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Methanol Masers and Massive Star Formation

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Abstract. Starting from the Onsala Methanol Maser Blind Survey of the Galactic Plane, stressing the recent results from the follow-up observations of newly the detected sources and making some statistical considerations, we try to make conclusions about the link between massive star formation and the presence of methanol masers. Moreover, 1.2 mm dust continuum emission seems to be ubiquitous wherever 6.7 GHz masers are found. Furthermore, the intensity ratio between 6.7 and 12.2 GHz maser emission seems to lie between 10 and 20. Finally the overall distribution of methanol masers in the Galaxy seems to follow the one of OB associations.

1. Introduction

Methanol masers are know to be excellent tracers of regions where intensive star formation is taking place. They often appear together with typical massive star formation tracers as OH and H_2O masers, strong IR sources, and Ultra Compact (UC) HII regions. For this reason they represent a valid tool to study the early stages of evolution of massive stars, a research field in expansion in the last decades.

Many searches for methanol masers (especially at 6.7 GHz) have been undertaken in order to increase the sample of objects suited for extended studies. Both selective criteria applied to IRAS sources, and *blind* searches, where large regions of sky are consistently covered by observations, have been reported in a number of works (Caswell et al. 1995a, 1995b; Ellingsen et al. 1996; Szymczak, Hrynek, & Kus 2000). Selective surveys were successful to about 15–20%, whereas blind surveys were more effective in finding new types of objects.

VLBI observations of strong sources have revealed that methanol masers can show linear structures having linear velocity gradients, which are interpreted as rotating Keplerian discs (e.g. Minier, Booth, & Conway 1998). Recent studies suggest that methanol masers may consist of two components, a compact intense core and an extended masing region. This structure should justify the difference in correlated flux between single dish and interferometry measurements.

At the Onsala Space Observatory we have started an extensive study of methanol masers, both using VLBI observations of known sources and by consistently surveying the portion of Galactic plane visible from Onsala at 6.7 GHz. Towards the detections of the survey we have performed a large follow-up observational campain using single dish and VLBI. The main results are the detection of new methanol maser sources that do not seem to be associated with known tracers of massive star formation, the detection of 1.2 mm continuum toward all observed sources, the testing of the modeling of the maser radiation, and the suggestion for the existence of extended maser emission which was resolved out at the shortest EVN baselines. From the compilation of a general catalogue of 6.7 GHz methanol masers we are able to trace the distribution of such sources in the Galaxy.

2. Technicalities

The technical settings of the Onsala survey are described in Pestalozzi et al. (2001). These make us confident to detect all methanol maser sources that could be observed at high resolution using VLBI, i.e. that are strong enough to reveal fringes.

The follow-up observations were carried out using SIMBA mounted on SEST (1.2 mm dust continuum emission, Pestalozzi, Humphreys, & Booth 2002), the Onsala 20 m millimetre telescope (spectral line emission in the 80-100 GHz range as well as 12.2 GHz methanol masers), and the European VLBI Network (EVN) and the Jodrell Bank - Cambridge single baseline interferometer (both at 6.7 GHz). We will report on the dust continuum emission and the 6.7 and 12.2 GHz observations, leaving the millimetre spectral line studies for a later publication.

The criterion for association of the methanol masers and the other emissions is defined by the position accuracy claimed by the different searched catalogues (IRAS and MSX, $1'$ and $5''$ respectively) and the position accuracy of the telescopes used during the observations. For the millimetre continuum observations (SIMBA) the position accuracy is $24''$ and for the 12.2 GHz observations $2'$. The accuracy of the EVN observations is about 5 mas and the single baseline positions are accurate to 10 mas.

The general catalogue of 6.7 GHz methanol masers used for some statistical considerations in this paper has been compiled using the source lists appeared in the literature since 1990. Galacto-centric kinematical distances have been calculated using the Brand & Blitz (1993) velocity curve.

3. Results

3.1. Statistics

After having surveyed and analysed 50 deg^2 of Galactic plane we count 11 detections, 5 of which are new. Comparison with previous blind surveys (Caswell et al. 1995a, 1995b; Ellingsen et al. 1996) shows that the Onsala detection rate fits in the expectation of the distribution of 6.7 GHz methanol masers in the Galaxy. Furthermore, the radial distribution of methanol masers in the Galactic plane

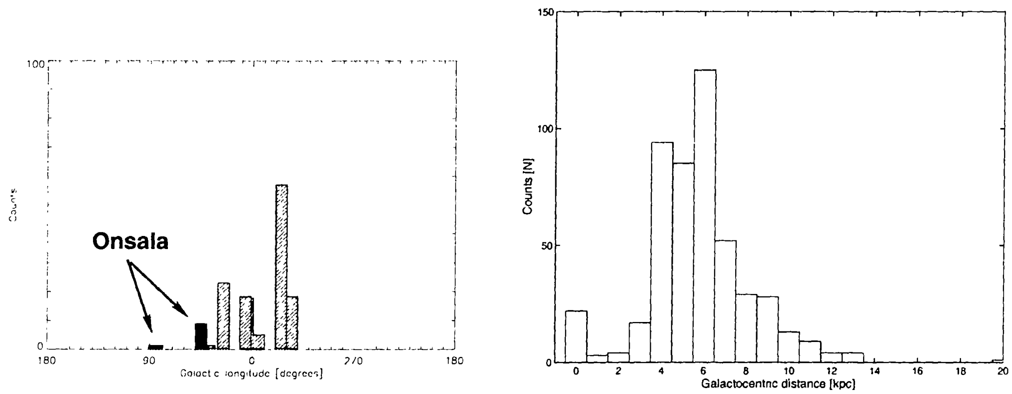

Figure 1. Distribution of methanol masers detected during blind surveys versus Galactic longitude **(Left)** and distribution of 6.7 GHz methanol masers versus Galacto-centric distance, in 1.0 kpc bins **(Right)**. The highest column visible in the left panel refers to observations carried out at a higher sensitivity, using the ATCA, the Australian interferometer.

shows clearly a peak around $0.55R_0$, where R_0 is the distance of the Sun from the Galactic center, here 8.5 kpc (see Figure 1). This is in agreement with the studies by Bronfman et al. (2000), where the authors find an analogous distribution pattern for OB associations. We have thus an additional evidence supporting the hypothesis that 6.7 GHz methanol masers trace massive star formation.

3.2. IR Associtaions

An efficient energy pumping source is necessary to get maser emission and in the case of 6.7 GHz methanol masers a strong infrared (IR) source is required (Sobolev, Cragg, & Godfrey 1997). It is therefore important to check the newly detected methanol masers sources for associations with known IR sources. As already pointed out by Ellingsen et al. (1996), it is not always possible to uniquely associate methanol maser sites to a known IR source. This is confirmed by the Onsala data, where two of the detected sources are not associated with any IR emitting object, and two others seem to be close to a source seen in the mid-IR only (MSX Point source catalogue). One possible interpretation of this fact is that methanol masers may trace very early stages of massive star formation, where the protostar is still deeply embedded in its primordial dust cocoon.

3.3. 1.2 mm Dust Continuum Observations

Millimetre dust continuum was searched for around a sample of sources where we believed the methanol maser was not associated to any IR known source. It seems that methanol masers are indeed associated with 1.2 mm emission in all cases (Pestalozzi et al. 2002). Furthermore, when methanol masers can be associated with an IRAS source, the latter shows features of typically young embedded objects. According to the IRAS classification and modelling by Ivezic & Elitzur (2000), the faint IRAS sources associated to methanol masers have a high optical depth and a fairly flat dust density profile (Pestalozzi et al. 2002).

Table 1. Results of the analysis of the VLBI observations of two Onsala sources using both the EVN and the Jodrell-Cambridge baseline.

Source name	Position (RA,DEC J2000)	Extended emission
G 41.34-0.14	19:07:21.87 07:25:17.34	to be confirmed
G 85.40-0.07	20:54:13.71 44:54:07.85	seen in the maps

The high optical depth could justify the absorption of the IR radiation preventing it from escaping the protostellar dust cloud; the flat density profile accounts for the not yet defined geometry of the protostellar region, which could be considered as a sign for young age. Finally, these observations have revealed a third class of objects, where the methanol maser is accompained only by an MSX source (in addition to the 1.2 mm emission). The nature of these object is not yet clear.

3.4. 12 GHz Observations

A sample of 6.7 GHz methanol maser sources of the northern hemisphere has been observed at 12.2 GHz, using a room temperature receiver newly mounted on the 20 m Onsala telescope. Forty-two sources were observed to a 0.1 to 0.4 Jy noise level, 15 detections were made, 4 of them new (not appearing in the literature). This follow-up is to be considered the start of a consistent multitransitional observing campain with the goal of best testing the methanol maser modeling. We believe that this is the method to follow if the maser mechanism is to be understood.

Using the observations, we checked the only methanol maser model available (Sobolev et al. 1997). In general, the ratio between the intensities of the masers at 6.7 and 12.2 can give good constrains in the parameter space studied by the model (number and column densitiy, dilution factor of the background continuum source, etc.). The 6.7/12.2 ratio from our observations lies between 10 and 30. These values seem to be lower than expected according to previous studies (Caswell et al. 1995a, 1995b). The values for number and column densities of methanol resulting from the comparison of the observations with the model agree with recent results obtained using thermal line emission of methanol in the 96 GHz band (Minier & Booth 2002).

3.5. VLBI Observations

Using VLBI observations we expected to be able to recognise circumstellar discs as previously noticed and studied (e.g. NGC 7538). Because our single dish positions were accurate to only about 15″, we used the 250 km long Jodrell-Cambridge baseline to refine the positions of the masers and then easily find them in the phase referenced EVN maps. The resulting positions are summarised in Table 1.

From the single baseline observations it was possible to notice the existence of extended emission connecting the emission points revealed by the EVN-only observations. This strongly supports the previously mentioned *core/halo* structure of methanol masers (Minier, Booth, & Conway 2002). Accurate amplitude calibration will be soon available and will give us the possibility to quantify the drop of the correlated flux with u,v-distance, which is the main confirmation of the extended emission.

4. Summary

The Onsala Methanol Maser Blind Survey of the Galactic Plane has given not only new sources to be studied but also the opportunity to consistently investigate the maser phenomenon. In particular, by following-up the (new) detections using different techniques we have been able to infer some characteristics of the regions hosting methanol masers. Methanol masers seem to appear in regions of massive star formation, where the thick circumstellar dust cocoon prevents the IR radiation from escaping. The methanol number and column densities can be constrained by multitransition studies, and seem to lie in the lower part of the parameter space used for modeling. The maser emission seems to be made of two components, a compact core surrounded by an extended emission. The latter seems to connect different compact cores.

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Discussion

Debra Shepherd: Have you detected methanol masers toward any EARLY O stars or are they only detected toward late O/early B stars?

Michele Pestalozzi: Since the the survey is blind, not targeted, the new detections are not yet identified. The first (and only!) information we have is the presence of a methanol maser, and (in some cases) IRAS fluxes of listed nearby IRAS sources. I suppose the best way to indentify them will be tracing their SED, and this is our next step.

James De Buizer: (Comment on D. Shepherd's question) The observations I have conducted of methanol maser sources show no early O type stars. This means that disks don't last long around early O stars if you believe the disk hypothesis for methanol masers *or* that the conditions around the most massive O stars are not suitable for maser emission.

Bringfried Stecklum: If the methanol masers reside in disks, one would expect that the radio continuum emission from the ionized inner part of the disk is centered on the distribution of maser spots, can you comment on that?

Michele Pestalozzi: The sources detected by the survey are probably too young to show any cm-continuum emission.

José-María Torrelles: Have you tried to detect methanol masers toward low mass stars?

Michele Pestalozzi: We did that, tagetting our search toward a number of forming low mass star candidates. We did not detect any masers in our sample (about 50 sources, 0.6 to 0.9 Jy at one sigma noise level).

Luis F. Rodríguez: Your source IRAS 19049+0720 seemed to have modest IRAS flux densities. Is it truly a luminous, massive object?

Michele Pestalozzi: I have to double check...if we believe the equation "search for massive stars = search for methanol masers", I would say it is a very young and embedded object, an early stage massive star!

Paul Ho: Have you pressed the sensitivity level down to see if there is a population of fainter masers?

Michele Pestalozzi: I have considered that, even if not yet realized. At Onsala, the telescope has a natural sensitivity limit that would make such a project difficult to realize.

Kate Brooks: Can you comment on the time variability of methanol masers? Could you be missing sources at a minimum in their variability at the time of your survey?

Michele Pestalozzi: We did not check for variability. Knowing the range of variability, both in time frequency and amplitude from previous work (Caswell et al. 1995), we believe that the missing detections are a negligible number.