Abstract. We report SIMBA 1.2 mm dust continuum observations of the environments of eight methanol maser sources, all discovered during spatially fully-sampled, un-targeted surveys of the galactic plane. We summarise our search for possible associations of the masers with IR sources (IRAS and MSX) and find that it is not always possible to make definite associations. A preliminary characterisation of the IR sources found in the maser neighbourhood is given according their position in the [60-25] – [25-12] colour-colour diagram.

Key words: Masers – Stars: formation – Infrared: stars – circumstellar matter – HII regions – Stars: evolution
First SIMBA observations toward CH$_3$OH masers

Masers from blind surveys mark the earliest stages of massive star formation

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Received December 2001 / Accepted January 2002

1. Introduction

Massive star formation has attracted increasing interest in recent years, with the mounting evidence that methanol masers provide excellent tracers and probes of the high-mass star formation process (e.g. Hunter et al. 1998; Minier et al. 2001). Such evidence has led to several surveys aimed at identifying new high-mass stars, often targeting IRAS colour-selected UCHII regions (Caswell et al. 1995; Schütte et al. 1993; Szymczak et al. 2000). Although making significant contributions to the discovery of new massive star forming regions (MSFRs), such surveys have yielded only a $\sim 15\%$ detection rate of methanol masers.

An alternative approach for discovering MSFRs has been provided by blind surveys of 6.7 GHz methanol masers. In particular, the surveys of Ellingsen et al. (1996) and Pestalozzi et al. (2002, in prep.) have sampled in a consistent manner large regions of the galactic plane from the southern and northern hemispheres respectively. Since the majority of methanol masers revealed in these surveys does not have a clear association (within the positional accuracy) with IRAS sources, the question has arisen: could they be tracing early stages of the high-mass star formation process, in which the still highly-embedded, nascent star is radiating much of its flux in the millimetre and submillimetre regions (as suggested by Walsh et al. 1999)?

With the aim of answering this question, in addition to ascertaining the SEDs for regions for which there is existing IR data (IRAS and MSX), we report here on 1.2 mm bolometer observations of the regions surrounding eight 6.7 GHz methanol masers detected in blind surveys. This constitutes the first part of our follow-up investigations for understanding the methanol maser phenomenon, and the evolutionary route to forming massive stars.

2. Observations

Observations were made using the SIMBA 1.2 mm bolometer array on the SEST on 19 October 2001. SIMBA is a 37-channel hexagonal array in which the HPBW of a single element is about 24" and the separation between elements on the sky is 44". The bandwidth in each channel is about 50 GHz. Spectral line emission present in the band may contribute to the total continuum flux values reported in this paper, though not more than 30% as in the case of molecular rich clouds (e.g. IRC+10216, L-Å Nyman, priv. comm.). These observations were made in fast-mapping mode. Areas typically of 600" x 384" were imaged in order to detect nearby IRAS sources in the field, using a scan speed of 80" s$^{-1}$. Typical total observation times were around one hour per source, during which 5 to 6 maps were produced. Zenith opacities lay in the range 0.217 – 0.270 throughout the observing run. The resulting data were reduced with the MOPSI mapping software package developed by R. Zylka, using a "deconvolution" algorithm$^1$ to remove the contribution of the electronics arising from the fast-mapping observing mode, the "converting" algorithm (Salter 1983) to convert the coordinates from rectangular to equatorial, and partly the NOD2 and GILDAS libraries. The calibration of our data was performed using 1.2 mm Uranus data for 19 October. The multiplication factor between counts and Jy was 166.5 mJy count$^{-1}$ beam$^{-1}$ (Table 1).

3. Results & Discussion

Figs. 1 and 2 show the images obtained at 1.2 mm for the sources listed in Table 1. The same table gives the peak and integrated fluxes of the detections of the 1.2 mm dust continuum. For the position accuracy of the 1.2 mm emission we adopt the FWHP of one channel of the array (24°). For the IR sources we refer to the literature (1-2' for IRAS, 5" for MSX). The positions of the southern methanol masers are accurate to better than 1 arcsec (Ellingsen, priv. comm.). The position of G41.34-0.14 has been determined to an accuracy of 5 mas$^2$, while for G40.25-0.19 the uncertainty is larger (about 1'). We refer to Ivezić &

$^1$ Developed within the SIMBA collaboration
$^2$ Observed with the Jodrell-Bank – Cambridge baseline
Table 1. Source list with J2000 coordinates, radial velocities of the methanol maser emission, 1.2 mm peak, integrated flux emission and rms. References: 1) Pestalozzi et al. 2002 in prep.; 2) MacLeod & Gaylard 1992; 3) Ellingsen et al. 1996; 4) Walsh et al. 1998; 5) Phillips 1998.

| Source       | RA(2000) | Dec(2000) | v_{lsr} [kms^{-1}] | Peak [Jy] | Int. flux [Jy/beam] | rms          |
|--------------|----------|-----------|---------------------|-----------|---------------------|--------------|
| G40.25−0.19  | 19 05 32.6 | +06 25 38 | +70.0               | 2.55      | 2.64                | 0.164        |
| G41.34−0.14  | 19 07 21.870 | +07 25 17.34 | +14.0              | 0.30      | 0.38                | 0.036        |
| 327.12+0.51  | 15 47 32.729 | −53 52 38.90 | −87.1              | 1.54      | 2.06                | 0.070        |
| 327.59−0.09  | 15 52 36.824 | −54 03 18.97 | −86.3              | 0.34      | 0.44                | 0.050        |
| 327.62−0.11  | 15 52 50.241 | −54 03 00.71 | −97.5              | 0.43      | 0.72                | 0.050        |
| 329.34+0.15  | 16 00 33.154 | −52 44 40.00 | −106.5             | 4.37      | 6.67                | 0.132        |
| 332.35−0.44  | 16 17 31.560 | −51 08 21.55 | −53.1              | 0.67      | 0.76                | 0.052        |
| 333.13−0.56  | 16 21 35.742 | −50 40 51.29 | −56.8              | 3.06      | 4.83                | 0.200        |

3.3. 327.12+0.51

This strong (80 Jy, three spectral features) methanol maser was first detected by MacLeod & Gaylard (1992). It has OH and H_2O associated masers (Caswell et al. 1980; Batchelor et al. 1980), making it a classical high mass star formation region. IRAS 15437-5343 shows colours of an UCHII region and appears deeply embedded (high optical depth \( \tau_{\nu} \sim 100 \)). Its density profile is fairly flat (0 \( \leq p \leq 0.5 \)) at 8.6 GHz and 6.67 GHz continuum emission (12 and <12 mJy respectively) have been observed by Walsh et al. (1998) at more than 1 arcmin offset from the IRAS source. Phillips (1998) detected a 0.5 mJy 8.6 GHz continuum peak at 1 arcsec from the methanol maser. VLBI observations of the methanol maser (Phillips 1998) show a linear distribution of the maser components with a linear velocity gradient. Assuming a Keplerian disc, the mass for the central object is estimated to be 14.7 M_\odot.
3.4. 327.59-0.09 & 327.62-0.11

There are two weak (3 Jy), single featured methanol masers in the SIMBA field, a, b as 327.59-0.09 and 327.62-0.11 respectively (Ellingsen et al. 1996). Both show clearly associated 1.2 mm and MSX counterparts. IRAS 15490-3353 could be related to component b. No other counterpart is visible. As for 333.13-0.56, we suggest that the methanol masers trace very deeply embedded objects.

A third 1.2 mm peak of emission is visible in the field (component c), having an MSX and probably an IRAS counterpart, but no methanol maser.

3.5. 329.34+0.15

This single featured 15 Jy methanol maser has been discovered by Ellingsen et al. (1996) and is clearly associated with IRAS 15567-5236, an UCHII region. Schutte et al. (1993) did not detect any methanol maser above their 5 Jy limit. Walsh et al. (1998) detect both a 8.6 and a 6.67 GHz continuum peak (<20 and 270 mJy/beam respectively). The colours of IRAS 15567-5236 suggest that we are observing a young object with very low optical depth (τν < 0.1). The density profile is fairly flat, p=0.5.

3.6. 332.35-0.44

This weak (4 Jy, one spectral feature) methanol maser was discovered by Ellingsen et al. (1996). It seems to lie on the edge of a 5 GHz peak of emission (Haynes et al. 1978). Both IR sources appearing in the SIMBA field fall on top of the 1.2 mm peak of emission, within the positional accuracies. Since the angular distance between the IR sources and the methanol maser is greater than 1°, there is no clear association between the two emitting components. Ellingsen et al. exclude it as an association because the colours of the IRAS source are not representative for an UCHII region. The IRAS source seems to have a flat density profile (p = 0) and low optical depth, τν ~ 0.1.

3.7. 333.13-0.56

This 6.7 GHz maser source was detected by Ellingsen et al. (1996). It shows three distinct spectral features, the strongest being about 17 Jy. It does not have any IRAS counterpart within the positional accuracies. An MSX source lies at a distance of >1.5 arcmin from both the methanol maser position and the peak in the 1.2 mm emission. The methanol maser and the strong 1.2 mm emission are spatially coincident within the positional accuracies. This indicates that the methanol maser is tracing a very deeply embedded object.

4. Conclusions

We can divide the observed source list into two separate groups: 333.13-0.56, 327.59-0.09, 327.62-0.11, G41.34-0.14 in the first group; 327.35-0.44, 327.12+0.51, 329.34+0.15 in the second. G40.25-0.19 is left out of the discussion because of the poor positional accuracy of the methanol maser. The first group collects all sources with either no IRAS counterpart or a weak one. These sources could have been detected only by blind surveying. The 1.2 mm dust continuum confirms the existence of dust where a methanol maser is detected. We consider them as the group of young, still embedded sources. The sources of the second group have clear IRAS and MSX counterparts. The colours of the IRAS sources fulfil the selection criteria by Wood & Churchwell (1989) or Szymczak et al. (2000), so we can consider them as (young) UCHII regions. The lack of cm continuum emission towards most of the sources can be explained in two ways: we can see it as a further argument to strengthen our hypothesis that these sources are in early stages of the stellar evolution; it could also be argued that those central stars are not massive enough to produce Lyman α photons. We prefer the former idea, as methanol masers are known to trace massive stars.

Despite the clear separation into two classes of the sources, it remains nevertheless difficult to find correlations between the 1.2 mm flux density and the methanol flux density. Furthermore it is puzzling to notice that 327.59-0.09 and 327.62-0.11 do have an 1.2 mm and an MSX counterpart but no clear IRAS counterpart. These topics will be investigated further, by observing in the submillimetre range (850-450 μm).

The observations lead us to the following conclusions:

– Blind surveys of methanol masers facilitate the detection of young, still deeply embedded high-mass star formation regions;
 – IRAS sources associated with methanol masers show a flat density profile (0 ≤ p ≤ 0.5), which means that they can be classified as objects in an early stage of massive star formation.

Acknowledgements. SIMBA was built and installed at the SEST at La Silla (Chile) within an international collaboration between the University of Bochum and the MPIfR in Bonn, Germany, the Swedish National Facility (OSO) and ESO. We thank the SEST team for their help with the observations and data reduction. We thank Dr M. Albrecht and collaborators for providing the planet maps for our data calibration. We thank Dr Simon Ellingsen for providing accurate positions of some methanol masers and useful comments on the manuscript. EMLH thanks STINT for funding her research position and the Vetenskaprådet for a travel bursary to the SEST.

References

Batchelor R.A., Caswell J.L., Goss W.M., et al. 1980, Aust. J. Phys. 33, 139
Batrla W., Matthews H.E., Menten K. & Walmsley C.M. 1987, Nature 326, 49
Caswell J.L., Batchelor R.A., Forster J.R. & Wellington K.J. 1983, Aus J. Phys. 36, 401
Fig. 2. See Fig. [ ].

Caswell J.L., Vaile R.A., Ellingsen S.P. et al. 1995, MNRAS, 272, 96
Charnley S.B., Kress M.E., Tielens A.G.G.M. & Millar T.J. 1995, ApJ 448, 232
Ellingsen S.P., von Bibra M.L., McCulloch P.M. et al. 1996, MNRAS, 280, 378
Haynes R.F., Caswell J.L. & Simons L.W. 1978, Aust. J. Phys., Astrphys. Suppl., 45, 1
Hunter T.R., Neugebauer G., Benford D.J., et al. 1998, ApJL 493, 97
Ivezić Z. & Elitzur M. 2000, ApJL 534, 93
MacLeod G.C. & Gaylard M.J. 1992, MNRAS, 256, 519
Minier V., Conway J.E. & Booth R.S. 2001, A&A 369, 278
Phillips C.J. 1998, PhD Thesis, University of Tasmania
Salter C.J. 1983, NRAO 12-m Telescope User’s Guide
Schutte A.J., van der Walt D.J., Gaylard M.J. & MacLeod G.C. 1993, MNRAS 261, 783
Szymczak M., Hrynek G. & Kus A.J. 2000, A&ASS 143, 269
Walsh A.J., Burton M.G., Hyland A.R. & Robinson G., MNRAS 1998, 301, 640
Walsh A.J., Burton M.G., Hyland A.R. & Robinson G., 1999, MNRAS, 309, 905