Radio continuum emission associated with Class II methanol maser sources

D. J. van der Walt,1⋆ E. Churchwell,2 M. J. Gaylard3 and S. Goedhart3

1Space Research Unit, Potchefstroom University for CHE, Private Bag X6001, Potchefstroom, 2520 South Africa
2Astronomy Department, University of Wisconsin, 475 N Charter Street, Madison, WI 53706
3Hartebeesthoek Radio Astronomy Observatory, PO Box 433, Krugersdorp, 1740, South Africa

Accepted 2003 January 9. Received 2003 January 8; in original form 2002 April 8

ABSTRACT
Class II methanol masers are believed to be associated with high-mass star formation. Recent observations by Walsh et al. and Phillips et al. reported a very low detection rate of radio continuum emission toward a large sample of 6.7-GHz methanol masers. These results raise questions about the evolutionary phase and/or the mass range of the exciting stars of the masers. Here we report the results of a VLA search for 8.4-GHz continuum emission from the area around five Class II methanol masers, four of which were not detected by Walsh et al. at 8.6 GHz. Radio continuum emission was detected in all five fields although only two of the nine maser spot groups in the five fields were found to be superimposed on radio continuum sources that appear to be ultra-compact HII (UCH II) regions. This suggests that continuum counterparts for some masers might be found in further surveys for which the sensitivity level is lower than 1 mJy beam−1. Considering our results as well as observations from other studies of methanol masers we conclude that masers without radio continuum counterparts are most likely associated with high-mass stars in a very early evolutionary stage, either prior to the formation of a UCH II region or when the H II region is still optically thick at centimetre wavelengths. With one exception all maser spot groups in the five fields were found to be associated with mid-infrared objects detected in the Midcourse Space Experiment survey.

Key words: masers – circumstellar matter – stars: formation – stars: pre-main-sequence – HII regions – radio continuum: ISM.

1 INTRODUCTION
Since the first detection of 6.7-GHz methanol masers by Menten (1991), a variety of surveys have increased the number of known methanol maser sources to more than 300. Although it is quite clear that the masers are associated with star formation regions, it is not clear as yet if they are associated with massive star formation only or if they are also associated with less massive non-ionizing stars.

A number of independent surveys of methanol masers have shown that a significant fraction of the detected sources do not seem to be associated with radio continuum emission (Phillips et al. 1998; Walsh et al. 1998; Caswell 1997, 1996; Ellingsen 1996a) as would be expected if they are related to young high-mass stars. Walsh et al. (1998) found that of 233 sites that have methanol maser emission, only 46 have associated radio continuum emission. Caswell (1996) detected radio continuum emission for only three of 57 methanol maser sources, Caswell (1997) noted that the sources surveyed by Caswell (1996) were selected because their methanol masers were much stronger than the associated OH masers at 1665 MHz. Caswell (1997) found that methanol masers with strong OH maser emission are more likely to have associated radio continuum emission than those with no OH masers.

The lack of associated radio continuum emission for some methanol maser sources could be because: (1) The exciting star is too cool to produce an H II region; or (2) rapid accretion suppresses the formation of an H II region; or (3) the radio continuum is below the detection limit. The reader is referred to Phillips et al. (1998) for a more extensive discussion.

Understanding the population of methanol maser sources depends critically on whether they are associated with embedded ionizing stars or whether they can also be excited by less massive non-ionizing stars. Phillips et al. (1998) concluded from the detection statistics of their survey that the masers may also be associated with lower mass non-ionizing stars down to spectral type B5. However, a combination of effects (2) and (3) can also lead to a significant number of maser sources not having associated radio continuum emission. Of particular importance is the possibility that the masers are associated with young ionizing stars still in the rapid accretion phase. Since the 6.7-GHz methanol masers are very strong they

⋆E-mail: johan@fskdjvdw.puk.ac.za

© 2003 RAS
can be used to identify such early stages of massive star formation throughout a large fraction of the Galaxy. Obviously, the identification of such early stages of massive star formation has very important implications for the study of the formation of massive stars. Hence the necessity of trying to determine the nature of the stars associated with the methanol masers.

From an observational point of view the problem of whether the masers are also associated with lower mass non-ionizing stars can be addressed by (1) searching for methanol maser emission toward nearby low- and intermediate-mass pre-main-sequence stars (PMS) and (2) doing a very sensitive search for radio continuum emission towards methanol masers for which no associated radio continuum emission was detected in previous surveys. The question we would like to address in this paper is whether the non-detection of radio emission was detected in previous surveys. The question we would like to address in this paper is whether the non-detection of radio continuum emission toward a number of masers in the survey of Walsh et al. (1998) is perhaps a sensitivity effect. The present survey should be considered complimentary to that of Phillips et al. (1998) since the sensitivity levels of both surveys are comparable.

2 OBSERVATIONS AND DATA REDUCTION

Observations were made with the VLA. Table 1 summarizes the observing parameters while the coordinates of the five observed fields are given in Table 2.

To ensure good ultraviolet coverage the fields were observed in the order 18060–2005, 18134–1942, 18290–0924, 18440–0148 with appropriate nearby phase calibrators being observed between consecutive programme fields. The sequence was repeated three times. 17402–2938 was observed near transit due to its southerly declination. Some degree of shadowing occurred during the observation of 17402–2938 and the nearby phase calibrator 1744–312. As in the case of the other four fields, it was observed three times with a phase calibrator observed between consecutive observations. The total on-source time for each field was 54 minutes. The primary flux calibrator was 3C 286 which was observed once at the beginning of the run.

The AIPS package was used for data reduction. Calibration followed the procedures outlined in the AIPS Cookbook. Image cleaning was performed with the AIPS task IMAGR.

3 RESULTS

Continuum emission was detected in all five observed fields. As will become clear shortly, however, not all maser spot groups in the different fields have associated radio continuum counterparts. Walsh et al. (1998) did detect continuum emission associated with the field of 18060–2005, but our observations reveal considerably more detail.

Although it was our initial goal just to search for radio continuum emission toward a number of methanol maser sources, the interpretation of our results is greatly enhanced when also considering the corresponding mid-infrared images of the same fields as obtained with the Midcourse Space Experiment (MSX) Price et al. (2001). In what follows we will therefore present both the radio continuum and mid-infrared images of each field. The original MSX images have been transformed to equatorial coordinates for comparison with the VLA images. This resulted in a loss of resolution and the interested reader is advised to also inspect the original MSX images.

Table 3 summarizes some of the main statistics of the detections in the observed fields. The peak flux density is that of the strongest continuum emission peak in the field, which is not necessarily associated with maser emission. Peak flux densities and integrated fluxes of compact sources that are definitely associated, or that are most probably associated with a maser are indicated by an asterisk. The errors on the peak flux densities are the rms noise in the relevant field.

3.1 Discussion of individual sources

17402–2938. The radio continuum and MSX A-band (8.28 μm) images are shown in Fig. 1. This is the only one of our new detections where the maser is actually projected against a detectable radio continuum source. Inspection of Table 3 shows that our detection is barely greater than the 3σ noise level of Walsh et al. (1998). The angular separation between the two radio sources is about 11 arcsec.

Since nothing more is known about the continuum spectrum of the radio source with which the maser is associated, it cannot be stated with certainty that the H II region is optically thin at 8.4 GHz. However, if it is assumed that the H II region is indeed optically thin, a rough estimate of the spectral type of the exciting star can be made. Using the rotation curve of Wouterloot & Brand (1989), the near and far kinematic distances to the maser are 4.8 and 12.2 kpc respectively. Assuming the maser to be at the near kinematic distance it is found that log N = 45.9, with N the flux of ionizing photons. The corresponding spectral type is slightly later than B0.5 using the results of Panagia (1973). If the maser is located at the far kinematic distance we find log N = 46.7 which is close to a B0-type star.

It is interesting to note that if we assume that the second radio source is also located at the same distance as the maser, then at the near kinematic distance the two radio sources are only 0.26 pc apart. Using its integrated flux it is found that the spectral type of the exciting star for the second radio source corresponds to a B0.5 star.

The MSX A-band image shows a faint unresolved mid-infrared source at the position of the masers.
### Table 3. Summary of detections. Coordinates are for epoch J2000.

<table>
<thead>
<tr>
<th>Observed field</th>
<th>Peak flux density (mJy beam$^{-1}$)</th>
<th>Peak position RA (h m s)</th>
<th>Dec. ($^\circ$ $^\prime$ $^\prime\prime$)</th>
<th>Integrated flux (mJy)</th>
<th>Convolved beam size (arcsec × arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17402–2938</td>
<td>3.35 ± 0.10</td>
<td>17 43 25.5</td>
<td>−29 39 28.9</td>
<td>7.8 ± 0.6</td>
<td>7.09 × 1.98</td>
</tr>
<tr>
<td>18060–2005</td>
<td>143.0 ± 1.4</td>
<td>18 08 56.0</td>
<td>−20 05 53.5</td>
<td>760 ± 20</td>
<td>3.75 × 2.07</td>
</tr>
<tr>
<td>18134–1942</td>
<td>0.32 ± 0.04</td>
<td>18 16 22.6</td>
<td>−19 41 24.3</td>
<td>0.30 ± 0.07</td>
<td>3.66 × 2.07</td>
</tr>
<tr>
<td>18290–0924</td>
<td>1.02 ± 0.08</td>
<td>18 31 44.9</td>
<td>−09 22 03.2</td>
<td>2.93 × 2.22</td>
<td>2.60 × 2.34</td>
</tr>
<tr>
<td>18440–0148</td>
<td>0.33 ± 0.06</td>
<td>18 46 35.7</td>
<td>−01 44 27.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 1.** (a) VLA map of 17402–2938. In this and the following VLA images the maser positions are indicated with a star. (b) MSX A-band image. In this and the following MSX images the maser positions are indicated with upright crosses. The part of the field covered by the VLA image is indicated by the rectangle.

**18060–2005.** This field contains four groups of maser spots, numbered 1 to 4 in Fig. 2(a). We detected continuum emission associated with spot group 1 at a peak flux density of 143 mJy beam$^{-1}$ as well as extended emission to the west of maser group 2. The peak flux density of the extended emission is 40 mJy beam$^{-1}$. Although extended emission occurs close to maser group 2, no compact radio continuum source coincides with group 2. Also, no emission associated with maser group 3 could be found, while there appears to be evidence of faint emission to the east of maser group 4. Walsh et al. (1998) reported the detection of a strong continuum source associated with the maser at position 1 only.

The rms noise for this region was about 2 mJy beam$^{-1}$ which is significantly higher than the expected theoretical rms noise. Becker et al. (1994) reported relatively high noise values in this field. They ascribed the high noise levels in this field to either poor quality data or to bright sources in the sidelobes. As we will discuss below, there is also a more extended H\textsc{ii} region associated with this field (Altenhoff et al. 1979) which most certainly is the source of the higher noise levels.

The strong compact continuum source associated with maser group 1 was also detected by Zoonematkermani et al. (1990) at 1.4 GHz and by Becker et al. (1994) at 5 GHz. The measured integrated flux densities at these frequencies are 341 and 654 mJy respectively. Comparison of the flux densities at 1.4, 5 and 8.4 GHz (see Table 3) suggests that the H\textsc{ii} region is close to being optically thin at 8.4 GHz and that we can use our measurements to estimate the spectral type of the ionizing star. The radial velocity of the maser spot associated with the compact H\textsc{ii} region is 20 km s$^{-1}$. However, as we will argue below, the UCH\textsc{ii} region probably lies on the edge of an expanding shell with a systemic velocity of 11 km s$^{-1}$. Using the latter systemic velocity and the rotation curve of Wouterloot & Brand (1989), the kinematic distance to the source is found to be 2 kpc for the near distance and 14.8 kpc for the far distance. Assuming the source to be at the near distance and the electron temperature to be $10^4$ K we find the ionizing photon flux to be $\log N = 47.79$ which, according to Panagia (1973), is about equivalent to an O9.5-type star.

The **MSX A-band image** for 18060–2005 is shown in Fig. 2(b). Mid-infrared (MIR) counterparts can be identified for spot groups 1, 2 and 4. The NIR images of Goedhart, Van der Walt & Gaylard (2002) as well as the 2MASS $K$-band images of this field show that the $A$-band source associated with spot group 2 is associated with
Figure 2. (a) VLA map of 18060–2005. This region has four independent groups of maser spots. (b) MSX A-band image. The small rotated cross and circle give the centre and average half-power width of a more evolved HII region associated with the same star formation region as the masers.

Figure 3. (a) VLA map of 18134–1942. (b) MSX A-band image.
of the maser is about 3 arcsec. Using the velocity of 10.5 km s\(^{-1}\) determined by Molinari et al. (1996) from NH\(_3\) observations and the rotation curve of Wouterloot & Brand (1989), we find a near kinematic distance of 1.6 kpc. This implies a projected physical separation of about 0.02 pc (4800 au) between the peak of the radio continuum emission and the maser position. Phillips et al. (1998) reported the linear sizes of maser spot groups ranging from 200 au to 5600 au and diameters of associated radio continuum sources of a couple of thousand au. Considering these values it seems reasonable to speculate that the maser and the UCH\(\alpha\) region in this field might indeed be physically related.

Assuming the H\(\alpha\) region to be optically thin at 8.4 GHz, an ionizing flux of log \(N = 43.6\) is found for the exciting star. This corresponds to a spectral type slightly later than a B3-type star, which lies at the bottom of the mass range of ionizing stars according to Panagia (1973). This strongly suggests that the H\(\alpha\) region is still optically thick at 8.4 GHz. In fact, the expected flux density at 8.4 GHz from an optically thin H\(\alpha\) region excited by a B0 star and which is at a distance of 1.6 kpc, is about 960 mJy. This region may therefore indeed be in a very early evolutionary phase.

It is also interesting to note that the maser spectrum of this source is very rich, having 13 individual maser spots with velocities ranging from 6.3 km s\(^{-1}\) to 16.2 km s\(^{-1}\) (Walsh et al. 1998). The maser spots therefore have velocities that are both red- and blueshifted with respect to the systemic velocity, although all the maser spots are offset to the same side of the UCH\(\alpha\) region assumed to be associated with them. Such a situation is hard to reconcile with the hypothesis proposed by Norris et al. (1998) that the masers are located in rotating accretion discs around young high-mass stars if in this case the maser emission is associated with the compact radio source.

The MSX A-band image (Fig. 3b) shows clearly the presence of a mid-infrared source at the position of the radio continuum source.

**18290-0924.** The VLA image of this source is shown in Fig. 4(a). The continuum emission is located to the east of the maser spots and is extended. Close inspection shows two identifiable peaks (indicated by the arrows) with a maximum emission of 1.02 mJy beam\(^{-1}\). This is about the 1\(\sigma\) noise level of Walsh et al. (1998) and explains their non-detection. For our observations the rms noise in the field directly adjacent to the source was found to be 0.08 mJy beam\(^{-1}\). Due to the complex structure of the extended emission no attempt was made to find the integrated flux.

The methanol maser is not projected against the detected radio continuum emission. The angular separation between the radio peaks and the maser position is about 8 arcsec. Bronfman, Nyman & May (1996) found CS(2-1) emission for this object at \(V_{lsr} = 84.3\) km s\(^{-1}\). Using the rotation curve of Wouterloot & Brand (1989) we find the near distance to be 5.3 kpc and the far distance 10.4 kpc. The implied projected physical separations between the radio continuum source and the masers are 0.2 pc (42 000 au) and 0.4 pc (83 000 au) for the near and far kinematic distances respectively. If the maser is indeed associated with either of the two radio continuum sources, the large physical separation suggests that the masers may be associated with an outflow. The physical separations calculated here are not uncommon for the linear dimension of bipolar outflows associated with high-mass stars (Churchwell 1999).

The MSX A-band image (Fig. 4b) shows that the maser is associated with a MIR source. It is also seen that associated with this A-band source is a strong linear feature extending in a north-westerly direction, as well as two arc-like features that seem to connect with the MSX source. The latter features can best be seen in the original MSX images. Using the catalogue and maps of Altenhoff et al. (1979) we found a nearby more evolved H\(\alpha\) region, the centre of which is located at \(l = 22\text{:}398, b = +0\text{:}083\) and which has a half-power angular diameter of 5 arcmin. The centre of the H\(\alpha\) region is shown by the small cross in Fig. 4(b) and its diameter by the circle.

Lockman (1989) gives a recombination line velocity of 87.8 km s$^{-1}$ for the H II region which is similar to the CS(2-1) velocity. This suggests that the star formation region, with which the maser is associated, and the more evolved H II region are probably physically close to each other. It is also worth noting that the maser seems to lie at the edge of the evolved H II region thereby suggesting the possibility of star formation triggered by the expanding H II region. If this is indeed the case then the linear feature associated with the MSX source might be the result of either denser gas heated by the expanding H II region or the cumulative effect of a new generation of stars that heats the dust in their immediate environment.

18440–0148. Only clumpy extended emission was detected, with the brightest compact clump located at (epoch J2000) RA = 18h46m35.8, Dec. = −01° 44’ 27”. A second compact source might also be located slightly SSW of the stronger source. The two maser sources do not coincide with compact radio emission. They are about 15 arcsec from the nearest continuum emission. There are three maser spot groups in the field of 18440–0148, of which only spot group 1 lies in the field of our radio map. Spot group 1 has a coincident MSX A-band source although no radio continuum emission could be detected at this position. Altenhoff et al. (1979) list an H II region located at l = 30.82, b = +0.256 (indicated by the circle in Fig. 5b). Unfortunately no angular diameter is available.

Maser spot groups 2 and 3 both lie close to MSX A-band sources.

4 DISCUSSION

Considering the peak flux densities of the newly detected radio continuum sources and the rms noise levels of the different fields, it is clear that a deeper search for continuum emission toward maser sources where Walsh et al. (1998) did not detect continuum emission may indeed result in finding continuum emission counterparts for some of the masers. However, only two maser spot groups were found to be projected against UCH II regions while in the case of 18440–0148 a UCH II region was not detected even at our 3σ detection limit of 0.18 mJy beam$^{-1}$ for that field. On the one hand, therefore, we can expect that a large scale deeper search for radio continuum counterparts will change the detection statistics and find more masers projected against radio continuum sources. On the other hand, our results, as well as those of Phillips et al. (1998), show that even at very low noise levels there still are maser sources without any continuum counterparts. Thus, increasing the sensitivity level significantly beyond that of the survey of Walsh et al. (1998) has not led to an immediate clear observational answer to the question of the nature of the young stars with which the masers are associated.

In view of the fact that most of the maser spot groups in the sources we observed are not projected against a radio continuum source, it is worth reconsidering the hypothesis by Phillips et al. (1998) that the masers are also associated with non-ionizing stars. In the following discussion we have used the relation between the stellar mass and bolometric magnitude as well as the calibration of MK spectral types as given in Cox (1999). With these relations the mass of a B5-type star is 5.3 M$_\odot$, that of a B0 star is 15 M$_\odot$ and of an O5 star is 30 M$_\odot$. The upper limit to the stellar masses was taken as 60 M$_\odot$.

Using these values and the initial mass function (IMF) of Sagar et al. (1986), which has a single power-law dependence namely $\psi(M) \propto M^{-1.4}$, it is indeed found that there are twice as many stars in the range B5 to B0 than from B0 to O5. However, such a calculation does not say anything about the expected absolute number of stars and therefore of the expected number of methanol masers. To do this we normalize the IMF as described by Tinsley (1980). Then, assuming a star formation rate of $5 \times 10^{-9}$ M$_\odot$ pc$^{-2}$ yr$^{-1}$ and considering star formation within in radius of 12.5 kpc in the Galaxy, the Sagar et al. (1986) IMF predicts a total of 0.06r masers associated with young stars with spectral types in the range between B5 and B0, where $r$ is the lifetime of the masers. The predicted number in the range B0 to O5 is 0.03r and between B0 and 60 M$_\odot$ is 0.05r. It is clear that the duration of the masing phase is an important parameter in making theoretical estimates of the number of methanol masers in the Galaxy. At present only firm observational estimates of it exist. Assuming a duration of 5 $\times$ 10$^4$ year for the methanol masers, the expected number of masers in the Galaxy will exceed 5000. Just in the range B5 to B0 the predicted number is already 3000, which is equal to the total number of masers in the Galaxy as estimated by Ellingsen et al. (1996b). At present the number of known methanol masers is still less than 1000 which presents a serious problem.
with the hypothesis that the masers are also associated with lower mass non-ionizing stars. Reducing the lifetime of the masers to approximately $3 \times 10^7$ yr will bring the expected number of masers closer to the estimate of Ellingsen et al. (1996b). However, even in such a case one has to assume that the masers are excited with equal efficiency across the stellar mass range from spectral type B5 and earlier. Given the fact that the stellar luminosity decreases very rapidly with decreasing stellar mass ($L \propto M^{3.5}$) (Cox 1999) it seems unrealistic to assume such a constant efficiency. Although the masers appear to form most readily in cooler gas ($<100$ K), the gas-phase abundance of methanol is a key determinant of the observable maser activity (Cragg, Sobolev & Godfrey 2002). The gas-phase abundance obviously should depend on the luminosity of the embedded star heating the dust and gas. As the luminosity decreases rapidly with decreasing stellar mass, it can be expected that the pumping rate, the gas-phase abundance of methanol, and the volume in which the maser can be excited, will decrease rapidly, leading to a rapid decrease in the efficiency of exciting a maser. Explaining the non-detection of radio continuum counterparts for a significant number of methanol masers in terms of lower mass non-ionizing stars appears not to be the answer to explain the masers without radio continuum counterparts.

As for our own results we note the following with regard to the non-detection in the field of 18440–0148. Using the CS(2–1) velocity of 97.6 km s$^{-1}$ for this region as found by Bronfman et al. (1996), the near and far kinematic distances to the maser are 6.4 and 8.2 kpc respectively when using the rotation curve of Wouterloot & Brand (1989). We already pointed out that the low flux density of the H$\alpha$ region associated with the maser in 18134–1942 is most probably due to the fact that the H$\alpha$ region is optically thick at 8.4 GHz. If 18134–1942 was located at a distance of 6.4 kpc from the Sun, the expected peak flux density would only be 0.02 mJy beam$^{-1}$ which is significantly below the 3σ noise level of 0.18 mJy beam$^{-1}$ in the field of 18440–0148 and will result in a non-detection. The situation will be even worse if the maser is located at a distance of 8.2 kpc. The non-detection of a radio source associated with 18440–0148 may therefore readily be explained as due to the H$\alpha$ region still being optically thick at 8.4 GHz. This example illustrates that a lack of radio continuum emission associated with a maser source may, at least in some fraction of the cases, be due to the H$\alpha$ region being optically thick to such an extent that the radio continuum emission is too faint to be detectable.

Independent recent observations also support the hypothesis that the masers are associated with massive star formation only. Walsh et al. (1999) provided evidence of a 3.6-μm source (IRAS 15 541–5349) associated with a maser but with no radio continuum counterpart. From the NIR emission they concluded that the exciting star must be massive enough to produce ionizing radiation. Even more recently Beuther et al. (2002) found a 100 per cent association rate of methanol and water masers with massive molecular cores, the latter which are generally regarded as the sites of massive star birth. Only 20 per cent of the cases have associated cm continuum emission.

That the masers without radio continuum counterparts are associated with a very early stage of young massive star formation is also supported by Minier et al. (2002). These authors explicitly studied a number of so-called ‘isolated’ methanol masers, i.e. masers without radio continuum counterparts. Minier et al. (2002) conclude that since the environments of these masers show all the observational characteristics expected of the environment of massive protostars, they trace massive star formation regions that are still in a very early phase.

5 CONCLUSIONS

We presented the results of a deep search for radio continuum counterparts associated with five methanol masers for which Walsh et al. (1998) did not detect such counterparts. Continuum emission was detected in all the fields, although only in two cases were the masers projected against a UCHII region. In the remaining cases the masers were found offset from the detected radio continuum emission.

Considering our results we conclude that deeper surveys towards more masers without radio continuum counterparts at the 1 mJy beam$^{-1}$ level, will be only partially successful in finding continuum counterparts. Based on evidence from this survey as well as on that from other independent observations, we conclude that masers without cm continuum counterparts are most probably high-mass stars in a very early evolutionary stage and that there is no reason to believe that the masers are also associated with lower mass non-ionizing stars.

ACKNOWLEDGMENTS

The authors would like to thank an anonymous referee for constructive comments.

REFERENCES


This paper has been typeset from a TeX/LaTeX file prepared by the author.