10}$ cm$^{-3}$. These ranges for the parameters are those expected in hot corinos and in outflow shocks, as we expect emission coming from either of these two types of environments. We fitted the measured CH$_3$OH-E and CH$_3$OH-A line intensities simultaneously via comparison with the LVG model predictions, leaving $N_{\text{CH}_3\text{OH}, \text{H}_2}$, $T_{\text{kin}}$, and the source size ($\theta$) as free parameters. Then, because the lines are optically thin in the cases of CSO33-b-a and SIMBA-a, there is a degeneracy between the source size and the column density, and the best fit of the LVG analysis actually provides the product $\theta \times N_x$. For these sources, we reran the best-fitting procedure, this time by fixing the source size and leaving $N_{\text{CH}_3\text{OH}, \text{H}_2}$ and $T_{\text{kin}}$ as free parameters. We then varied the source size around its best-fit value to find when the $\theta \times N_x$ product does not give the same chi square, namely, where the degeneracy disappears.

The best fit for the total CH$_3$OH column densities ranges between $8 \times 10^{15}$ and $4 \times 10^{18}$ cm$^{-2}$ with reduced $\chi^2_{\text{red}}$ between 0.1 and 1.6. All the lines for CSO33-b-a and SIMBA-a, and the CH$_3$OH line for MMS5 are optically thin ($\tau_L \leq 1$; $\tau_L$ being the line optical depth). For the other sources, methanol lines are mostly optically thick (FIR6c-a: $\tau_L = [1.1 - 5.2]$, MMS9-a: $\tau_L = [1.2 - 5.7]$, MMS5: $\tau_L = [0.9 - 4.2]$). The derived gas temperature and density are $\geq 85$ K and $\geq 3 \times 10^6$ cm$^{-3}$ for all sources, with the highest gas density for CSO33-b-a and the lowest gas density for FIR6c-a. The highest gas temperature is derived toward MMS9-a ($\geq 130$ K). The

![Figure 2](image-url)
observed lines are predicted to be emitted by sources between 0.07 and 0.6 (≈28–236 au) in diameter. Figure 4 shows as an example the result of the LVG fit for MMS5. The best-fit solutions and ranges obtained for each source are reported in Table 1.

3.3. LTE versus Non-LTE analysis

We provide the results we obtained with the rotational diagram method (LTE) using the same lines as in the LVG analysis in Table 1, in Figure C1. Depending on the sources, the LTE and non-LTE analyses can give similar or different results. In the cases of FIR6c-a and MMS9, the column densities can differ by up to two orders of magnitude. However, this is because, for these sources, we did not know a priori the size of the emitting region, and we thus used the sizes from Bouvier et al. (2021), which happened to be larger (up to ≈40%) than those we derived with the LVG analysis. Additionally, we see that the lines in these sources are optically thick. In general, the optical depth and the source size can be

![Figure 3. Methanol spectral lines detected in each source. The lines taken into account in the LVG analysis have a blue background. The lines with the red background are likely contaminated by a line of $^{33}$SO$_2$ and are thus left out from the LVG analysis. The transition of each line is marked in the top-left corner of the boxes. Dashed green lines show the $3\sigma$ level and dashed gray lines the averaged fitted peak velocity of all transitions of the associated source, $V_{\text{peak}}$, determined from the Gaussian line fitting.](image-url)
corrected using the population diagram method (Goldsmith & Langer 1999). However, a population diagram cannot correct for non-LTE effects if they are present.

For each transition line, the excitation temperature corresponding to the best fit of the LVG analysis is indicated in Table B1. Comparing with the kinetic temperatures derived in the LVG analysis, we can see that some lines are subthermally populated and that there are maser lines at 218440 and 261805 MHz. We note that for CSO33-a, where the lines are optically thin and under LTE conditions, we find consistent results between the LTE and LVG analyses. For the source FIR6c-a, for which the excitation temperatures are very different from the derived kinetic temperature, we checked that non-LTE effects remain present even after correcting the rotational diagram for size and optical depth (there is still a scatter of points). In other words and as expected, the population diagram method can give a good approximation of the results if the lines are close to being thermally populated, which is only known when a non-LTE analysis is carried out.

3.4. Derivation of Methanol Abundances.

In the previous ORANGES study, we focused on the continuum analysis of the sources (Bouvier et al. 2021). We used the spectral energy distribution method to constrain several dust parameters such as the optical depth, the temperature, the H$_2$ column density, and the (envelope+disk) mass. These parameters were estimated for a source size derived from a fit in the visibility plane and are reported in Table 1 with the associated source size.

We therefore used these H$_2$ column densities to derive the methanol abundance with respect to H$_2$, X(CH$_3$OH), toward each of the five sources. The results are reported in Table 1. However, because the source size derived from Bouvier et al. (2021) can be larger (up to $\sim$40%) than the size of the methanol emission derived from the LVG analysis, the H$_2$ column densities can be thus underestimated in some cases, and the derived abundances would then need to be taken as upper limits. The abundances range from $3 \times 10^{-11}$ and $2 \times 10^{-6}$. For CSO33-b-a, only a lower limit could be derived for the H$_2$ column density, so the methanol abundance derived here is an upper limit. SIMBA-a seems to have a lower methanol abundance than the other sources but because the LVG analysis was performed with only a few data points for most of the sources, the accuracy of the fit is not very elevated.

4. Discussion

4.1. New Hot Corinos Discovered in the OMC-2/3 Filament

So far, only three hot corinos have been identified in the OMC-2/3 filament, the intermediate-mass protostars HOPS-87 and HOPS-370 (Tobin et al. 2019; Hsu et al. 2020), and HOPS-108 (Tobin & Megeath 2019; Chahine et al. 2022). One of the questions we aim to answer is: How many hot corinos are present in the OMC-2/3 filament?

Our results show that methanol is detected toward five protostars from our source sample and that the emission comes from a hot ($\geq 85$ K), dense ($\geq 3 \times 10^5$ cm$^{-3}$), and compact (0$^\prime$1–0$^\prime$6 or $\sim$39–236 au) region. According to the hot corino definition, i.e., a compact (\leq 100 au), hot (\geq 100 K), and dense (\geq 10$^7$ cm$^{-3}$) region enriched in iCOMs (Ceccarelli 2004; Ceccarelli et al. 2007), CSO33-b-a, FIR6c-a, MMS9-a, MMS5, and SIMBA-a are, therefore, bona fide hot corinos. The methanol abundances derived toward the OMC-2/3 hot corinos are comparable to what is derived in other hot corinos in Orion (HOPS-87, HOPS-168, HOPS-288, G192.12-11.10, and HH 212; Lee et al. 2019; Hsu et al. 2020) and in other SFRs (e.g., B335, IRAS 16293–2422; Imai et al. 2016; Jørgensen et al. 2016, 2018), except for SIMBA-a, for which the methanol abundance is about two orders of magnitude lower. However, for FIR6c-a and MMS9-a, the abundances could be overestimated (see Section 3.4), and most of the LVG analyses were performed with only three lines. Our results should thus be taken with caution.

The five hot corinos show very different spectra as shown in Figure 5. MMS5 and MMS9-a present line-rich spectra with strong iCOM emission while CSO33-b-a, FIR6c-a, and SIMBA-a present line-poor spectra, likely because the iCOM

\textsuperscript{9} In this work, we targeted only CH$_3$OH, which is the most abundant iCOMs found in hot corinos. Other iCOMs could be also present but their identification will be the subject of a future work.
emission is faint. We will address the analysis of the other iCOMs detected toward the sources in a forthcoming paper.

4.2. Is the Dust Hiding Other Hot Corinos?

A recent study by De Simone et al. (2020) showed that hot corinos detected at centimeter wavelengths could be obscured by optically thick dust at millimeter wavelengths. Could it be the case for some of our sources?

Figure 6 shows the line intensity of the CH$_3$OH transition line at 243915 MHz as a function of the dust opacity. The latter has been derived for each source of the sample in Bouvier et al. (2021). For sources where no methanol is detected, we calculated the $3\sigma$ upper limit for the line intensity. If the optical depth was a dominant factor, we would expect to see an anticorrelation between the methanol intensity and $\tau$, with the sources presenting methanol lines having the lowest range of dust optical depths. We do not see any anticorrelations, which suggests that the dust opacity is not the main parameter affecting the detection of methanol, and hence the detection of hot corinos, in the OMC-2/3 filament. However, we note that the dust optical depth ranges derived in Bouvier et al. (2021) do not always correspond to the sizes derived from the LVG analysis performed in this work. In some cases (FR6c-a and MMS9-a), we derived methanol emission sizes that are smaller than the size of the continuum emission. This would indicate that we are underestimating the dust optical depth at the scale probed by the methanol emission. Therefore, our conclusion needs to be taken with caution. Additionally, we can see that for four of our sample sources (MMS2-a, MMS2-b, MMS9-b, and MMS9-d), the upper limits for the derived dust optical depths are larger than 1. In these sources, we, thus, cannot exclude the possibility that the dust absorbs methanol emission at 1.3 mm.

4.3. Are ORANGES Different From PEACHES?

Several studies targeting methanol and other iCOMs toward low-mass protostars have been conducted. Yang et al. (2021) surveyed 50 sources in the Perseus Molecular cloud in the context of PEACHES. They detected CH$_3$OH toward 56% of their source sample and other O-bearing iCOMs toward 32% of the source sample. Belloche et al. (2020) surveyed 16 Class 0 protostars located in various low-mass SFRs as part of the Continuum And Lines in Young ProtoStellar Objects (CALYPSO) IRAM Large Program survey, with the Plateau de Bure Interferometer (PdBI; the predecessor of the current NOEMA interferometer). They detected methanol emission toward 50% of their source sample but no more than 30% of them with at least three iCOMs detected. van Gelder et al. (2020) (ALMA) surveyed seven Class 0 sources in the Perseus and Serpens molecular clouds and detected methanol toward three of them (∼43%). Finally, Bergner et al. (2017) IRAM-30m targeted iCOMs toward 16 Class 0/1 protostars and detected the iCOMs CH$_3$CHO, CH$_3$OCH$_3$, and CH$_3$OCHO toward 37%, 13%, and 13% of the sources, respectively. However, contrary to the other surveys cited above, the temperatures derived by Bergner et al. (2017) being too low.

Table 1

| Source Properties, LTE Results, Best-fit Results and 1σ Confidence Level (Range) from the Non-LTE LVG Analysis, and Derived Methanol Abundances with Respect to H$_2$ | CSO33-b-a | FIR6c-a | MMS9-a | MMS5 | SIMBA-a |
|---|---|---|---|---|---|
| Source size [" x"] | 0.6 x 0.6 | 0.31 x 0.13 | 0.44 x 0.14$^b$ | 0.15 x 0.13 | 0.13 x 0.11 |
| (Envelope + disk) mass [$10^{-2}$ $M_\odot$] | ≥0.2 | 1.5–4 | 2–7 | 1–2 | 1–3 |
| $T_d$ [K] | 10–200 | 89–134 | 80–200 | 149–159 | 160–200 |
| $H_2$ [$10^{14}$ cm$^{-2}$] | ≥0.08 | 7–15 | 5–19 | 10–15 | 18–36 |

| Source Properties$^c$ |
|---|
| Size used ["] | 0.6 | 0.2 | 0.25 | 0.14 | 0.12 |
| $T_{	ext{rot}}$ [K] | 124 ± 262 | 169 ± 54 | 142 ± 22 | 117 ± 14 | 151 ± 598 |
| $N_{\text{rot}}$ [$10^{15}$ cm$^{-2}$] | 13 ± 11 | 21 ± 6 | 48 ± 7 | 150 ± 20 | 20 ± 30 |

**Notes.**

$^a$ Derived from a continuum analysis in Bouvier et al. (2021).

$^b$ Derived from a continuum analysis in Tobin et al. (2020).

$^c$ The size is calculated using the formula $\sqrt{a \times b}$, where $a$ and $b$ are the major and minor axes of the source size derived in Bouvier et al. (2021).

$^d$ The $H_2$ column densities can be underestimated when the source size is larger than the region of emission of methanol. The abundances derived in this work should then be taken as upper limits in these cases.

$^e$ The methanol abundances are likely upper limits, as the source sizes used to derive the $H_2$ column densities are larger than the methanol emission sizes derived in the LVG analysis.

| Source Properties$^c$ |
|---|
| $n_{\text{H}_2}$ [$10^{17}$ cm$^{-3}$] best fit | 300 | 0.4 | 0.7 | 5 | 1.5 |
| $n_{\text{H}_2}$ [$10^{17}$ cm$^{-3}$] range | ≥20 | 0.3–0.5 | 0.6–1 | 2–20 | ≥0.7 |
| $T_{\text{kin}}$ [K] best fit | 105 | 180 | 170 | 105 | 190 |
| $T_{\text{kin}}$ [K] range | 95–120 | 85 | 130 | 90–125 | ≥100 |
| $N_{\text{CH}_3\text{OH}}$ [$10^{16}$ cm$^{-2}$] best fit | 0.7–16 | 120 | 120 | 200 | 120 |
| $N_{\text{CH}_3\text{OH}}$ [$10^{16}$ cm$^{-2}$] range | 0.1–0.6 | 0.07–0.13 | 0.1–0.13 | 0.13–0.24 | 0.08–0.38 |
| Size ["] best fit | 0.39 | 0.1 | 0.12 | 0.2 | 0.17 |
| Size ["] range | 0.1–0.6 | 0.07–0.13 | 0.1–0.13 | 0.13–0.24 | 0.08–0.38 |
| X(CH$_3$OH) × 10$^{-8}$ | ≤200 | 5.3–29$^e$ | 10–120$^e$ | 9.3–80 | 0.003–0.2 |
for the iCOMs to originate from a hot corino region, the emission of iCOMs could trace a more external component. These surveys show that by selecting a mix of usual targets, methanol is largely detected in solar-mass protostars located in low-mass SFRs. Here, we compare our results with those of PEACHES only, as this is the only unbiased survey targeting iCOMs toward all the protostars of a single low-mass SFR. Additionally, PEACHES and ORANGES were designed to compare directly the low-mass protostellar chemical content of two different environments, the Perseus Molecular Cloud and the OMC-2/3 filament. In both regions, the selected targets are mostly Class 0, I, or 0/1 protostars with a low fraction of other (Class II or unknown) sources (7% and 11% of the sources in PEACHES and ORANGES, respectively). The relative fraction of Class 0 and I sources in each region cannot be determined accurately as the current classification of the protostars is either based on Herschel observations, for which the angular resolution is not sufficient to disentangle close multiple sources.

Figure 5. Spectra of each source from the large spectral window, setup 1. The spectra are extracted from a pixel at the peak of the emission.

Figure 6. Line intensity of the CH$_3$OH line at 243915 MHz as a function of the dust optical depth, $\tau$. For clarity, we slightly shifted vertically the upper limits for the line intensity of several sources. The initial upper limit for the CH$_3$OH line is 3.6 K km s$^{-1}$ for the components of the systems CSO33 and MMS9, 3.7 K km s$^{-1}$ for the FIR1a and MMS2 components and for CSO3-b, and 3.8 K km s$^{-1}$ for FIR2. Upper limits are represented by colored filled triangles or arrows.
emission centered toward five out of the 19 targeted sources. After performing a non-LTE LVG analysis, we showed that the methanol-emitting regions are hot \((T \gtrsim 85 \text{ K})\), dense \((n_{\text{H}_2} \gtrsim 3 \times 10^6 \text{ cm}^{-2})\), and compact \((\sim 0\arcsec 1-0\arcsec 6 \text{ or } \sim 39-236 \text{ au in diameter})\), and correspond to hot corino regions. We thus detected five new bona fide hot corinos in the OMC-2/3 filament, which corresponds to \((26 \pm 23\%)\% of the sample sources.

On the other hand, a similar study performed in the less illuminated low-mass SFR of Perseus found a high detection rate, \((56 \pm 14\%)\%, of hot corinos (Yang et al. 2021). Hot corinos thus seem scarcer in a highly illuminated environment, such as the OMC-2/3 filament. This result indicates that the environment may very likely play a role in solar-mass protostars’ chemical content and that ORANGES are different from PEACHES.

Are hot corinos always abundant in low-mass SFRs analogous to Perseus and more scarce in analogs to the OMC-2/3 filament? We would need to perform more studies analogous to PEACHES and ORANGES in other SFRs to confirm this result. Finally, although hot corinos are present in a region similar to the one in which our Sun is born, they are not prevailing. The question of whether our Sun experienced a hot corino phase in its youth needs further investigations before being answered.

We deeply thank the anonymous referee for helpful comments that contributed to significantly improving the paper. While the paper was under review, three additional hot corinos were detected in the OMC-2/3 filament (HOPS-84-A, HOPS-84-B, and MMS1) by Hsu et al. (2022). Moreover, they targeted 56 Class 0/I protostars throughout the Orion Molecular Cloud and detected warm methanol towards \(\sim 20\%)\% of their sample sources, which is comparable to what we found in this work. This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation program, for the Project The Dawn of Organic Chemistry (DOC), grant agreement No. 741002. This paper makes use of the following ALMA data: ADS/JAO.ALMA/#2016.1.00376.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ.

Appendix A

Observational Details

We present here the details of the observations. Table A1 lists the targeted sources and their coordinates, and Table A2 shows the list of methanol transitions detected and used in this work and their spectral parameters. Channel spacing and primary beam size for the spectral windows containing the methanol lines are also indicated.
Appendix B

Gaussian Fit Results and CH$_3^{18}$OH Spectrum

The Gaussian fit results of the CH$_3$OH and CH$_3^{18}$OH lines are reported in Table B1. Contaminated lines are not reported in the table as they are not included in the LVG fit. Figure B1 shows the detected transition of CH$_3^{18}$OH toward MMS5.

Table A1
Sample Sources, Coordinates of the Dust Peak Continuum (D), Coordinates of the Positions Selected to Extract the Spectra (P), Source Classification, and Associated HOPS Names

| Source   | R.A. (D) (J2000) | Decl. (D) (J2000) | R.A. (P) (J2000) | Decl. (P) (J2000) | HOPS name$^{ab}$ | Classification$^c$ | Notes               |
|----------|------------------|------------------|------------------|------------------|------------------|---------------------|---------------------|
| CSO33-a  | 05:35:19.41      | $-05$:15:38.41   | ...              | ...              | HOPS-56-B        | 0 or I              |                     |
| CSO33-b  | 05:35:19.48      | $-05$:15:33.08   | 05:35:19.48      | $-05$:15:33.10   | HOPS-56-A/B/C    | 0                   |                     |
| CSO33-c  | 05:35:19.81      | $-05$:13:35.22   | ...              | ...              | V2358 Ori II     | II                  |                     |
| FIR6c-a  | 05:35:21.36      | $-05$:13:17.85   | 05:35:21.36      | $-05$:13:17.85   | HOPS-409         | 0                   |                     |
| FIR2     | 05:35:24.30      | $-05$:08:30.74   | ...              | ...              | HOPS-68           | I                   |                     |
| FIR1a-a  | 05:35:24.87      | $-05$:07:54.63   | ...              | ...              | HOPS-394-B       | 0 or I              |                     |
| FIR1a-b  | 05:35:24.05      | $-05$:07:52.07   | ...              | ...              | HOPS-394-A       | 0                   |                     |
| MMS9-a   | 05:35:25.97      | $-05$:05:43.34   | 05:35:25.96      | $-05$:05:43.39   | HOPS-78-A        | 0                   |                     |
| MMS9-b   | 05:35:26.15      | $-05$:05:45.80   | ...              | ...              | HOPS-78-B        | 0 or I              |                     |
| MMS9-c   | 05:35:26.18      | $-05$:05:47.14   | ...              | ...              | HOPS-78-C        | 0 or I              |                     |
| MMS9-d   | 05:35:25.92      | $-05$:05:47.70   | ...              | ...              | HOPS-78-D        | II                  |                     |
| MMS5     | 05:35:22.47      | $-05$:01:14.34   | 05:35:22.48      | $-05$:01:14.35   | HOPS-88          | 0                   |                     |
| MMS2-a   | 05:35:18.34      | $-05$:00:32.96   | ...              | ...              | HOPS-92-A/B      | I                   |                     |
| MMS2-b   | 05:35:18.27      | $-05$:00:33.95   | ...              | ...              | HOPS-92-B        | 1                   |                     |
| CSO3-b   | 05:35:16.17      | $-05$:00:25.50   | ...              | ...              | HOPS-94          | 1                   |                     |
| CSO3-a   | 05:35:29.72      | $-04$:58:48.60   | 05:35:29.72      | $-04$:58:48.56   | HOPS-96          | 0                   |                     |

Notes.

$^a$ Fischer et al. (2013).

$^b$ Furlan et al. (2016).

$^c$ Bouvier et al. (2021).

$^d$ Tobin et al. (2020).

Table A2
Methanol Transition Lines Detected in this Work, Their Parameters, and Channel Spacing and Primary Beam Size of the Associated Spectral Windows

| Molecule | Frequency (MHz) | Transition | $E_{up}$ (K) | $g_{up}$ | $A_u \times 10^{-5}$ s$^{-1}$ | Channel Spacing (km.s$^{-1}$) | Primary Beam Size (") |
|----------|-----------------|------------|--------------|----------|-------------------------------|------------------------------|------------------------|
| CH$_3$OH | 218440          | 4$_{2,3}$$-3_{-1,2}$ E | 45.5        | 36       | 4.69                          | 0.5                          | 28.8                   |
|          | 232418          | 10$_{2,9}$$-9_{-3,7}$ A | 165.4       | 84       | 1.87                          | 1.3                          | 27.1                   |
|          | 232945          | 10$_{3,3}$$-11_{-2,9}$ E | 190.4       | 84       | 2.13                          | 1.3                          | 27.1                   |
|          | 234683          | 4$_{2,1}$$-5_{1,4}$ A | 60.9        | 36       | 1.87                          | 0.5                          | 26.8                   |
|          | 234698          | 5$_{2,5}$$-6_{1,3}$ E | 122.7       | 44       | 0.63                          | 0.5                          | 26.8                   |
|          | 243915          | 5$_{1,4}$$-4_{2,3}$ A | 49.7        | 44       | 5.97                          | 0.5                          | 25.8                   |
|          | 261805          | 2$_{1,1}$$-1_{0,1}$ E | 28.0        | 20       | 5.57                          | 0.5                          | 24.1                   |
| CH$_3^{18}$OH | 231758         | 5$_{0,5}$$-4_{0,4}$ A | 33.4        | 44       | 5.33                          | 1.3                          | 27.1                   |

Note. Frequencies and spectroscopic parameters have been extracted from the CDMS catalog (Müller et al. 2005). For CH$_3$OH (TAG 032504, version 3) and CH$_3^{18}$OH (TAG 034504, version 1), the available data are from Xu et al. (2008) and Fisher et al. (2007), respectively.
Figure B1. Spectra toward MMS5 where the frequencies of the seven CH$_3^{18}$OH lines expected to be the most intense ($E_u < 75$ K) are indicated. Detected lines are marked in green, contaminated lines are marked in magenta, and undetected lines are marked in black. The 3σ level is indicated by the dashed blue line.

### Table B1

List of Frequencies of the Detected Methanol Lines, Synthesized Beams, and Line-fitting and LVG Results

| Molecule | Frequency (MHz) | Synthesized Beam MAD(″)×MIN(″) (PA $^{\perp}$) | $\int T_d V$ G (K km s$^{-1}$) | $\int T_d V$ D (K km s$^{-1}$) | V$_{peak}$ (km s$^{-1}$) | FWHM (km s$^{-1}$) | rms (K) | $T_{kin}$ (K) | $T_{ex}$ (K) | $\tau_L$ |
|----------|----------------|-----------------------------------------------|----------------|----------------|----------------|----------------|--------|--------------|-------------|-------|
| CH$_3$OH | 218440         | 0.52 × 0.29 (106)                           | 18.5 ± 2.6 | 17.2 ± 2.2 | 9.4 ± 0.5 | 5.7 ± 0.7 | 0.6 | 105 | 126 | 6.10$^{-2}$ |
|          | 234683         | 0.43 × 0.41 (−27)                           | 6.0 ± 1.2 | 5.2 ± 1.2 | 8.2 ± 0.5 | 3.4 ± 1.0 | 0.4 | 101 | 24.10$^{-3}$ |
|          | 243915         | 0.32 × 0.28 (101)                           | 26.8 ± 3.1 | 25.6 ± 2.6 | 9.2 ± 0.5 | 5.1 ± 0.5 | 0.4 | 105 | 9.10$^{-2}$ |
|          | 261805         | 0.29 × 0.25 (−78)                           | 19.4 ± 2.6 | 17.3 ± 2.0 | 9.2 ± 0.5 | 6.7 ± 0.7 | 0.5 | 112 | 4.10$^{-2}$ |
| CH$_3$OH | 218440         | 0.52 × 0.29 (107)                           | 10.4 ± 1.4 | 11.2 ± 1.3 | 11.2 ± 0.1 | 2.5 ± 0.4 | 0.6 | 180 | 13200 | 5.10$^{-2}$ |
|          | 239295         | 0.48 × 0.27 (−71)                           | 9.3 ± 1.4 | 8.9 ± 1.6 | 10.8 ± 0.2 | 4.4 ± 0.6 | 0.2 | 44.8 | 5.2 |
|          | 234683         | 0.47 × 0.27 (109)                           | 10.2 ± 2.2 | 8.6 ± 1.7 | 11.4 ± 0.3 | 3.6 ± 0.8 | 0.5 | 50.3 | 3.9 |
|          | 234698         | 0.47 × 0.27 (109)                           | 6.7 ± 1.5 | 5.2 ± 0.9 | 10.9 ± 0.6 | 3.3 ± 1.1 | 0.5 | 39.6 | 1.1 |
|          | 243915         | 0.32 × 0.27 (−78)                           | 22.4 ± 2.6 | 20.4 ± 2.2 | 10.7 ± 0.1 | 3.2 ± 0.3 | 0.5 | 169 | 4.8 |
|          | 261805         | 0.30 × 0.25 (−77)                           | 16.6 ± 2.6 | 12.1 ± 1.4 | 10.8 ± 0.4 | 4.0 ± 1.0 | 0.5 | 99.5 | 3.4 |
| CH$_3$OH | 218440         | 0.52 × 0.29 (107)                           | 51.9 ± 5.4 | 51.0 ± 5.3 | 11.0 ± 0.5 | 6.7 ± 0.5 | 0.6 | 170 | 1130 | 0.9 |
|          | 239295         | 0.49 × 0.27 (−71)                           | 40.8 ± 4.4 | 39.2 ± 4.1 | 11.8 ± 1.2 | 7.5 ± 1.2 | 0.3 | 70.1 | 5.7 |
|          | 234683         | 0.47 × 0.27 (109)                           | 40.8 ± 4.6 | 40.0 ± 4.2 | 11.1 ± 0.5 | 6.2 ± 0.5 | 0.5 | 75 | 4.4 |
|          | 234698         | 0.47 × 0.27 (109)                           | 28.1 ± 3.7 | 27.3 ± 3.0 | 10.9 ± 0.5 | 6.1 ± 0.6 | 0.5 | 73.6 | 1.2 |
|          | 243915         | 0.52 × 0.27 (−256)                          | 89.6 ± 9.1 | 85.8 ± 8.7 | 11.1 ± 0.5 | 6.7 ± 0.5 | 0.5 | 165 | 7.8 |
|          | 261805         | 0.30 × 0.25 (−75)                           | 62.9 ± 6.7 | 60.3 ± 6.1 | 11.8 ± 0.5 | 7.0 ± 0.5 | 0.5 | 122 | 4.4 |
| CH$_3$OH | 218440         | 0.52 × 0.3 (107)                            | 73.2 ± 7.4 | 71.9 ± 7.5 | 10.4 ± 0.5 | 3.2 ± 0.5 | 0.6 | 105 | 139 | 11.2 |
|          | 239295         | 0.48 × 0.28 (−71)                           | 52.5 ± 5.4 | 52.2 ± 5.2 | 10.3 ± 1.2 | 3.5 ± 1.2 | 0.3 | 93.5 | 4.2 |
|          | 234683         | 0.46 × 0.27 (−71)                           | 56.3 ± 6.7 | 56.6 ± 6.7 | 10.3 ± 0.5 | 3.2 ± 0.5 | 0.6 | 93.5 | 5.0 |
|          | 234698         | 0.46 × 0.27 (−71)                           | 49.2 ± 5.1 | 49.2 ± 5.0 | 10.3 ± 0.5 | 3.0 ± 0.5 | 0.6 | 120 | 0.9 |
|          | 243915         | 0.32 × 0.28 (−78)                           | 102.8 ± 10.3 | 101.2 ± 10.4 | 10.3 ± 0.5 | 3.4 ± 0.5 | 0.5 | 105 | 17.7 |
|          | 261805         | 0.30 × 0.25 (−77)                           | 96.1 ± 9.8 | 96.5 ± 9.9 | 10.3 ± 0.5 | 3.1 ± 0.5 | 1.0 | 110 | 7.6 |
| CH$_3^{18}$OH | 231758 | 0.48 × 0.28 (−71)                           | 3.5 ± 1.3 | 3.3 ± 1.3 | 10.3 ± 1.2 | 2.6 ± 1.1 | 0.3 | 108 | 6.10$^{-2}$ |
| SIMBA-a  |               |                                              |               |               |               |               |     |     |     |       |
| CH$_3$OH | 218440         | 0.52 × 0.3 (106)                            | 2.6 ± 0.8 | 3.0 ± 0.7 | 13.0 ± 0.3 | 2.0 ± 0.7 | 0.5 | 190 | 195 | $-7.10^{-2}$ |
|          | 234683         | 0.32 × 0.28 (−259)                          | 4.7 ± 1.0 | 5.0 ± 1.0 | 13.2 ± 0.4 | 2.2 ± 0.6 | 0.4 | 172 | 9.10$^{-2}$ |
|          | 261805         | 0.30 × 0.26 (−78)                           | 1.9 ± 1.0 | 1.7 ± 0.6 | 13.1 ± 0.3 | 1.8 ± 0.6 | 0.4 | 3150 | $-2.5.10^{-3}$ |

Notes. Results of the Gaussian fit (G) and of the direct integration of channel intensities (D) for the integrated intensities are reported in columns 4 and 5, respectively. The calibration uncertainty of 10% has been included in the line intensity errors. $T_{kin}$ is the best fit for the kinetic temperature obtained from the LVG analysis, and $T_{ex}$ and $\tau_L$ are the associated excitation temperature and line optical depth. Lines in italics are those that were not taken into account in the LTE and LVG analyses.
Appendix C
LTE Analysis: Rotational Diagrams

We show here in Figure C1, below, the rotational diagram (RD) obtained for each source. We can clearly see that the line at 45.4 K is masing and that points are scattered due to optically thick and/or non-LTE effects.

Figure C1. Rotational diagrams. Non-LTE and optically thick effects are clearly visible in FIR6c-a, MMS9-a, and MMS5, as the points are scattered throughout the plots.
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