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The protostellar mass limit for 6.7 GHz methanol masers⋆

I. A low-mass YSO survey

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Abstract. We report the results of a search for 6.7 GHz methanol masers toward low-mass young stellar objects (YSOs) and (pre)protostellar condensations with the Australia Telescope Compact Array (ATCA). Our sample consisted of 13 class 0 protostars and 44 class I YSOs as well as 66 (pre)protostellar condensations. A single detection was obtained toward NGC 2024: FIR4 in the Orion B region. This is the first detection of a 6.7 GHz methanol maser in Orion. The nature of FIR4 has been a subject of debate with some evidence suggesting that it is a very cold high-mass (pre)protostellar condensation and others arguing that it is a low-mass YSO. The discovery of a methanol maser associated with this source is inconsistent with both of these hypotheses and we suggest that FIR4 probably harbours an intermediate- or high-mass YSO. The less massive objects in our sample do not exhibit any methanol maser stronger than 400 mJy (4σ). Based on the nil detection rate toward the low-mass YSOs we can place an upper limit of 3×10^6 K on the brightness temperature of any methanol maser associated with class 0, I or II sources. These results support the hypothesis that no strong methanol masers are associated with low-mass star formation ($\lesssim 3\ M_{\odot}$).

Key words. masers – stars: formation – stars: circumstellar matter

1. Introduction

Whether the 6.7 GHz (and 12.2 GHz) methanol masers are exclusively associated with high-mass ($M > 8\ M_{\odot}$) star formation is currently a matter of debate. Despite their original detection toward sites of high-mass star formation (e.g. giant molecular clouds, IRAS colour selected sources, H II regions), more and more methanol maser sources are found *not* associated with any traditional signpost of high-mass star formation (e.g. Ellingsen et al. 1996; Szymczak et al. 2002). This tendency is confirmed at higher resolution. ATCA (Phillips et al. 1998; Walsh et al. 1998) and VLBI (Minier et al. 2001) observations have revealed that the very large majority (up to 80%) of methanol masers, originally thought to be coincident with IRAS colour selected sources and ultra-compact H II (UC H II) regions, are indeed separated from them by more than 10^4 AU[1]. These sources are often referred to as *isolated* methanol masers to distinguish them from those closely associated with radio continuum or far infrared IRAS sources. These isolated methanol masers are, however, always coincident with (sub)millimetre (mm) continuum emission (Pestalozzi et al. 2002; Walsh et al. 2003).

This led to two hypotheses on the nature of methanol maser sites. Methanol masers may signpost high-mass protostars that have not yet significantly ionised their environment (Walsh et al. 1998). This is supported by VLBI work for a subset of methanol maser sources (Minier et al. 2001). Alternatively, methanol masers may signpost weakly or non-ionising young stars (Phillips et al. 1998), i.e. intermediate-mass ($3 < M \lesssim 8\ M_{\odot}$) or low-mass ($M \lesssim 3\ M_{\odot}$) young stellar objects (YSOs). This second scenario is supported by mid-IR observations (De Buizer et al. 2000). In both hypotheses, the methanol masers would not have any strong (i.e. >10 mJy) radio emission counterpart.

The present paper is the first in a series to try and determine the stellar mass range and evolutionary phase which gives rise to 6.7 GHz methanol masers. Here we investigate the possible association of 6.7 GHz methanol masers with low-mass ($0.1 < M \lesssim 3\ M_{\odot}$; e.g. André & Montmerle 1994) YSOs as well as

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⋆ Table 1 is only available in electronic form at
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[1] 10^4 AU is the typical size of hot molecular cores and protostellar envelopes.

(pre)protostellar condensations[2] ($0.1 < M < 40\ M_\odot$; e.g. Motte et al. 1998). Future work will search for 6.7 GHz methanol masers toward intermediate-mass star-forming regions. There have been several unpublished and published searches for methanol masers toward low-mass YSOs, especially toward T Tauri stars (e.g. Koo et al. 1988), all of which failed to detect any emission or absorption. The targeted sources were, however, in a relatively advanced pre-main sequence evolutionary phase and the searches had relatively poor sensitivity (5–7 Jy). With the increase in the number of new methanol maser detections with a flux density lower than 6 Jy (Szymczak et al. 2002), high sensitivity ($1\sigma \sim 0.1$ Jy) observations are required to fully investigate the methanol maser origin. The aim of the observations presented in this paper is to for the first time make a sensitive search toward a large number of objects associated with low-mass star formation.

2. Observations and results

2.1. Source sample

The search for 6.7 GHz methanol masers toward low-mass YSOs was conducted in August 2000 with the ATCA in the 6A configuration. The source sample consisted of 13 class 0 low-mass protostars and 66 (pre)protostellar condensations as well as 44 class I low-mass YSOs. Class 0 and I YSOs and (pre)protostellar condensations are surrounded by a large amount of protostellar material that may contain methanol in sufficient abundance to enable masers to form. These sources represented all the southern hemisphere class 0 and I objects and (pre)protostellar condensations that had been published at the time of the observations. The (pre)protostellar condensations searched have masses ranging from 0.1 to 40 $M_\odot$. The condensations in ρ Ophiuchi are classified as isothermal protostars, starless clumps and pre-stellar cores (Motte et al. 1998) with masses between 0.1 and 3.2 $M_\odot$. They are very cold, low-mass objects. The condensations in OMC 2-3 are more massive (Chini et al. 1997) and many of them have the properties of class 0 objects. Three protoplanetary disks (proplyds) in NGC 3603 were also searched, making a total of 126 primary targets. In addition to the targeted objects many other types of sources associated with low-mass star formation were also present within the field of view of the observations. In total 34 class II, 7 class III and 8 unclassified YSOs were serendipitously observed in this manner. Combining the primary targets and serendipitous sample a total of 175 low-mass YSOs and (pre)protostellar condensations were observed (Table 1), most being in a very early evolutionary phase.

The 175 YSOs and (pre)protostellar condensations observed exhibit numerous kinds of emission and features: X-ray, Herbig-Haro jets, IR, (sub)mm continuum, CO(outflows), HCO^+(infall), H_2O masers and weak radio continuum (<1 mJy beam^{-1}). The sample is not biased toward any particular property, but instead tends to represent all the major emission properties of low-mass YSOs and (pre)protostellar condensations (see Table 1 for references). It also reflects properties seen in the isolated methanol maser sources: weak radio emission (<10 mJy), mm and sub-mm emission from dust. Furthermore, the selected sources belong to representative star-forming regions: typical low-mass star-forming regions (e.g. ρ Ophiuchi, Corona Australis and Chameleon); dark clouds (e.g. Lynds 1830); intermediate-mass to high-mass star-forming regions with luminous H II regions (NGC 2024, NGC 3603, OMC 2-3). All the parent molecular clouds and emission properties are reported in Table 1 with references.

2.2. Observations and data analysis

The 175 sources were observed in 32 separate pointings of the ATCA[3] over a 24 hour period, which yielded on average 18 min on-source per field of view and adequate uv-coverage for proper imaging. This corresponds to 9 hours on-source when all 15 baseline and 2 polarisation data are averaged. 4 MHz filters with 1024 correlator channels were used. This provides a bandwidth of 3.9 kHz per channel, a velocity resolution of 0.17 km s^{-1} and a total velocity coverage of 178 km s^{-1}. The line-of-sight velocity was not known for many of the candidate sources, but as most are relatively nearby it was sufficient to centre the observed frequency at the local standard of rest. The ATCA data were processed with AT AIPS using the standard procedure (Killeen 1993). Three types of data set were produced for each field of view and source. First, scalar- and baseline-averaged spectra were inspected for the 32 observed fields of view. The scalar average is only sensitive to relatively strong maser features (>2–4 Jy) due to a noise baseline offset in the spectrum. A narrow line feature was found in the scalar averaged spectrum of NGC 2024 at a level of 0.6 Jy with a 2.8-Jy noise baseline offset. Data cubes were, then, created for all the sources in order to search for the weakest masers (below a few Jy in intensity). The production of 32 data cubes with 1024 channels being resource intensive, the channel maps were averaged every 3 channels (~0.5 km s^{-1}). With a theoretical rms noise level of 92 mJy beam^{-1} in the ATCA image, an intensity below 400 mJy (~4σ) was considered as null detection. The maximum noise level in the channel maps for 29 data cubes varied between 238 and 382 mJy (see Table 1). Three data cubes have a maximum intensity level above 400 mJy: NGC 2024 (1 Jy), Lynds 1830 (424 mJy) and NGC 3603 (433 mJy). Finally, CLEANed images and vector averaged spectra at the position of the possible maser spots were produced for these detection candidates. Vector averaged spectra are only useful if the source is within the synthesized beam (~$2'' \times 2''$ to $2'' \times$ a few arcmin); this is not the case for most sources with a positional error larger than 2 arcsec in both right ascension and declination.

2.3. Results and re-observations

The results of our search is that only one detection was made toward NGC 2024: FIR4 a protostellar object among

[2] The term "(pre)protostellar condensation" defines various classes of cold isothermal starless condensations and also pre-stellar clumps in the process of collapsing and forming a protostar with a central hydrostatic core.

[3] The *FWHM* of the ATCA primary beam at 6.7 GHz is 8.4 arcmin.

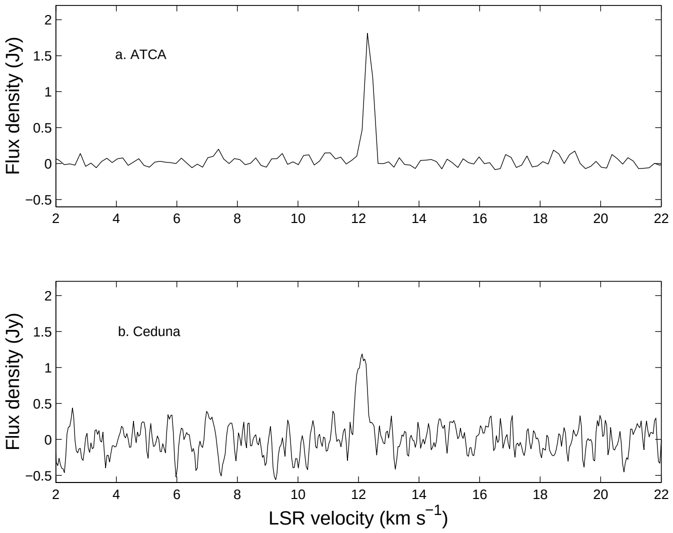

Fig. 1. The 6.7 GHz methanol maser spectrum of NGC 2024: FIR4 observed with the ATCA **a)** and Ceduna radio telescope **b)**. The ATCA spectrum is a vector and baseline averaged spectrum after shifting the phase centre to the position of the methanol maser.

the protostellar condensation sample. A peak flux density of 1.48 Jy was measured in the channel map for $v_{\rm lsr}$ = 12.29 km s^{-1} (Fig. 1a) at the J2000 absolute position RA = 05$^{\rm h}$41$^{\rm m}$44.15$^{\rm s}$ and Dec = −01°54′44.9″.

NGC 2024: FIR4 was re-observed in September 2002 with the Ceduna radio telescope operated by the University of Tasmania. The source was observed during 220 min in a position switching mode with a 4 MHz bandwidth and 4096 channels. The ATCA detection was confirmed (Fig. 1b). However, no Doppler tracking was applied, implying a drift in velocity of ∼0.4 km s^{-1} over the observations, and a broader, smaller amplitude peak than in the ATCA plot. A Gaussian fit gives an amplitude of 1.2 Jy, a *FWHM* of 0.4 km s^{-1} and a velocity of 12.1 km s^{-1}.

3. Discussion

3.1. Non-detection in class 0 and I YSOs and (pre)protostellar condensations

Any discussion of the (non-)detection of methanol masers toward different classes of astrophysical object needs to take place in the context of current models of methanol masers. These maser models typically quote their results in terms of the brightness temperature of the maser transition, where as our observations have determined an upper limit to the flux density. To convert between the two we must make some assumptions about the likely size of the masing region. Very long baseline interferometry observations of 6.7 and 12.2 GHz methanol masers by Minier et al. (2002) have found that they consist of a compact core of emission with a typical size of a few to 10 AU, surrounded by a diffuse halo which is an order of magnitude larger in scale. The size of the maser spots is governed by the degree of velocity coherence along a particular line of sight. The smaller physical dimensions of low-mass YSO environments would suggest that the size of any velocity coherent regions are unlike to exceed those seen in high-mass star-forming regions. If we assume that the linear size of any maser in a low-mass star-forming region is likely to fall in the range 1–10 AU, then the 400 mJy sensitivity limit of our observations corresponds to a brightness temperature upper limit, which ranges from 3×10^6 K (for a 10 AU maser at 150 pc) up to 3×10^9 K (for a 1 AU maser at 500 pc).

The prevalent model for 6.7 GHz methanol masers is the Sobolev-Deguchi model (Sobolev & Deguchi 1994; Sobolev et al. 1997). This model has recently been further refined to examine in detail the large number of methanol maser transitions observed in NGC 6334F and G345.01+1.79 (Cragg et al. 2001) and W3(OH) (Sutton et al. 2001). The model of Sobolev et al. (1997) is the only one which has been able to reproduce the high brightness temperatures ($>10^{12}$ K) observed toward strong methanol maser sources. This model has approximately ten free parameters, with the most important in terms of producing strong methanol masers being the gas temperature, the dust temperature, the density and the methanol column density. The model requires the temperature of the gas producing the masers to be moderately cool (∼30 K), with a hydrogen number density in the range of 10^6–10^8 cm^{-3}. In addition a nearby region of warm (>175 K) dust is necessary to produce the submillimetre and FIR photons required to create the population inversion and a methanol column density of $\sim 5 \times 10^{17}$ cm^{-2} is needed to account for the observed brightness temperatures. The parameter values required to produce strong maser are in broad agreement with the observed physical conditions in high-mass star formation regions, but have yet to be rigorously tested through complementary observations. However, it is currently the best framework we have for evaluating and understanding the physical conditions required to produce methanol maser.

Comparing the physical conditions which have been observed in class 0 and class I YSOs and (pre)protostellar condensations with the parameters of the Sobolev-Deguchi model which produce strong masers, our non-detection toward these sources is not surprising. Although methanol is relatively abundant in the environment of class 0 protostars (Goldsmith et al. 1999; Garay et al. 2002), the mechanism for releasing methanol molecules from dust grains differs from that seen in the protostellar envelope of high-mass YSOs. In the heated envelope of high-mass YSOs ($L_* \sim 10^5$ $L_\odot$), the dust temperature ($T_{\rm d}$) is expected to be greater than 90 K at 1000 AU from the centre (van Dishoeck & Blake 1998). At $T_{\rm d} > 90$ K CH_3OH and H_2O completely evaporate from the icy dust grains. Hence, a dust temperature $T_{\rm d} \gtrsim 100$ K plays a dual role in producing methanol masers, it is required to release methanol from the dust grains and also to provide pump photons for the population inversion.

In contrast, molecular line observations of low-mass YSOs locate the thermal methanol emission between 500 to 3000 AU from the core centre (van Dishoeck & Blake 1998 and references therein; Bachiller et al. 1998; Garay et al. 2002). At distances beyond 100 AU, Eq. (2) of Motte & André (2001) shows that $T_{\rm d} < 90$ K for low-mass stars ($\lesssim 3$ $M_\odot$). So methanol in low-mass YSO environments has to separate from dust grains by other means than evaporation. The coincidence of methanol emission with outflows in low-mass star-forming regions (Bachiller et al. 1998; Garay et al. 2002) suggests that methanol is released from the icy dust grain mantles through grain-grain collisions in shocked layers. These conditions ($T_\mathrm{d} << 175$ K and collisions) would appear to preclude any strong methanol maser action according to the Sobolev-Deguchi model.

The only observation of methanol emission close to a low-mass YSO is by Goldsmith et al. (1999) who detected methanol emission within the inner 200 AU of a class 0 protostellar disk, where T_d could plausibly reach levels sufficient to pump strong methanol masers. From their observations they derived $T_\mathrm{d} \simeq T_\mathrm{kin} \simeq 50$ K, a methanol column density of 4×10^{14} cm^{-2} and a relative methanol abundance between 10^{-8} and 10^{-7}. These quantities are inadequate for 6.7 GHz methanol masers according to models by Cragg et al. (2001). The dust temperature and methanol abundance are too low. The non-detection of methanol maser toward class 0 objects is consistent with the hypothesis that in low-mass star-forming regions methanol is mainly released from dust grains beyond 100 AU from the core centre.

The Sobolev-Deguchi model requires quite large dust temperatures in order to produce maser with a high brightness temperature. Earlier less sophisticated models (e.g. Cragg et al. 1992) were able to produce weaker methanol masers, with much lower dust temperatures. The model of Cragg et al. (1992) was limited to $T_\mathrm{d} < 50$ K because it only included levels from the vibrational ground state of methanol. Recent methanol maser modeling has focused upon explaining high brightness temperature masers, however this earlier work shows that there may be other parameter regimes which produce weak 6.7 GHz methanol masers. Our observations demonstrate that under reasonable assumptions for the methanol maser spot sizes any emission from low-mass star-forming regions must have a brightness temperature of less than approximately 3×10^6 K.

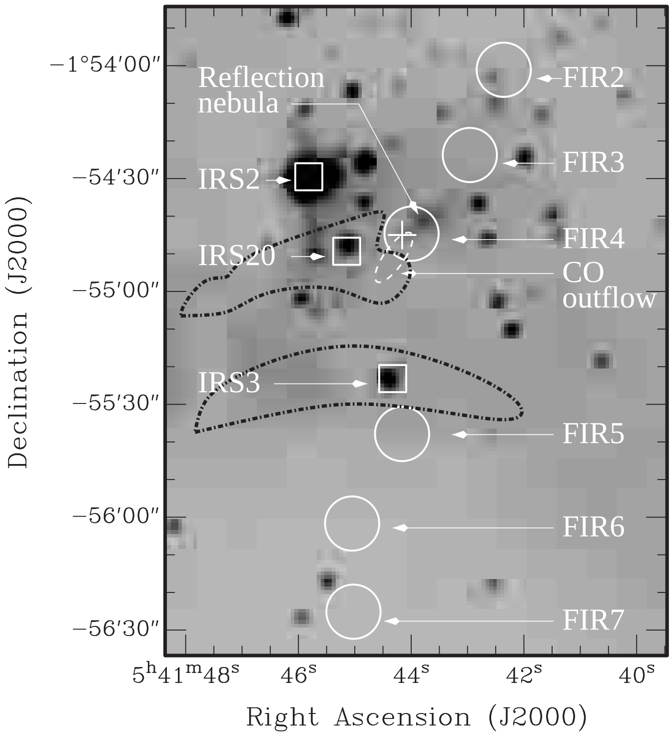

Fig. 2. Overview of NGC 2024: FIR2-FIR7. The background image is the 2MASS *K*-band image (`http://irsa.ipac.caltech.edu/`). The cross represents the methanol maser position, while the circles represent the millimetre source positions observed by Mezger et al. (1992) and Chandler & Carlstrom (1996). The circle diameter is 15″, which is the mean deconvolved source size in Mezger et al. (1992). The three brightest NIR sources, IRS2, 3 and 20 (Barnes et al. 1989), are also indicated (squares). The dashed ellipse indicates the position angle and extent of the CO outflow. The dashed-dotted contours illustrate the NCP and SCP radio source extents and positions (Gaume et al. 1992). FIR4 is associated with a faint NIR source and with the methanol maser within 2.5 arcsec.

3.2. The case of NGC 2024: FIR4

NGC 2024, a nearby (415 pc) H II region, is a site of active star formation in the Orion B region. For more than a decade, seven FIR/mm cores (FIR1–7) discovered by Mezger et al. (1992) in NGC 2024 have been the subject of many radio, millimetre and infrared studies and their nature is still a matter of debate. The detection of a methanol maser toward NGC 2024: FIR4 might bring new elements to the discussion on NGC 2024: FIR4.

Mezger et al. (1992) described the seven sources (FIR1–7) as isothermal condensations embedded within a cold envelope (22 K) and a warm dust interface (45 K) between the H II region and the molecular ridge (see Barnes et al. 1989 for an overview of NGC 2024). They derived for NGC 2024: FIR4 a dust temperature of 19 K, an H_2 column density of 10^{25} cm^{-2}, a density of 2.4×10^8 cm^{-3}, and a mass of 10 $M_\odot$ from dust emission flux densities between 350 and 1300 μm. Molecular line observations by Mauersberger et al. (2002) supported this view. Many of the FIR sources suffered from molecular depletion with NH_3 kinetic temperature (T_kin) <18 K. However, they also derived $T_\mathrm{kin} > 44$ K for NGC 2024: FIR4, and interpreted this temperature excess as due to an interaction between the H II region and the molecular ridge seen as the north continuum peak (NCP), adjacent to FIR4 (Fig. 2).

An alternative view of the FIR objects in NGC 2024 described them as low-mass, self-luminous YSOs, and perhaps, class 0 objects (André et al. 2000 and references therein). Lis et al. (1991) modelled the dust emission in FIR4 and reproduced the submillimetre data with 3–7 $L_\odot$ internal heating. Moore & Yamashita (1995) detected a NIR source coincident with FIR4. They estimated the bolometric luminosity of the NIR source to be 25 $L_\odot$, with an upper limit of 100 $L_\odot$ (due to the very rough estimate). A reflection nebula (Moore & Yamashita 1995) and an unipolar CO flow (Chandler & Carlstrom 1996) were also detected in FIR4 (Fig. 2). Chandler & Carlstrom (1996) derived a dynamical age of a few thousands years for FIR4 based on the dynamical timescale of the CO outflow. This suggests that FIR4 is in the earliest stages of star formation.

Despite a very abundant literature, no consensus has, to date, been reached on the nature of NGC 2024: FIR4. Then we may ask whether NGC 2024: FIR4 is a cold high-mass (pre)protostellar condensation or a low-mass class 0 YSO, and whether methanol masers could provide information on the location and nature of FIR4 in NGC 2024.

First, we shall consider that the 6.7 GHz methanol maser detected toward NGC 2024: FIR4 arises from inside the FIR/mm core. The LSR velocity of the methanol masers is 12.3 km s^{-1}, which differs from the LSR velocities (9.1–10.9 km s^{-1}) observed by Mauersberger et al. (2002) toward FIR4 in various molecular lines. The 9.1–10.9 km s^{-1} velocity range corresponds well to the velocity of the OH absorption line in the foreground dust lane (Barnes et al. 1989). The methanol maser line is therefore redshifted with respect to the systemic velocity of FIR4. The slight position offset of the maser with respect to the mm core centre (ΔRA = +2.32″, ΔDec = −0.2″) and to the 2MASS NIR source centre (ΔRA = +1.81″, ΔDec = −0.2″) would place it at the root of the redshifted CO outflow with a velocity range 13.5–20 km s^{-1} (Chandler & Carlstrom 1996). The coincidence of FIR4 with a NIR object within 2″ would also imply that FIR4 is in the foreground. In contrast, FIR5 and FIR6 in the background molecular cloud are not associated with any NIR source due to the higher extinction for a background protostar. In that case and in the context of the discussion on suitable conditions for maser action (see Sect. 3.1), the maser detection might reveal that FIR4 is neither a cold high-mass (pre)protostellar condensation nor a low-mass, self-luminous YSO. Instead, the presence of methanol masers would show that FIR4 contains a protostar sufficiently massive to heat the dust up to 175 K in the inner core, i.e. a high-mass ($M > 8\ M_{\odot}$) protostar or perhaps an intermediate-mass ($3 < M \lesssim 8\ M_{\odot}$) protostar; secondly, a large methanol column density is required for masing action, implying that the hot molecular core phase has already started in FIR4.

There might be an alternative origin for the masers. They could arise from a source behind FIR4. Given the RA positional accuracy of ∼2 arcsec for the OVRO and ATCA observations, the position offset (>1 arcsec) of the maser from the mm core centre in FIR4 might be significant. Lis et al. (1991) proposed another model in which FIR4 is externally heated by a O9 object at 0.25 pc. Given the dense (proto)stellar population in NGC 2024, alignment of multiple YSOs along the line-of-sight is possible. The methanol maser velocity would place the maser source in the background molecular core in which FIR5 and FIR6 form. In addition, no HCO^+ emission was detected toward FIR4 at 12.3 km s^{-1} (Barnes & Crutcher 1990) while FIR5 and FIR6 are bright in HCO^+ at this velocity. HCO^+ lines in FIR4 are seen at 9–10 km s^{-1} (Lis et al. 1991). This tends to indicate that the maser source could be located in the background molecular core and not associated with FIR4. However, why is there no molecular line emission at 12.3 km s^{-1} detected toward the maser position (i.e. toward the FIR4 position with the ∼30″ beam of a millimetre single dish telescope)? If the methanol maser really signposts a second YSO aligned with FIR4, molecular lines toward FIR4 should peak at two distinct velocities. That is not the case.

The first scenario is therefore favoured, i.e. *the methanol maser arises from FIR4, which could harbour a massive (>3 $M_{\odot}$) YSO and be located in the foreground dust lane*.

4. Conclusions

The question regarding the exclusive association of methanol masers with high-mass star formation has partially been answered. The present search toward low-mass YSOs allows us to set a protostellar mass limit for methanol maser action. Our results clearly demonstrate that bright (>3×10^6 K) methanol masers do *not* occur in the environment of low-mass ($\lesssim 3\ M_{\odot}$) YSOs. A lower protostellar mass limit for strong methanol masers is, therefore, ∼3 $M_{\odot}$. This latest result has to be confirmed for a larger source sample. A survey toward intermediate-mass YSOs was undertaken in March 2003 with the ATCA.

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