

LETTER TO THE EDITOR

First detection of the $J_{-1} \rightarrow (J - 1)_0 - E$ methanol maser transitions at $J = 7$ and 10

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ABSTRACT

Context. Class I methanol masers provide sensitive information about the shocked environment around star-forming regions. Among the brightest Class I methanol masers, we have those in the $J_{-1} \rightarrow (J - 1)_0 - E$ line series, currently reported for the $J = 4-9$ transitions, with the only exception being the $J = 7$ one at 181.295 GHz, and never expanded to higher J transitions.

Aims. We aim to search for population inversion in the $7_{-1} \rightarrow 6_0 - E$ and $10_{-1} \rightarrow 9_0 - E$ methanol transition lines at 181.295 and 326.961 GHz, respectively, and also extend the number of known low-mass star-forming sources harboring Class I methanol masers.

Methods. We employed the Atacama Pathfinder Experiment (APEX) 12 m telescope to survey low-mass Galactic sources, focusing on methanol emission lines. We built rotation diagrams for all sources with detected $J = 7$ methanol line transitions, while employing radiative transfer modeling (both in and out of local thermodynamic equilibrium) to characterize methanol excitation conditions in detail for one specific source with detected masers.

Results. We detected the $7_{-1} \rightarrow 6_0 - E$ and $10_{-1} \rightarrow 9_0 - E$ methanol transitions in 6 out of 19 sources. Among them, we firmly determined the $10_{-1} \rightarrow 9_0 - E$ maser nature in CARMA 7, L1641N, NGC 2024, and Serpens FIRS, and we show evidence for the presence of inverted population emission in the $7_{-1} \rightarrow 6_0 - E$ line toward CARMA 7 and L1641N. This represents the first report of methanol maser emission in these particular transitions. Our study supports previous works indicating that conditions for Class I methanol maser emission are satisfied in low-mass star-forming regions and expands the range of detectable frequencies toward higher values.

Key words. masers – stars: formation – stars: low-mass – stars: protostars – ISM: molecules – submillimeter: stars

1. Introduction

Methanol (CH_3OH) emission is quite common in the radio regime, with hundreds of transitions in the submillimeter window (e.g., Comito et al. 2005). This molecule is also prone to population inversion under specific excitation conditions, causing maser emission (e.g., Cragg et al. 1992). In particular, methanol masers (MMs) constitute unique tools for studying the physical properties of dense gas associated with young stellar objects (YSOs). Given their brightness and compactness (e.g., Menten 1991a), their positions can be determined with high-precision astrometry and over vast distances (e.g., Xu et al. 2021).

It was discovered early on that MMs can be divided into two classes: the collisionally pumped Class I (MMcIs) and the radiatively pumped Class II (MMcIIs) (Batra et al. 1987; Menten 1991b), which trace shocked regions, such as outflows (MMcIs)

or the circumstellar environment close to massive YSOs (MMcIIs), such as their protoplanetary disks. MMcIs have been detected toward high- and low-mass stars (Kalenskii et al. 2006, 2010, 2013, 2017; Rodríguez-Garza et al. 2017; Yang et al. 2023), while MMcIIs have only been detected toward high-mass YSOs (e.g., Minier et al. 2003; Breen et al. 2013). MMcIs are the only class definitely detected in emission beyond the Local Group of galaxies (i.e., beyond 1.5 Mpc) (Gorski et al. 2018; Humire et al. 2020; McCarthy et al. 2020; Humire et al. 2022), while absorption features have been reported for the Seyfert 2 system NGC 3079 (Impellizzeri et al. 2008). A tentative detection of MMcIIs was also recently reported at these distances (Chen et al. 2022).

Methanol maser emission in the $J_{-1} \rightarrow (J - 1)_0 - E$ series (hereafter MMcIs J_{-1}) has only been detected in the $J = 4-9$ transition range because low- J ($J < 4$) transitions are anti-inverted and higher J transitions have never been encountered as

masers. The difficulty in finding inverted populations in high- J transitions lies in the correlation between frequency (ν) and the time required to accumulate the inverted population ($\nu^{-3} \propto A^{-1}$, where A is the Einstein coefficient for spontaneous emission), making population inversion progressively harder to achieve in proportion to the cube of the frequency (for the case of hydrogen, see, e.g., [Scoville & Murchikova 2013](#), their Appendix A).

Accounting for the first detections of MMcIs J_{-1} , the $J = 4$ and $J = 5$ transitions in this line series (at 36 and 84 GHz) were first detected in space in the early 1970s ([Turner et al. 1972](#); [Zuckerman et al. 1972](#)). These transitions were later identified as masers in the 1980s by [Morimoto et al. \(1985\)](#) and [Batra & Menten \(1988\)](#), respectively. The first report of maser emission for the $J = 6$ transition at 132.9 GHz was made ten years later by [Slysh et al. \(1997\)](#), followed by the $J = 8$ transition at 229 GHz by [Slysh et al. \(2002\)](#). A decade ago, [Yanagida et al. \(2014\)](#) detected the $J = 9$ transition (at 278.3 GHz), which remains the highest J transition detected as a maser in the $J_{-1} \rightarrow (J-1)_0 - E$ line series.

Despite the long-term history of research, little attention has been paid to the $J = 7$ transition at 181.295 GHz. The mere detection of this line would represent a unique 16.7% (1/6) factor improvement in the number of detected maser lines for the MMcIs J_{-1} series of emission lines, if we stick to the range of transitions already detected. Maser models are expected to improve our capability of reproducing observations through synthetic spectra (see, e.g., [Lee et al. 2023](#); [Xue et al. 2024](#)), and therefore an accuracy of 16.7% better than currently achievable is desired.

Among the $J_{-1} \rightarrow (J-1)_0 - E$ methanol transition series, detecting the lines at $J = 7$ and $J = 10$ poses significant challenges due to their proximity to the telluric water lines at 181.310 and 325.153 GHz, respectively. This necessitates exceptionally favorable weather conditions to mitigate low atmospheric transmission and high noise levels during observations. However, successfully detecting these lines can benefit future observing campaigns targeting maser emission in the entire $J_{-1} \rightarrow (J-1)_0 - E$ methanol transition series within the same sources.

A strong argument for searching not only for the $J = 7$ transition but also for higher- J transition lines relates to the interstellar medium (ISM) conditions we are tracing, because specific J transitions of the same molecular species emerge at a certain restricted density range ([Shirley 2015](#); [Leurini et al. 2016](#)). The advent of improved facilities and atmospheric conditions in the submillimeter regime allows us to also search for the $J = 10$ transition, with an angular resolution that – for a given telescope – is almost twice as high (on a linear scale) as that of its $J = 7$ sibling.

In the following sections, we present our observations as well as details of the data reduction, and introduce our sample of sources (Sect. 2). In Sect. 3 we then describe the two methods used to identify methanol masers and present our results in the context of the latest advances in the field. Finally, we conclude in Sect. 4.

2. Observations

2.1. The sample

We conducted a survey of 19 low-mass star-forming regions searching for the $7_{-1} \rightarrow 6_0 - E$ and $10_{-1} \rightarrow 9_0 - E$ methanol transitions. The sample consists of the following sources: CARMA-7, L1641N, NGC 2024, IRAS 16293, Serpens FIRS, Serpens SMM4, YLW 16A, NGC 2027 North, Orion A West,

VLA 1623, HH1-2 VLA 1, HH 212, Haro 4-255, GSS 30-IRS1, L483, L483 FIR, HOPS 96, IRAS 18264-0143, and LDN 723-mm.

2.2. SEPIA180 and SEPIA345 observations

The observations were carried out with the Atacama Pathfinder EXperiment (APEX) 12 m telescope located in the Llano Chajnantor, Chile ([Güsten et al. 2006](#)), under projects M-0109.F-9512B-2022 and M-0109.F-9512C-2022 (P.I. A. Hernández-Gómez) at different dates: 1 April, 24–27 May, and 17 June 2022. We used the Swedish ESO PI receiver SEPIA ([Belitsky et al. 2018](#)), a double sideband (2SB) dual-polarization receiver working in the frequency range of 159–211 GHz. The backend was a Fast Fourier Transform fourth-generation spectrometer (FFTS4G) that consists of two sidebands with 4 GHz bandwidth each, covering a total bandwidth of 8 GHz. The observations were made using the wobbler-switching mode with a switching frequency of 1.7 Hz and a beam throw of 120''.

Here we used two frequency setups for the observations. With SEPIA180, we covered a frequency range of 181.140–185.140 GHz in the upper side band (USB) and 193.480–197.480 GHz in the lower side band (LSB). With SEPIA345, we covered a frequency range of 323.153–327.153 GHz in the USB and of 335.153–339.153 GHz in the LSB. The spectrometer has 65 536 channels, providing a spectral resolution of 61 kHz, corresponding to a velocity resolution of $\sim 0.1 \text{ km s}^{-1}$ at 183.310 GHz and $\sim 0.06 \text{ km s}^{-1}$ at 325.153 GHz. We applied the resample task inside GILDAS/CLASS¹ to produce a common 0.1 km s^{-1} channel width for both setups. This initial common velocity resolution changed after smoothing (see below).

The total observing time on each source varied slightly among sources depending on the precipitable water vapor (pwv) during the observations. The pwv varied between 0.023 and 1.14 mm. On average, the on-source time was ~ 15 min with SEPIA180 and ~ 25 min with SEPIA345. The system temperatures varied between 78 and 721 K during the observations. The following sources were used for focus and pointing calibrations: VY-CMA, IRC+10216, R-LEP, RAFGL 4211, IRAS 15194-51, IRC+00365, G327-ATCA, IRC+20370, and RAFGL 1922.

The calibrated data are delivered in antenna temperature units (T_A^*). To convert these to main beam brightness T_{MB} , we used the relation $T_{MB} = T_A^* (\eta_{fw} / \eta_{MB})$, where η_{fw} is the forward coupling efficiency (0.95) and η_{MB} is the main-beam efficiency. The main beam efficiency depends on the aperture efficiency η_a , which has a value of 0.71 for SEPIA180 and 0.67 for SEPIA345 based on observations toward Mars². As $\eta_{MB} = 1.2182 \times \eta_a$, then $\eta_{MB} = 0.865$ for SEPIA180 and $\eta_{MB} = 0.816$ for SEPIA345.

The absolute calibration uncertainty is estimated to be $\sim 10\%$ ([Dumke & Mac-Auliffe 2010](#)). The half-power beam width (HPBW) at 181.310 GHz is 34'', while it is 19.2'' at 325.153 GHz.

2.3. Data reduction

Data reduction was performed with the GILDAS/CLASS software developed by the Institut de Radioastronomie Millimétrique (IRAM). A first-order baseline was applied to the spectra by selecting windows free of line emission and subtracting them from the data. The resulting spectra were later

¹ <http://www.iram.fr/IRAMFR/GILDAS>

² The efficiencies can be found at <http://www.apex-telescope.org/telescope/efficiency/index.php>

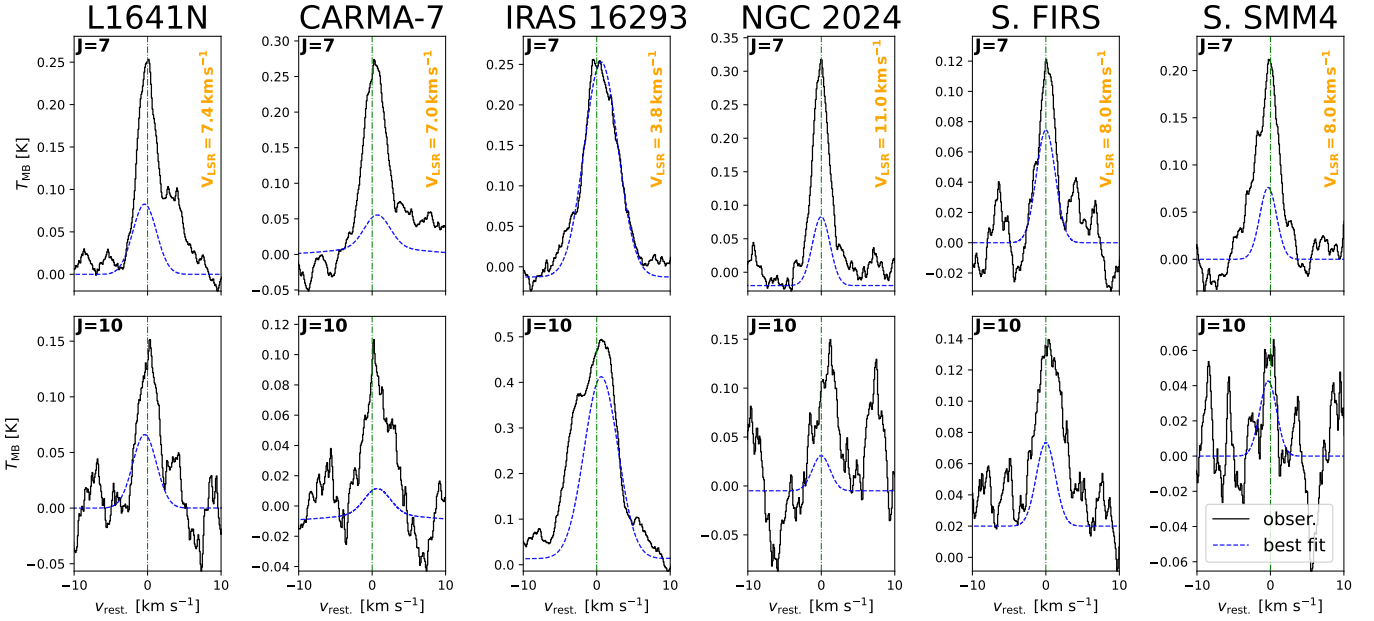


Fig. 1. Rest frame $J_{-1} \rightarrow (J-1)_0 - E$ methanol $J = 7$ and 10 transition spectra of our subsample (Sect. 2.1, solid black lines), along with the rotation diagram best fits (dashed blue lines, see Fig. B.1). The Local Standard of Rest velocities (V_{LSR} ; labeled in orange) of the different sources were obtained from the literature where we assume a common uncertainty of 1.0 km s^{-1} (see Sect. 2.3).

smoothed using a Box Kernel³ of width = 20, averaging the data over 20 points to reduce fluctuations and to enhance the signal-to-noise ratio in individual channels. Comparing the estimated radial and line-width velocities from a single Gaussian before and after smoothing, we see a difference of $\leq 0.2 \text{ km s}^{-1}$ in central velocities and $\leq 0.6 \text{ km s}^{-1}$ in line widths. We therefore estimate a conservative new velocity resolution of 1 km s^{-1} .

During our observational proposal process, we obtained the Local Standard of Rest velocities (V_{LSR}) for our entire sample from the literature, which was then recorded in the headers of our APEX files. The Local Standard of Rest velocities (V_{LSR}) for our subsample are highlighted with vertical orange labels in Fig. 1. Specifically, we referenced Podio et al. (2021) for CARMA-7, Bae et al. (2011) for L1641N, Pineda et al. (2012) for IRAS 16293, Buckle et al. (2010) for NGC 2024, Plunkett et al. (2015) for Serpens FIRS, and Narayanan et al. (2002) for Serpens SMM4. Due to an oversight, we mistakenly assigned a velocity of 7 instead of 8.1 km s^{-1} to CARMA-7. CASSIS later detected this error, and its line fitting provided – after several modeling iterations – a corrected velocity of $\sim 7.8 \text{ km s}^{-1}$, which should be adopted as the real V_{LSR} of this source.

Following Sect. 2.2, we adopt a conservative approach by assuming a uniform velocity uncertainty of 1.0 km s^{-1} across the entire dataset. To contextualize this value, it is larger than the statistical uncertainties derived from Markov chain Monte Carlo (MCMC) modeling, yielding uncertainties capped at 0.9 km s^{-1} for CARMA-7 (as detailed below).

3. Results and discussion

We report the detection of the $J_{-1} \rightarrow (J-1)_0 - E$ methanol lines at $J = 7$ and $J = 10$ in the following objects: CARMA-7, L1641N, NGC 2024, IRAS 16293, Serpens FIRS, and Ser-

pens SMM4. A summary of these source properties can be found in Appendix A, while the mentioned methanol line transitions are shown in Fig. 1. We refer to this subsample hereafter.

We observed a wide range of methanol transitions and specifically chose unblended emissions for inclusion in Table B.1, where line parameters were taken from the Cologne Database for Molecular Spectroscopy (CDMS; Müller et al. 2005)⁴. After confirming the detection of these selected transitions, our next task was to investigate whether they adhere to local thermodynamic equilibrium (LTE) conditions. As a first approach, we can use the rotation diagram method and then perform radiative transfer modeling in LTE using the best fit of our rotation diagrams as an initial condition. If the transition moves beyond LTE, it will exceed both the rotation diagram best fit and the synthetic modeling within LTE. In such instances, a subsequent attempt involves replicating maser line emission by considering synthetic spectra beyond LTE and searching for negative optical depths. If negative optical depths are present, the line is inverted; if not, and the line remains unreproduced within LTE, the transition is in quasi-thermal emission.

3.1. Rotation diagrams

The rotation diagram method involves some assumptions, including the premise that all emissions uniformly fill the entire beam (we refer the reader to Appendix B for further details). We emulate a filling factor of unity by setting a source size of $500''$ for the creation of the LTE models presented in Fig. 1 (dashed blue lines). This simplification is necessary due to the unknown extent of molecular gas emission, particularly from methanol tracing dense gas and weak shocks (Humire et al. 2022, and references therein). Figure A.1 shows a significant aperture difference between our lines at ~ 181 – 190 and ~ 338 GHz for one of our sources as an example case. Despite this, our rotation diagrams perform well once transitions outside LTE (quasi-thermal

³ See <https://docs.astropy.org/en/stable/api/astropy.convolution.Box1DKernel.html>

⁴ <https://cdms.astro.uni-koeln.de/>

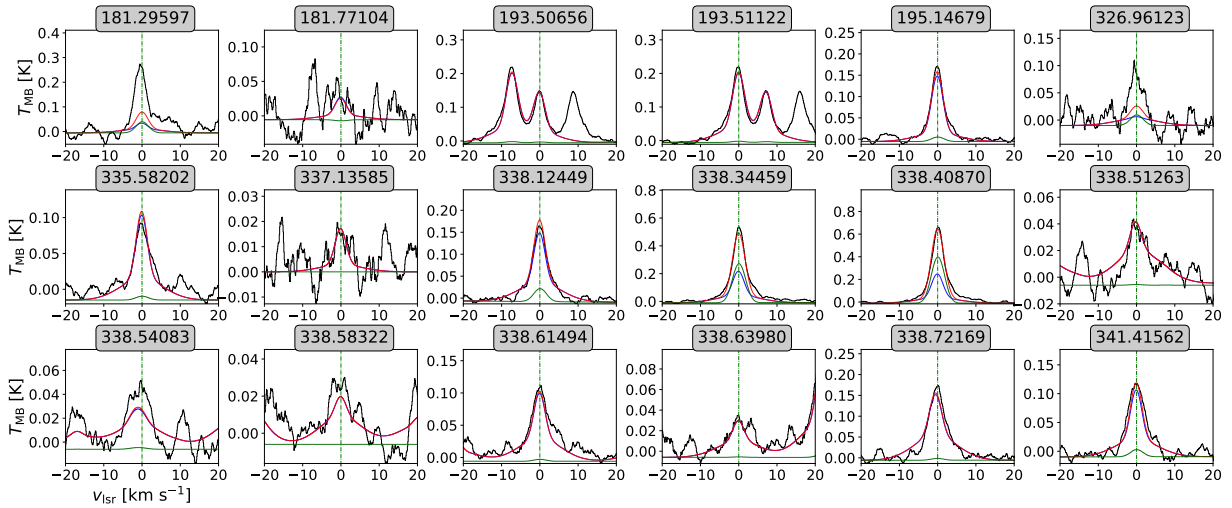


Fig. 2. Non-LTE plus LTE modeling for the CARMA-7 spectrum obtained from the best-fitting results (see Table 1). Line rest frequencies are indicated at the top of each subpanel. Rest-frame velocities and temperatures are labeled at the bottom and left-side positions in each subpanel. Observed spectra are shown in black, LTE modeling (narrow plus broad components) is indicated in blue, RADEX modeling is in green, and the combination of LTE plus RADEX emission is in red. An LSR velocity of $\sim 7.8 \pm 1.0 \text{ km s}^{-1}$ (see Sect. 2.3, Fig. 1, and Table 1 for the used references, initially adopted and calculated V_{LSR} , respectively) was previously subtracted.

and maser emission) are identified and discarded from the fit. Concerning quasi-thermal emission lines, which exhibit non-LTE behavior but positive optical depths, our radiative transfer model – discussed in the following section – illustrates the essential role of a non-LTE component in reproducing their emissions. This is particularly evident in Fig. 2, which shows lines at 338.344 and 338.408 GHz where non-LTE emissions (indicated by the green lines) are predominant. Therefore, we classify these lines as quasi-thermal.

Our rotation diagrams are plotted in Fig. B.1, where maser lines are in red, quasi-thermal lines are in blue, and LTE lines are in green. In the ISM, deviations from LTE are likely to occur in molecules with complex level diagrams, particularly when radiative and collisional processes vie for dominance in excitation and de-excitation. However, given the success in the fitting (see below), it can be inferred that potential blending lines in Table B.1 are, in most cases, not significantly contaminating. The fitting results, including 1σ uncertainties, are labeled inside each subplot of Fig. B.1.

Including a couple of highly improbable blended transitions with upper-level energies (E_{up}) exceeding 240 K, Table B.1 lists the unblended methanol transitions detected in our subsample. We obtained rotation diagrams using the transitions presented in this table from inside the CASSIS⁵ software. For this purpose, we used the CDMS catalog, which does not discriminate between methanol A and E forms. This is because we do not have a sufficient number of transitions for such a separation to be possible when creating rotation diagrams.

As blended transitions above an upper energy level (E_{up}/k) of 150 K tend to be dominated by their lower-energy counterparts, as we showed in a recent study (Humire et al. 2022), for the creation of the rotation diagrams we concentrate on methanol transitions with $E_{\text{up}}/k < 150 \text{ K}$. Moreover, we do not consider methanol lines separated from each other by less than their full width at half maximum (FWHM): when there is a low blending likelihood, we discard the transition from the global fit.

From the analysis presented above, we report the detection of the $7_{-1} \rightarrow 6_0 - E$ and $10_{-1} \rightarrow 9_0 - E$ methanol transitions as maser emission for the first time. To be rated as masers, the lines must be out of LTE by more than 3σ from our rotation diagram’s best fits (and must also have negative optical depths; see the following section). The 1σ of the rotation diagram is the $\ln(N_{\text{up}}/G_{\text{up}})$ dispersion of our LTE transitions (green points in Fig. B.1), which accounts for the difference between our best fit and the observed values. Maser transitions in both lines have been detected in CARMA-7 and L1641N (see Fig. B.1). For NGC 2024 and Serpens FIRS, only the $10_{-1} \rightarrow 9_0 - E$ transition exceeds LTE conditions without any doubt. Both in NGC 2024 and Serpens FIRS, the $10_{-1} \rightarrow 9_0 - E$ line profiles are not as clear as for CARMA-7 and L1641N; we obtain a low signal-to-noise ratio for NGC 2024 and a large line width in Serpens FIRS relative to other methanol transitions.

Although we would expect to measure both the $7_{-1} \rightarrow 6_0 - E$ and $10_{-1} \rightarrow 9_0 - E$ maser lines with the same departure from LTE conditions, this is not the case in our sample. In CARMA-7 and L1641N, the $J = 7$ transition departs more strongly from LTE conditions than the $J = 10$ transition. This can be explained in terms of the differences in frequency, with the $J = 7$ line having ~ 1.8 times smaller frequency than the $J = 10$ line, implying approximately six times more time to accumulate the inverted population (see also Sect. 1). On the other hand, in NGC 2024 and Serpens FIRS, the $J = 7$ line lies even below quasi-thermal emission (blue points in Fig. B.1), and only the $10_{-1} \rightarrow 9_0 - E$ transition line can be considered as maser in these sources. One possible explanation for the latter could be the higher ($\times 1.8$ in linear scale) angular resolution we use to observe the $J = 10$ line.

Finally, we also have the case of Serpens SMM 4, where only the $J = 7$ transition exceeds the 3σ fit. However, depending on the continuum level we choose for the Gaussian fitting in creating the rotation diagrams, this transition may or may not be considerably (3σ) beyond LTE. In addition, this transition does not surpass the two quasi-thermal lines (denoted with blue points in the rotation diagrams). We therefore only determine a tentative detection for the $7_{-1} \rightarrow 6_0 - E$ line in Serpens SMM 4.

⁵ <http://cassis.irap.omp.eu>

Table 1. Best-fit parameters from our LTE plus non-LTE modeling for CARMA-7.

Component	$N(\text{Sp})$ [$\times 10^{13} \text{ cm}^{-2}$]	T_{kin} or T_{ex} [K]	FWHM [km s^{-1}]	V_{LSR} [km s^{-1}]	n_{H_2} [cm^{-3}]	ISO	Size [$''$]
Non-LTE	$41.49^{+13.87}_{-2.48}$	$99.60^{+4.36}_{-0.64}$	$3.86^{+0.18}_{-0.03}$	$0.90^{+0.01}_{-0.01}$	$7.27 \times 10^4^{+0.23}_{-0.22}$	$0.95^{+0.06}_{-0.02}$	$6.28^{+0.32}_{-1.18}$
LTE (narrow)	$79.48^{+8.77}_{-6.62}$	$15.85^{+1.13}_{-0.21}$	$3.36^{+0.04}_{-0.01}$	$0.73^{+0.01}_{-0.03}$	–	$1.33^{+0.13}_{-0.02}$	$9.21^{+0.18}_{-0.68}$
LTE (broad)	$5.7^{+0.10}_{-0.33}$	$40.48^{+0.40}_{-6.55}$	$13.21^{+0.84}_{-0.11}$	$0.84^{+0.01}_{-0.01}$	–	$1.35^{+0.04}_{-0.02}$	$41.44^{+0.95}_{-1.21}$

Notes. Uncertainties correspond to 3σ . Velocity uncertainties are of the order of the instrumental uncertainty ($\sim 1.0 \text{ km s}^{-1}$). Column density ($N(\text{Sp})$) values for A-type methanol can be obtained by dividing the E-type methanol values shown in the table by the ISO number given at the next-to-last column, while the rest of the parameters are the same for both methanol symmetric types. The dash symbol (–) indicates that no n_{H_2} was derived as the model is in LTE. An LSR velocity of $7 \pm 1.0 \text{ km s}^{-1}$ (see Sect. 2.3 and Fig. 1) was previously subtracted. Therefore, the real V_{LSR} value, of about $7.8 \pm 1.0 \text{ km s}^{-1}$, depending on the component, is obtained by summing up these values.

Among the mentioned sources, CARMA-7 exhibits the most prominent inverted population detection in the $7_{-1} \rightarrow 6_0 - E$ transition, considering a 3σ separation. Even when quasi-thermal emission is included in the LTE fit, along with error bars and all detected methanol transitions, as depicted in its rotation diagram (middle upper panel in Fig. B.1), the mentioned $J = 7$ transition in CARMA-7 remains beyond LTE conditions by more than 3σ . In these rotation diagrams, the departure from LTE (observed upper level column density over the expected one from the LTE best fit) for maser emission in CARMA-7 is 1.25 dex. At the same time, for L1641N, it is 0.83 dex. These values reflect the amplification effect due to negative optical depths, rather than indicating the actual upper level column density of the source.

3.2. LTE plus non-LTE modeling

As CARMA-7 is the source where the $7_{-1} \rightarrow 6_0 - E$ and $10_{-1} \rightarrow 9_0 - E$ methanol transitions show the clearest departures from LTE conditions, we focus on its spectrum to create radiative transfer models. Using RADEX (van der Tak et al. 2007) (non-LTE) or LTE modeling separately does not reproduce our observations. However, using both models together, specifying the interacting mode on CASSIS, we can adjust the spectra, with the sum of those models reaching the expected values. While we focus on its results in the present section, a detailed explanation of our model procedure can be found in Appendix C.

Similar to previous work on methanol masers (Humire et al. 2022), we find that E-CH₃OH is more abundant than its A-CH₃OH counterpart for the LTE components. This is striking because the E-to-A methanol column density ratio (hereafter ISO, as it is called in CASSIS for “isotopic ratio”⁶) should be less than or equal to unity at production temperatures up to approximately 40 K, and exactly unity at temperatures above this threshold (Wiström et al. 2010). Forcing the code to take an ISO of up to 1.0 for all the components never replicates several E-CH₃OH lines in the $7_k \rightarrow 6_k - E$ methanol series, such as those at $\sim 338 \text{ GHz}$.

A possible cause of ISO values above unity may come from the shocked nature of the methanol emission we observe, producing a mixture of methanol molecules from different environments along our line of sight. The latter is also a good argument for the line width and temperature of the broad LTE component. On the other hand, the narrow LTE component is the densest and coldest counterpart, which may arise from the cen-

tral continuum source. This leads us to believe that the methanol emission we observe comes from a mixture of stellar outflows (broad LTE component and maser emission) and the central continuum source (narrow LTE component) in CARMA-7 (see also Appendix C), depicted in Fig. A.1.

In Fig. 2 we demonstrate how the non-LTE plus LTE approach reproduces the observations in CARMA-7. Table 1 presents the best-fit parameters. The $7_{-1} \rightarrow 6_0 - E$ transition line falls approximately into the middle of the isotropic MMcIs luminosity distribution detected in low-mass star-forming regions (Kalenskii et al. 2013). Therefore, the newly detected masers likely represent a broadening in the maser luminosity versus source luminosity relation of the Class I maser population detected so far toward low-luminosity sources (see Sect. 3.3).

As stated in Sect. 1, masers in high- J transitions are hard to find due to the difficulty of keeping inverted populations. Among all the transitions detected by us in the spectrum of CARMA-7, we found only two transitions with negative optical depths, both in the $J_{-1} \rightarrow (J-1)_0 - E$ family series: the $7_{-1} \rightarrow 6_0 - E$ line at 181.295 GHz and the $10_{-1} \rightarrow 9_0 - E$ at 326.961 GHz . Due to our coarse resolution and software limitations (see van der Tak et al. 2007, their Sect. 3.6), we cannot ensure precise excitation temperatures and optical depths in our non-LTE models. Instead, we can assess the need for negative optical depths regarding the proposed maser emission. For the case of CARMA-7, the $10_{-1} \rightarrow 9_0 - E$ line is quite beyond LTE conditions. At the frequencies of the lines observed with SEPIA345 ($\geq 323.153 \text{ GHz}$), the beam size is $19.2''$. Therefore, we can conclude that the emission comes predominantly from CARMA-7 and not from the neighboring source CARMA-6, whose nucleus cannot be completely disentangled in the low-frequency regime observed with SEPIA180 (indicated by an orange circle in Fig. A.1). Based on the CASSIS outputs for our non-LTE model, we derive excitation temperatures (and optical depths) of -5.85 (-0.12) and -12.10 (-0.009) in the $J = 7$ and $J = 10$ lines, respectively.

The resulting parameters for the three components of the best-fitting model are presented in Table 1. From the inner to the outer layers, these components can be physically associated to the following: the warmest one comes from the shocked environment where Class I maser spots emerge (see stellar outflows in Fig. A.1). The narrow LTE component is associated with the coldest and denser gas of the main source, corresponding to the ALMA 1 mm continuum source presented in Fig. A.1. The broad LTE component is linked to an external warm and more diffuse (less dense) envelope around CARMA-7. This last component is affected by the shocked environment present in CARMA-7, which can account for its large line widths, temperature, and

⁶ https://cassis.irap.omp.eu/docs/CassisScriptingDoc/setup/components_creation.html

source extension. The resulting synthetic spectrum is shown in Fig. 2, where we separate between LTE (narrow plus broad, in blue lines) and non-LTE (green lines) emissions. More details about the model and results can be found in Appendix C.

The evolution of the different free parameters versus iteration number in our models, considering all components, is shown in Fig. C.1. Corner plots of our non-LTE and LTE narrow and broad component modeling are shown in Figs. C.2, C.3, and C.4, respectively.

3.3. Maser luminosity versus bolometric luminosity

As pointed out by the review of Kalenskii et al. (2013), the isotropic luminosity of Class I methanol masers at 44 GHz is proportional to the bolometric luminosity of the object harboring it. This relation holds for low- to intermediate- and high-mass protostars. A long-monitoring study on low-mass protostars (Kalenskii et al. 2017) indicates that maser intensity in these objects does not change significantly over time, with small line profile changes rather attributed to calibration uncertainties than to intrinsic properties of the sources.

The above-mentioned proportionality is plotted in our Fig. D.1, where we conservatively associate 10% variability to the masers, given the $\geq 20\%$ short-term (hours to days) variability found in 44 GHz MMcIs arising from massive star-forming regions (Pratap et al. 2007). New data from this study are added to literature information provided by Bae et al. (2011) and previously taken by Kalenskii et al. (2013). As can be seen in Fig. D.1, we find that the relation is not fulfilled for high- J transitions found in this study, as the isotropic luminosities measured for L1641N and CARMA-7 are two orders of magnitude stronger than expected by the mentioned relation.

Accounting for L_{bol} uncertainties, we include an average luminosity dispersion encountered in the literature for L1641N. In the case of CARMA-7, the difference between its bolometric luminosity inferred from 70 μm observations and the bolometric luminosity of the closest source around the source position is included (see Appendix A). As neither Bae et al. (2011) nor Kalenskii et al. (2013) provide L_{bol} uncertainties for the whole sample included in our Fig. D.1 (gray dots), we conservatively assume an L_{bol} uncertainty of 21%. The latter is motivated by the recent study of Pitts et al. (2022), who found L_{bol} uncertainties in the range of 3–35% (their Table 4), with a mean of 21% for a sample of intermediate- to high-mass star-forming regions.

4. Conclusions

In the present article, we report the first detections of the methanol $7_{-1} \rightarrow 6_0 - E$ and $10_{-1} \rightarrow 9_0 - E$ transitions out of LTE, which we consider to be maser emission. We detect these masers without any doubt in the low-mass star-forming regions CARMA-7 and L1641N. We claim additional tentative detections of the $7_{-1} \rightarrow 6_0 - E$ transition in NGC 2024, Serpens FIRS, and Serpens SMM 4. In NGC 2024 and Serpens FIRS, the $10_{-1} \rightarrow 9_0 - E$ transition line departs from LTE ($\gg 3\sigma$) and is also interpreted as maser emission.

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References

- Araya, E., Hofner, P., Kurtz, S., Bronfman, L., & DeDeo, S. 2005, *ApJS*, **157**, 279
- Bae, J.-H., Kim, K.-T., Youn, S.-Y., et al. 2011, *ApJS*, **196**, 21
- Batrla, W., & Menten, K. M. 1988, *ApJ*, **329**, L117
- Batrla, W., Matthews, H. E., Menten, K. M., & Walmsley, C. M. 1987, *Nature*, **326**, 49
- Belitsky, V., Lapkin, I., Fredrixon, M., et al. 2018, *A&A*, **612**, A23
- Belloche, A., Garrod, R. T., Müller, H. S. P., et al. 2019, *A&A*, **628**, A10
- Breen, S. L., Ellingsen, S. P., Contreras, Y., et al. 2013, *MNRAS*, **435**, 524
- Buckle, J. V., Curtis, E. I., Roberts, J. F., et al. 2010, *MNRAS*, **401**, 204
- Chen, X., Yang, T., Ellingsen, S. P., McCarthy, T. P., & Ren, Z.-Y. 2022, *ApJ*, **926**, 48
- Choi, M., Kang, M., Byun, D.-Y., & Lee, J.-E. 2012, *ApJ*, **759**, 136
- Comito, C., Schilke, P., Phillips, T. G., et al. 2005, *ApJS*, **156**, 127
- Cragg, D. M., Johns, K. P., Godfrey, P. D., & Brown, R. D. 1992, *MNRAS*, **259**, 203
- Crimier, N., Ceccarelli, C., Maret, S., et al. 2010, *A&A*, **519**, A65
- Curiel, S., Rodriguez, L. F., Gomez, J. F., et al. 1996, *ApJ*, **456**, 677
- Dumke, M., & Mac-Auliffe, F. 2010, in *Observatory Operations: Strategies, Processes, and Systems III*, eds. D. R. Silva, A. B. Peck, & B. T. Soifer, *SPIE Conf. Ser.*, **7737**, 77371J
- Dzib, S. A., Ortiz-León, G. N., Hernández-Gómez, A., et al. 2018, *A&A*, **614**, A20
- Enoch, M. L., Glenn, J., Evans, Neal J., I., et al. 2007, *ApJ*, **666**, 982
- Fischer, W. J., Megeath, S. T., Furlan, E., et al. 2017, *ApJ*, **840**, 69
- Girart, J. M., Estalella, R., Palau, A., Torrelles, J. M., & Rao, R. 2014, *ApJ*, **780**, L11
- Goldsmith, P. F., & Langer, W. D. 1999, *ApJ*, **517**, 209
- Gorski, M., Ott, J., Rand, R., et al. 2018, *ApJ*, **856**, 134
- Großschedl, J. E., Alves, J., Meingast, S., et al. 2018, *A&A*, **619**, A106
- Güsten, R., Nyman, L. Å., Schilke, P., et al. 2006, *A&A*, **454**, L13
- Haisch, K. E., Jr., Lada, E. A., Piña, R. K., Telesco, C. M., & Lada, C. J. 2001, *AJ*, **121**, 1512
- Humire, P. K., Henkel, C., Gong, Y., et al. 2020, *A&A*, **633**, A106
- Humire, P. K., Henkel, C., Hernández-Gómez, A., et al. 2022, *A&A*, **663**, A33
- Hunter, T. R., Brogan, C. L., Cyganowski, C. J., & Young, K. H. 2014, *ApJ*, **788**, 187
- Impellizzeri, C. M. V., Henkel, C., Roy, A. L., & Menten, K. M. 2008, *A&A*, **484**, L43
- Jacobsen, S. K., Jørgensen, J. K., van der Wiel, M. H. D., et al. 2018, *A&A*, **612**, A72
- Jørgensen, J. K., van der Wiel, M. H. D., Coutens, A., et al. 2016, *A&A*, **595**, A117
- Kahle, K. A., Hernández-Gómez, A., Wyrowski, F., & Menten, K. M. 2023, *A&A*, **673**, A143
- Kalenskii, S. V., Promyslov, V. G., Slysh, V. I., Bergman, P., & Winnberg, A. 2006, *Astron. Rep.*, **50**, 289
- Kalenskii, S. V., Johansson, L. E. B., Bergman, P., et al. 2010, *MNRAS*, **405**, 613
- Kalenskii, S. V., Kurtz, S., & Bergman, P. 2013, *Astron. Rep.*, **57**, 120
- Kalenskii, S. V., Kurtz, S., & Hofner, P. 2017, *Astron. Astrophys. Trans.*, **30**, 161
- Koukel, M., Hartmann, L., Loinard, L., et al. 2017, *ApJ*, **834**, 142
- Lee, K. L. K., Loomis, R. A., Xue, C., El-Abd, S., & McGuire, B. A. 2023, <https://doi.org/10.5281/zenodo.8118192>
- Laurini, S., Menten, K. M., & Walmsley, C. M. 2016, *A&A*, **592**, 31
- Levine, J. L., Steinhauer, A., Elston, R. J., & Lada, E. A. 2006, *ApJ*, **646**, 1215
- Maury, A. J., André, P., Men'shchikov, A., Könyves, V., & Bontemps, S. 2011, *A&A*, **535**, A77
- McCarthy, T. P., Ellingsen, S. P., Breen, S. L., et al. 2020, *MNRAS*, **491**, 4642
- Menten, K. M. 1991a, *ApJ*, **380**, L75
- Menten, K. M. 1991b, in *Atoms, Ions and Molecules: New Results in Spectral Line Astrophysics*, eds. A. D. Haschick, & P. T. P. Ho, *ASP Conf. Ser.*, **16**, 119
- Minier, V., Ellingsen, S. P., Norris, R. P., & Booth, R. S. 2003, *A&A*, **403**, 1095
- Mizuno, A., Fukui, Y., Iwata, T., Nozawa, S., & Takano, T. 1990, *ApJ*, **356**, 184
- Morimoto, M., Ohishi, M., & Kanzawa, T. 1985, *ApJ*, **288**, L11
- Mottram, J. C., van Dishoeck, E. F., Schmalzl, M., et al. 2013, *A&A*, **558**, A126
- Müller, H. S. P., Schlöder, F., Stutzki, J., & Winnewisser, G. 2005, *J. Mol. Struct.*, **742**, 215
- Nakamura, F., Miura, T., Kitamura, Y., et al. 2012, *ApJ*, **746**, 25
- Narayanan, G., Moriarty-Schieven, G., Walker, C. K., & Butner, H. M. 2002, *ApJ*, **565**, 319

- Ortiz-León, G. N., Loinard, L., Dzib, S. A., et al. 2018, [ApJ](#), **869**, L33
- Ortiz-León, G. N., Plunkett, A. L., Loinard, L., et al. 2021, [AJ](#), **162**, 68
- Ortiz-León, G. N., Dzib, S. A., Loinard, L., et al. 2023, [A&A](#), **673**, L1
- Pineda, J. E., Maury, A. J., Fuller, G. A., et al. 2012, [A&A](#), **544**, L7
- Pitts, R. L., Kristensen, L. E., Jørgensen, J. K., & van der Walt, S. J. 2022, [A&A](#), **657**, A70
- Plunkett, A. L., Arce, H. G., Mardones, D., et al. 2015, [Nature](#), **527**, 70
- Plunkett, A. L., Fernández-López, M., Arce, H. G., et al. 2018, [A&A](#), **615**, A9
- Podio, L., Tabone, B., Codella, C., et al. 2021, [A&A](#), **648**, A45
- Pratap, P., Strelitski, V., Hoffman, S., & Lemonias, J. 2007, in [Astrophysical Masers and their Environments](#), eds. J. M. Chapman, & W. A. Baan, 242, 34
- Richer, J. S., Hills, R. E., & Padman, R. 1992, [MNRAS](#), **254**, 525
- Rodríguez, L. F., Gómez, Y., & Reipurth, B. 2003, [ApJ](#), **598**, 1100
- Rodríguez-Garza, C. B., Kurtz, S. E., Gómez-Ruiz, A. I., et al. 2017, [ApJS](#), **233**, 4
- Scoville, N., & Murchikova, L. 2013, [ApJ](#), **779**, 75
- Shirley, Y. L. 2015, [PASP](#), **127**, 299
- Skinner, S., Gagné, M., & Belzer, E. 2003, [ApJ](#), **598**, 375
- Slysh, V. I., Kalenskii, S. V., Val'tts, I. E., & Golubev, V. V. 1997, [ApJ](#), **478**, L37
- Slysh, V. I., Kalenskii, S. V., & Val'tts, I. E. 2002, [Astron. Rep.](#), **46**, 49
- Turner, B. E., Gordon, M. A., & Wrixon, G. T. 1972, [ApJ](#), **177**, 609
- van der Tak, F. F. S., Black, J. H., Schöier, F. L., Jansen, D. J., & van Dishoeck, E. F. 2007, [A&A](#), **468**, 627
- van Terwisga, S. E., & Hacar, A. 2023, [A&A](#), **673**, L2
- Wilson, T. L. 2009, arXiv e-prints [arXiv:0903.0562]
- Wirstrom, E. S., Bergman, P., Black, J. H., et al. 2010, [A&A](#), **522**, A19
- Xu, Y., Bian, S. B., Reid, M. J., et al. 2021, [ApJS](#), **253**, 1
- Xue, C., Remijan, A., Faure, A., et al. 2024, [ApJ](#), **967**, 164
- Yanagida, T., Sakai, T., Hirota, T., et al. 2014, [ApJ](#), **794**, L10
- Yang, W., Gong, Y., Menten, K. M., et al. 2023, [A&A](#), **675**, A112
- Zuckerman, B. E., Turner, B. E., Johnson, D. R., Palmer, P., & Morris, M. 1972, [ApJ](#), **177**, 601

Appendix A: Individual sources

The whole sample used in the present study consists of low-mass YSOs located in our Galaxy.

CARMA-7 is the strongest radio source of the Serpens South protostellar cluster. It presents a bipolar outflow which extends ~ 0.16 pc north-south (PA $\sim 4^\circ$ east of north) in CO emission (Fig. A.1; Plunkett et al. 2015) and also shows water maser emission at 22 GHz (Ortiz-León et al. 2021). We can adopt a distance of 440.7 ± 4.6 pc for CARMA-7, as recently measured by Ortiz-León et al. (2023) from H₂O maser emission at 22 GHz in CARMA-6.

Considering the closest Class 0 object to CARMA-7, identified as SerpS-MM18 by Maury et al. (2011) at an angular resolution of $11''$, if we assume it is CARMA-7, it would likely have a bolometric luminosity (L_{bol}) of $46L_\odot$ at a distance of 440.7 pc. This estimation is however much larger than the one obtained for CARMA-7 with the Herschel $70\mu\text{m}$ band ($8''$) measurements, conducted by Podio et al. (2021). Upon adjusting for the updated distance measured by Ortiz-León et al. (2023), this latter L_{bol} becomes $20L_\odot$. Hence, we may assume a L_{bol} range of 20 to $46L_\odot$ for CARMA-7. Given that Podio et al. (2021) presented the highest angular resolution, we will consider their value as the more accurate and the one of Maury et al. (2011) as the upper limit.

L1641N(orth) is a dark cloud located in the southern part of our nearest giant molecular cloud, the Orion A region, located ~ 7.2 pc southward from the Orion nebula cluster, assuming a distance of 414 pc (Großschedl et al. 2018). Studies of FUV irradiation in protoplanetary disks indicate that L1641N presents the oldest population of stars in the L1641 region (van Terwisga & Hacar 2023).

Based on $^{12}\text{CO } J=1-0$ observations, Nakamura et al. (2012) inferred cloud-cloud collisions and protocluster winds. The latter may explain the presence of CO shells roughly centered at L1641N. The authors attribute the existence of multiple shells either to a fluctuating star formation rate or a single shell expanding into an inhomogeneous medium.

Following Fischer et al. (2017), who detected 173 protostars in L1641, the median L_{bol} in L1641 is $2.0 \pm 4.7L_\odot$. We will adopt this value for L1641N since the luminosity distribution in the entire complex is quite homogeneous among object classes.

NGC2024 is a nearby HII region located in Orion B, and constitutes its most active and youngest star-forming region, with a median age of 0.5 Myr. (Levine et al. 2006). VLBA measurements determine distances ranging between ~ 350 and 540 pc, depending on the binary system (Kounkel et al. 2017).

Among the several far infrared cores (FIR) located along its north-south distribution, we observed the brightest and oldest FIR 5 source (VLA 10 in Rodríguez et al. 2003, and references therein). FIR 5 is the driving source of a unipolar molecular CO jet which collimates as its velocity increases up to 45 km s^{-1} (reaching an opening angle as low as $\sim 2^\circ$; Richer et al. 1992).

Judging for common bolometric luminosities measured around this source by Haisch et al. (2001), we can assume values in the $2-3L_\odot$ range, where the closest source, numbered 58 by the mentioned study, shows a L_{bol} of $2.3L_\odot$. Chandra observations did not detect any emission source, likely because it is heavily obscured by dust (Skinner et al. 2003).

Serpens SMM4 is a Class 0 protostellar system with an inverse P-Cygni profile initially claimed to be an infall signature (Narayanan et al. 2002) but lately associated with large-scale cloud flows or foreground emission (Mottram et al. 2013). Being

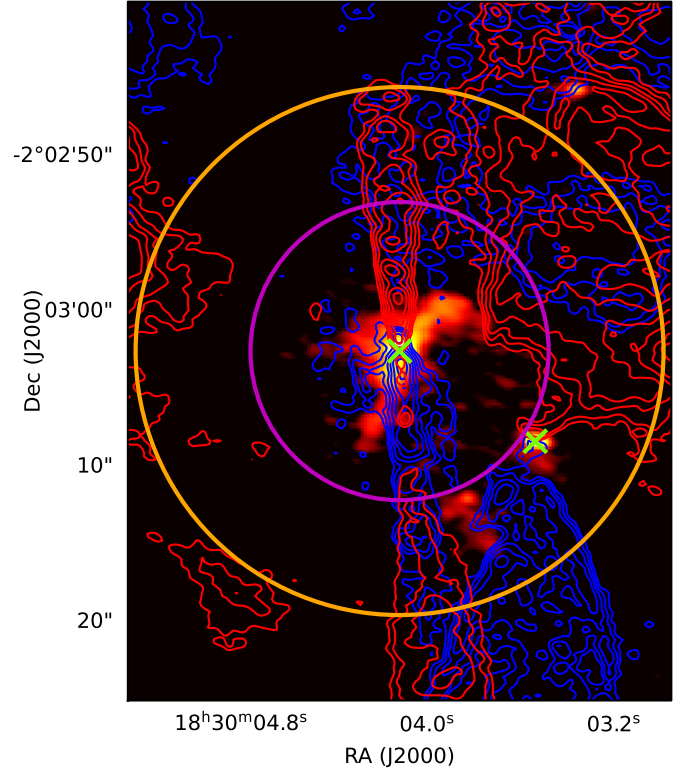


Fig. A.1. CO ($J=2-1$) emission associated with the large-scale outflow of CARMA-7 (central red and blue contours; Plunkett et al. 2015). The integration ranges are -20 to 4 km s^{-1} for the blueshifted component and $12-40 \text{ km s}^{-1}$ for the redshifted component. The n th contour occurs at a level of $(\sqrt{2})^n \times p$ times the maximum signal strength, where the maximum signal strengths are 3.5 and $6.3 \text{ Jy beam}^{-1} \text{ km s}^{-1}$ and p represents 10% and 9% of the signal strength for the blueshifted and redshifted emissions, respectively. Here, n ranges from 0 onwards, incrementing by integers. The background is an ALMA map of 1 mm continuum emission (Plunkett et al. 2018). APEX has a half-power beam width of $34''$ at 181.310 GHz (denoted by an orange circle) and $19.2''$ at 325.153 GHz (denoted by a magenta circle). The companion source whose center is also indicated by a green cross in the southeast is CARMA-6.

part of the Serpens South cluster, its distance can be approximated to 440.7 ± 4.6 pc (Ortiz-León et al. 2023).

Serpens FIRS 1 is a Class 0 protostar located in the main core of the Serpens Molecular Cloud at a distance of 436 ± 9 pc (Ortiz-León et al. 2018). Also known as Serpens SMM 1, this protostar is associated with a bipolar radio jet (e.g., Curiel et al. 1996). It is the most embedded, massive, and luminous YSO in the Serpens dark cloud, with a total flux of 5.9 Jy at 1.1 mm , a mass of $15 M_\odot$ (Enoch et al. 2007) and a bolometric luminosity of $91 L_\odot$ (Bae et al. 2011), after correcting for the updated distance. High angular resolution observations at $0''.6$ revealed a second YSO indicating a binary configuration for this system (Choi et al. 2012).

IRAS 16293-2422 is a well-studied Class 0 hierarchical system of solar type protostars, composed by two main condensations, IRAS 16293-2422A and IRAS 16293-2422B, surrounded by an extended envelope of $\sim 8000 \text{ AU}$ (Crimier et al. 2010; Jacobsen et al. 2018). It is located in the L1689N region of the ρ Ophiuchus cloud at a distance of 141 pc (Dzib et al. 2018). This multiple system shows a wealth of molecular species at both small (Jørgensen et al. 2016) and large scales (Kahle et al. 2023). In addition, a multiple outflow system has been observed toward this source (Mizuno et al. 1990; Girart et al. 2014).

Appendix B: Rotation diagrams

We use rotation diagrams as our first and simplest method to unveil the presence of methanol masers. Its construction assumes LTE conditions, a filling factor of unity, and that the lines are optically thin. It also assumes the Rayleigh-Jeans (RJ) approximation⁷, valid when ν [GHz] $\ll$ 20.84 T_{ex} [K] (e.g., Wilson 2009). Given that the lowest excitation temperature derived

by this method is 29.2 K (see CARMA-7 in Fig. B.1), the RJ approximation is valid for frequencies much lower than $\sim$ 610 GHz, which is the case of this study. The rotation diagram method also assumes a negligible background continuum (e.g., Belloche et al. 2019). Since we subtracted the continuum emission before our analysis (see Sect. 2.3), this assumption does not represent a problem for us. More details about this method can be found in Goldsmith & Langer (1999).

Table B.1. Selected methanol transitions.

Transition	ν [GHz]	A/E	E_{up}/k [K]	L1641N	CARMA-7	IRAS 16293	NGC 2024	Serpens FIRS	Serpens SMM4	potential blending lines
$7_{-1} \rightarrow 6_0$	181.295971	E	70.55	✓	✓	✓	✓	✓	✓	$^{13}\text{CC}_2\text{N}$, CH_3OH with $E_{\text{up}}=1025.4$ K
$4_1 \rightarrow 3_1$	193.506559	E	44.26	✓	✓	✓	✓	✓	✓	
$4_1 \rightarrow 3_1$	195.146790	A ⁻	37.95	✓	✓	✓	✓	✓	✓	CH_3OCHO
$9_1 \rightarrow 9_0$	322.239462	A ⁺⁺	119.88	✓	✓	✓	✓	✓	✓	–
$10_1 \rightarrow 10_0$	326.630583	A ⁺⁺	143.27	–	–	✓	–	✓	✓	–
$10_{-1} \rightarrow 9_0$	326.961232	E	133.15	✓	✓	✓	✓	✓	✓	S^{17}O , H_2CCCHCN
$7_1 \rightarrow 6_1$	335.582017	A ⁺	78.97	✓	✓	✓	✓	✓	✓	–
$7_0 \rightarrow 6_0$	338.124488	E	78.08	✓	✓	✓	✓	✓	✓	–
$7_{-1} \rightarrow 6_{-1}$	338.344588	E	70.55	✓	✓	✓	✓	✓	✓	–
$7_0 \rightarrow 6_0$	338.408698	A ⁺	64.98	✓	✓	✓	✓	✓	✓	CH_3OH with $E_{\text{up}}=243.8$ K
$7_{-3} \rightarrow 6_{-3}$	338.559963	E	127.71	✓	✓	✓	–	✓	✓	–
$7_3 \rightarrow 6_3$	338.583216	E	112.71	✓	–	✓	✓	✓	–	^{33}SO , CH_3SH
$7_1 \rightarrow 6_1$	338.614936	E	86.05	✓	✓	✓	✓	✓	✓	CH_3OCHO
$7_2 \rightarrow 6_2$	338.639802	A ⁺	102.72	✓	–	✓	✓	✓	✓	$\text{C}_2\text{H}_5\text{C}-^{13}\text{N}$
$7_1 \rightarrow 6_1$	341.415615	A ⁻	80.09	✓	✓	✓	✓	✓	✓	cis-DCOOH, n-C ₃ H ₇ CN

Notes. Selected methanol lines used to perform our rotation diagrams (Fig. A.1). Possible contamination with other molecules is mentioned in the rightmost column. ✓ indicates well-distinguished/confidently-detected lines while the dash symbol (–) indicates a poor signal or non-detection. Certain methanol species that are highly improbable to blend with others are also identified: The $7_{-1} \rightarrow 6_0 - E$ line falls within the range of frequencies of the $19_2 \rightarrow 18_3 - E$ methanol line in all sources while the $7_0 \rightarrow 6_0 - A^+$ methanol transition falls within the frequency range of the $7_6 \rightarrow 6_6 - E$ methanol transition for the case of IRAS 16293 and CARMA 7, given the higher FWHM of the CH_3OH lines in these sources compared to the rest of the sample. Line frequencies and upper-level energies were taken from the CDMS database (Müller et al. 2005).

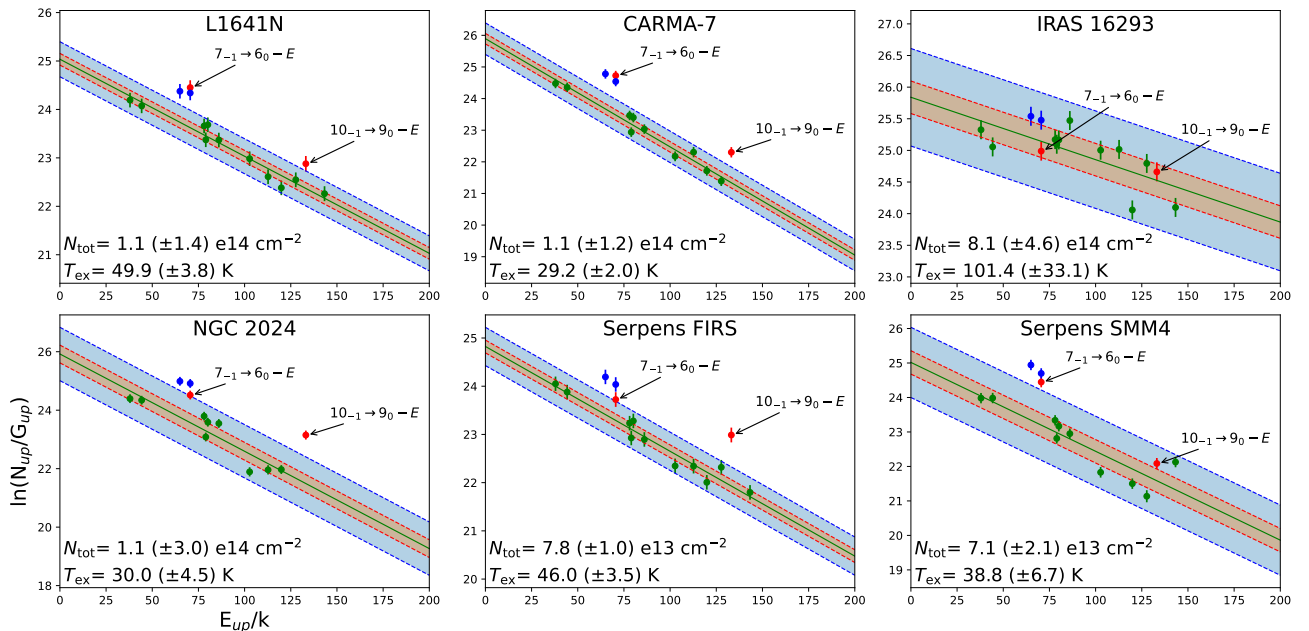


Fig. B.1. Rotation diagrams for sources with detected $7_{-1} \rightarrow 6_0 - E$ methanol transition (indicated with an arrow). The shaded red and blue regions represent the uncertainty level at 1 and 3 σ , respectively. Methanol lines in the $J_{-1} \rightarrow (J-1)_0 - E$ line series, prone to be masers, are in red, thermal lines are in green, and quasi-thermal emission (those out of LTE best fit, positive optical depths and strong presence of a non-LTE component in our models) are in blue. These quasi-thermal transitions correspond to the $7_{-1} \rightarrow 6_{-1} - E$ and $7_0 \rightarrow 6_0 - A^+$ transition lines at 338.344588 and 338.408698 GHz, respectively. Only unblended lines were used for the fit. Best fit results (total column densities (N_{tot}) and excitation temperatures (T_{ex}) plus 1 σ uncertainties) are labeled in the bottom left corner of each subplot. Transitions detected in each source are listed in Table B.1.

⁷ See, for instance, the derivation presented in Araya et al. (2005), between Eqs. A9 and A10.

Appendix C: Details about the model

Our procedure to create the CASSIS modeling was as follows: We started with a single LTE model with the rotation diagram best fits as inputs, and then we added a non-LTE component attempting to reproduce the quasi-thermal and maser emission. We selected a slab geometry for this latter as this configuration is the most appropriate for shocks (see, e.g., [Leurini et al. 2016](#)). The quasi-thermal transitions correspond to the $7_{-1} \rightarrow 6_{-1} - E$ and $7_0 \rightarrow 6_0 - A^+$ transition lines at 338.344588 and 338.408698 GHz, respectively. They depart ($>3\sigma$) from LTE conditions in our rotation diagrams for the case of L1641N, CARMA 7, NGC 2024, Serpens FIRS, and Serpens SMM 4, as seen in Fig. B.1, and could not be fitted by our LTE model alone. Therefore, we included them for the LTE plus non-LTE modeling as inputs.

Since masers are non-LTE phenomena, they were also not reproduced by our single LTE modeling. This corresponds to the $7_{-1} \rightarrow 6_0 - E$ and $10_{-1} \rightarrow 9_0 - E$ methanol transition lines at 181.295 and 326.961 GHz, respectively. We did not try to fit these lines in our LTE plus non-LTE modeling since maser emission can depart far from the non-LTE conditions obtained using RADEX. On the other hand, we reproduced the quasi-thermal transitions with a mixture of LTE plus non-LTE components (see Fig. 2).

Both the $7_{-1} \rightarrow 6_0 - E$ and $10_{-1} \rightarrow 9_0 - E$ transitions were not reproduced by our LTE plus non-LTE models, as seen in Fig. 2. Even so, we note that the $J = 7$ transition seems to be more diluted in its corresponding APEX beam ($34''$), as depicted in Fig. A.1, than its higher- J transition counterpart, the $J = 10$ line, observed with a beam of $\sim 19.2''$, and which presents a more peaked profile. The same effect can be inferred from the line profiles in L1641N and NGC 2024 in Fig. 1.

Initially, we fixed a V_{LSR} of 7.82 km s^{-1} for the LTE component, derived from previous attempts with all parameters being free. The ISO value was set to vary freely since the lowest reduced χ^2 (χ^2_{red}) were only obtained with an ISO greater than unity. Testing with several independent models, we found that an ISO greater than unity is particularly critical to reproduce the $7_k \rightarrow 6_k - E$ methanol transitions with $k = 0$ and $+1$ at 338.124488 and 338.344588 GHz, respectively. After finding good solutions for the LTE model, we added a non-LTE (RADEX) component to it aiming to reproduce quasi-thermal emission. We reached convergence after 1000 iterations using a constant V_{LSR} of 7.8755 km s^{-1} , which was obtained from previous modeling after reaching convergence. This way, we obtained an acceptance rate of 0.42. The same LTE plus non-LTE model delivers an ISO of 1.11, that slightly varied across the 1000 iterations (between 1.02 and 1.12). We fixed the V_{LSR} to 7.88 and the ISO value to the expected 1.0 upper limit ([Wirström et al. 2010](#)) for the non-LTE modeling.

Aiming at reproducing the broad component in our spectra, most clearly seen in the $4_k \rightarrow 3_k A^+/E$ transitions (with $k = 1$ and -2), at $\sim 193.51 \text{ GHz}$ (top middle panels of Fig. 2), we added an extra broad LTE component with an FWHM of 13.9 km s^{-1} , an ISO of 1.4, and a V_{LSR} of 7.83 km s^{-1} . To obtain these initial conditions we freely vary the broad LTE component after fixing the previously encountered best values for the LTE plus non-LTE models over the parameter space.

Finally, after several attempts including interacting and non-interacting conditions, we obtained the best initial conditions presented in Table C.1, allowing all of them to vary freely within the indicated values.

Based on the resulting synthetic spectrum, we found the best solutions in the interacting mode. In this setup, CASSIS uses the

spectrum calculated for the first component as the continuum background for the next one (E. Caux, priv. comm.).

Typically, denser and warmer regions are situated behind colder ones. Consequently, we designated the warmest non-LTE component as the initial layer. An exception to this arrangement occurs when the outer, more widespread foreground component experiences a temperature increase due to shocks. Considering that scenario, we assigned the narrow LTE component as the second layer, despite its best-fitting values indicating lower temperatures than those of the broad LTE component. This decision is substantiated by its more concentrated emission, as depicted in the ALMA continuum image of CARMA-7 (Fig. A.1).

The broad LTE component was then positioned as the third and final layer. These components, arranged from the innermost to the outermost layers, can be associated with the following physical phenomena.

The warmest one can be associated with the shocked environment where Class I maser emission emerges (see stellar outflows in Fig. A.1). As maser coherent emission mainly arises from the plane of the sky, this component possesses low line widths. The narrow LTE component is associated with the coldest and denser gas of the main source, showing the lowest line width as it is not affected by shocks. The broad LTE component is linked to an external warm envelope such as the ISM around CARMA 7 which, to some extent, may share CARMA 6 emission in the lowest frequency regime. Being so extended, its emission surpasses the APEX beam with a size of $41''.4$, at these dimensions, we expect a significant contribution from the LTE components of the shocked environment present in CARMA-7, which can also account for the line widths of 13.2 km s^{-1} .

In the MCMC algorithm, the step size determines how far the walkers, which are a set of values for the variables (i.e., column densities, temperatures, sizes, etc.), move in a single iteration of the MCMC algorithm. A large step size allows a wider range of parameter values to be explored in each step but can lead to higher rejection rates; on the other hand, a smaller step size limits the movement of the walkers, something that can lead to more accurate estimation of the posterior distribution but slow the exploration of the parameter space and increase computational cost. Similar to the procedure described in [Hunter et al. \(2014\)](#), we adjusted the step size based on the resulting acceptance rate⁸ and established a cutoff parameter, set at half the total iterations, to control the step size.

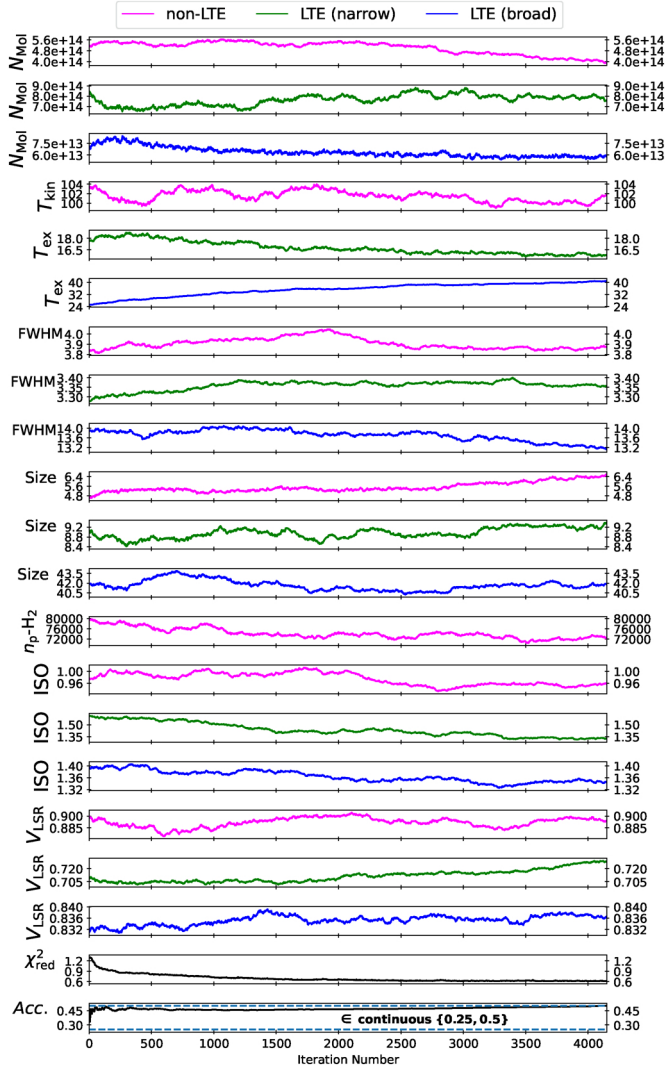
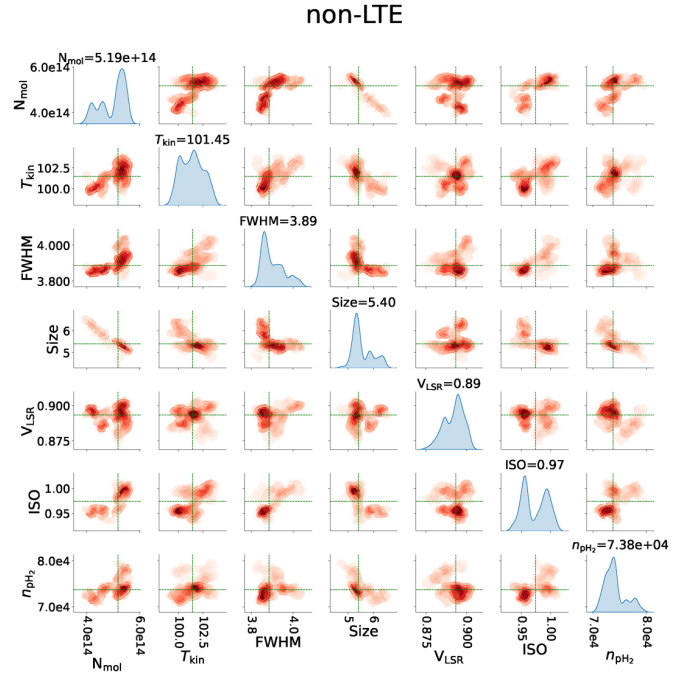
We found good results after 4151 iterations with an acceptance rate of 0.49 using a step size of 200, and a χ^2_{red} of 0.61. The best-fit parameters are indicated in Table 1. In Fig. C.1 we illustrate the evolution of the free parameters in our MCMC modeling throughout the model iteration number. We consider only those values where the acceptance rate (shown in the bottom panel of the figure) consistently falls between 0.25 and 0.5 for the corner plots in Figs. C.2 to C.4. After 4151 iterations, our model continued till the maximum of 10000 iterations we initially set, but its acceptance rate increased over 0.5, reaching a final value of 0.57. These last 6000 iterations were therefore not included in the results.

⁸ The acceptance rate in the context of MCMC sampling refers to the proportion of proposed moves that are accepted during the sampling process. It is calculated as the ratio of the number of accepted moves to the total number of proposed moves.

Table C.1. Initial conditions used for our CARMA-7 model.

Component	$N(\text{Sp})$ [$\times 10^{13} \text{ cm}^{-2}$]	T_{kin} or T_{ex} [K]	FWHM [km s^{-1}]	V_{LSR} [km s^{-1}]	n_{H_2} [cm^{-3}]	ISO [$\times 10^4 \text{ cm}^{-2}$]	Size [$''$]
non-LTE	51.35 (10–200)	102.96 (40–140)	3.83 (2.5–4.9)	0.90 (0.5–0.95)	8 (4–20)	1.0 (0.6–1.5)	4.62 (3–30)
LTE (narrow)	83.97 (7–500)	17.74 (15–60)	3.27 (3–43)	0.71 (0.6–0.88)	–	1.6 (0.6–3.0)	8.92 (3–20)
LTE (broad)	7.24 (2–100)	25.15 (15–60)	13.89 (10–23)	0.83 (0.75–0.9)	–	1.4 (0.6–1.5)	41.8 (20–70)

Notes. Initial conditions and range of permitted values provided parenthetically for the parameters in our LTE plus non-LTE radiative transfer modeling of CARMA-7.

**Fig. C.1.** Evolution of the free parameters in each component vs. model iteration number.**Fig. C.2.** Corner plots of the derived free MCMC parameters after 4151 iterations, only contiguous iterations with an acceptance rate in the 0.25–0.5 range are shown. This model was used to create the non-LTE best fit for CARMA-7 inside CASSIS. Median values are labeled above each Gaussian distribution and also marked by green dashed lines inside each subplot.

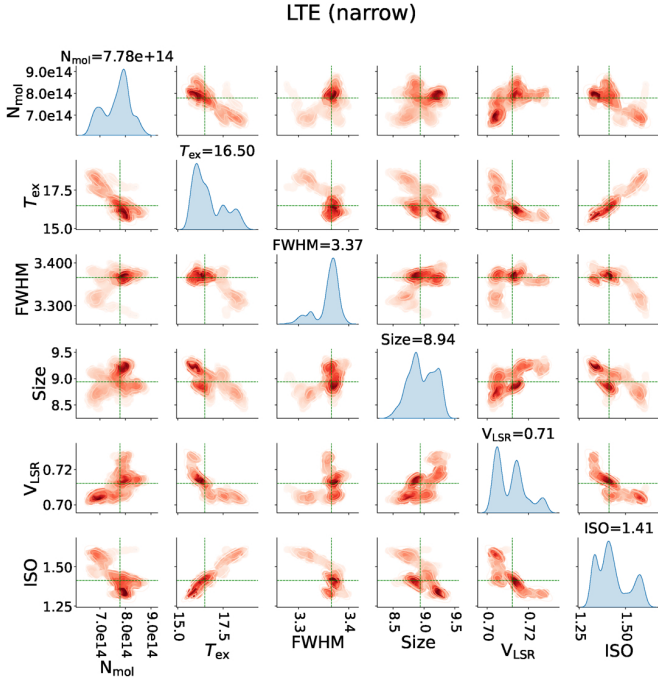


Fig. C.3. Corner plots of the derived free MCMC parameters used to create the LTE narrow component best fit for CARMA-7 inside CASSIS, same as for Fig. C.2 but with excitation temperatures instead of kinetic temperatures and devoid of molecular para-hydrogen density (n_{p-H_2}) (see Appendix C).

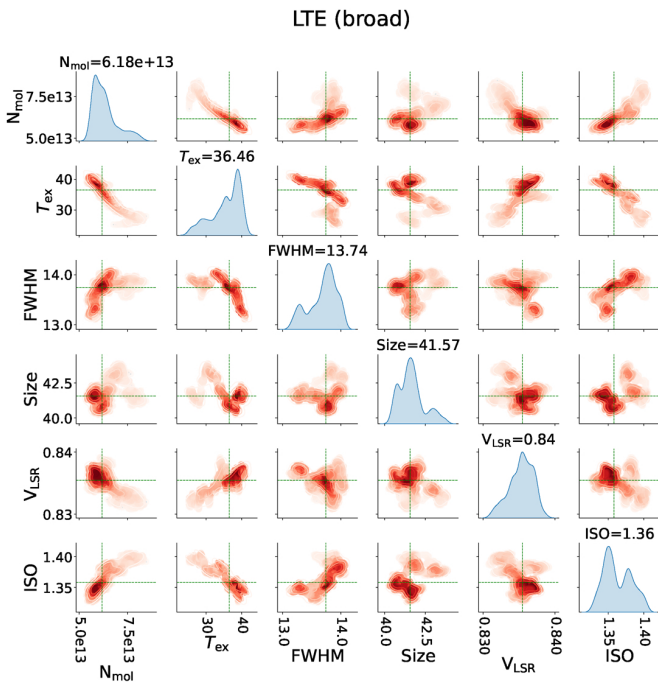


Fig. C.4. Corner plots of the derived free Markov chain Monte Carlo (MCMC) parameters used to create the LTE broad component best fit for CARMA-7 inside CASSIS, same as for Fig. C.3.

Appendix D: Comparison with previous work

To put our results in context, we consider the sample analyzed by Bae et al. (2011) regarding methanol masers at 44 GHz and integrate our new findings. While we explained the adopted bolometric luminosities in our Sect. 3.3, in the following we will

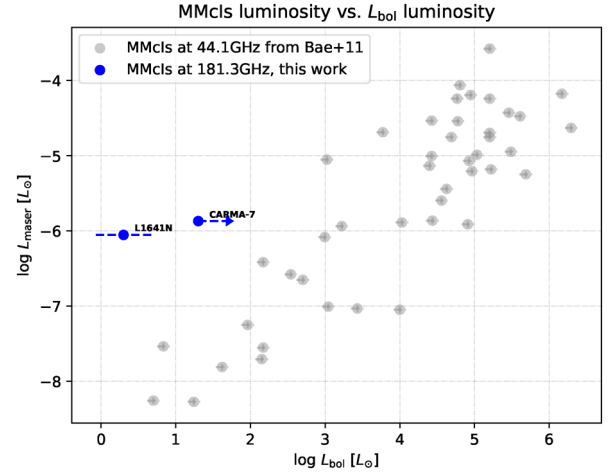


Fig. D.1. Isotropic MMcIs luminosity at 181 GHz in low-mass star-forming regions (blue points, this work) and archive data (grey points) on 44 GHz MMcIs considering low- to high-mass star-forming regions, all this compared to the bolometric luminosity L_{bol} of the mentioned objects. Archive information comes from Bae et al. (2011). These data were directly extracted from Kalenskii et al. (2013, their Fig. 2).

provide details regarding the calculations of the isotropic maser intensities.

Applying a single Gaussian fitting, we obtain peak temperatures of 0.2748 and 0.2474 K, and FWHMs of 3.7519 and 3.0833 km s⁻¹ for the MMcIs J_{-1} at $J = 7$ in CARMA-7 and L1641N, respectively. With these values, we perform the following calculations to determine the maser isotropic luminosity:

First, we transform our peak temperature (T_{peak} in Kelvin) to Jy using the Kelvin to Jansky conversion factor described in the APEX website⁹. In our case, this factor equals 24.4/0.71, where 24.4 is the constant provided in the mentioned website and 0.71 is the aperture efficiency, η_a , for SEPIA180 (see Sect 2.3); then we have

$$S_{peak} = \frac{24.4}{0.71} T_{peak}, \quad (D.1)$$

where S_{peak} is the peak flux density in Jy. After that, approximating the maser emission by a Gaussian profile, we can infer the integrated intensity using the FWHM:

$$I = S_{peak} V_{FWHM} \sqrt{\frac{\pi}{4 \ln(2)}}. \quad (D.2)$$

To translate apparent luminosity from Jy km s⁻¹ to isotropic luminosity in $L_{\odot}$, we multiply by 10⁻²³ for Janskys to erg s⁻¹ cm⁻² Hz⁻¹ and by 10⁵ for km s⁻¹ to cm s⁻¹. Then we divide by the speed of light in cm s⁻¹ and multiply by the line frequency in Hz. Finally, we divide by the solar luminosity (3.9×10³³ erg s⁻¹) and multiply by the square of the distance in cm to get the result in solar luminosities:

$$L_{maser}[L_{\odot}] = 4\pi d^2 \nu I / c, \quad (D.3)$$

where the distance, d , is in cm and the integrated intensity I is in $L_{\odot}$ cm⁻² cm s⁻¹. In the denominator, the frequency is in Hz, and c is the speed of light in cm s⁻¹. For CARMA-7 and L1641N we assume distances of 440.7 pc and 414 pc, respectively (see Appendix A). The above computes isotropic luminosities of 1.35×10⁻⁶ and 8.88×10⁻⁷ $L_{\odot}$ for CARMA-7 and L1641N, respectively.

⁹ <https://www.apex-telescope.org/telescope/efficiency/index.php.old>