Continuum emission associated with 6.7-GHz methanol masers

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Received dd Month Year; in original form dd Month Year

ABSTRACT

We have used the Australia Telescope Compact Array (ATCA) to search for continuum emission toward three strong 6.7-GHz methanol maser sources. For two of the sources, G339.88-1.26 and NGC 6334F (G351.42+0.64), we detect continuum emission closely associated with the methanol masers. A further three clusters of masers showed no radio continuum emission above our sensitivity limit of 1-5 mJy. We find the position of the 6.7-GHz methanol masers in G339.88-1.26 to be consistent with the hypothesis that the masers lie in the circumstellar disc surrounding a massive star. We also argue that one of the clusters of methanol masers in NGC 6334F provides indirect observational support for the circumstellar disc hypothesis.

Key words: HII regions – masers – stars:formation – nebulae:individual:NGC 6334 – nebulae:individual:G339.88-1.26

1 INTRODUCTION

Maser emission from the 31 → 60 A+ (6.7-GHz) transition of methanol was first detected by Menten (1991), who found it to be common towards star formation regions. Subsequent observations have confirmed this, and there are presently more than 250 published sites of 6.7-GHz methanol emission within the Galaxy (MacLeod & Gaylard 1992; MacLeod & Nicolson 1992; Schutte et al. 1992; Houghton & Whiteoak 1995; van der Walt et al. 1995; Ellingsen et al. 1995). Currently all 6.7-GHz methanol masers are thought to be associated with regions of massive star formation, although the untargeted survey of Ellingsen et al. (1995) detected a number of sources with no known associations.

The 6.7-GHz transition of methanol produces the second strongest Galactic masers of any molecule. This makes it ideal for interferometric observations, as the accuracy with which we can determine the spatial distribution of maser spots is largely dependent on the signal-to-noise ratio. The first high-resolution spatial images of the 12.2-GHz methanol masers (Norris et al. 1988) showed that, unlike OH or H2O, the methanol masers often exhibit a simple spatial morphology. Subsequent observations of the 6.7-GHz methanol masers in many of the same sources (Norris et al. 1988; Norris et al. 1995) revealed that they also frequently have a curved or linear spatial structure.

Interferometric observations of the 12.2- and 6.7-GHz methanol masers show that the methanol masers often emanate from the same region as the OH masers (Menten et al. 1988; Menten et al. 1992; Caswell et al. 1993). The similarity in the spectra of many 6.7- and 12.2-GHz methanol masers was first noted by Menten (1991). The observations of Menten et al. (1992) and Norris et al. (1993) show that when there is a correspondence between one or more 12.2- and 6.7-GHz spectral features, the maser emission at the two frequencies appears to originate from the same location.

It has been suggested that 6.7- and 12.2-GHz methanol masers occur in the circumstellar disc which surrounds massive stars during their formation (Norris et al. 1993; Norris et al. 1995). If we are observing these discs nearly edge-on, then this provides an explanation for the curved and linear structures observed in many methanol masers. One of the predictions of this model is that the masers should show a simple velocity structure, and Norris et al. (1993) have presented evidence for this. Another prediction is that the masers should be approximately coincident with the peak of the continuum emission. This is in contrast to OH masers, which are typically found near the edge of HII regions (Gaume & Mutel 1987). The primary aim of this paper is to examine whether this prediction is supported by observation.

2 OBSERVATIONS

We have used the ATCA to image the continuum emission of the HII regions associated with the 6.7-GHz methanol
masers G318.95-0.20, G339.88-1.26 and NGC 6334F (G351.42+0.64). Our observations of NGC 6334F include three separate clusters of masers, and so subsequent discussions refer to a total of five clusters of 6.7-GHz methanol masers. The observations were made during 1993 November 7 with the array in the 6A configuration. This has minimum and maximum baseline lengths of 0.33 and 5.9 km respectively. The correlator was configured to record both a 128-MHz band centred at 8.590 GHz, and an 8-MHz band which was alternated between 8.584 and 6.669 GHz. This enabled us to make observations of the 6.7-GHz methanol masers and the H91α recombination line whilst simultaneously imaging the continuum emission. The 8-MHz band was split into 512 channels yielding a velocity resolution of 0.84 km s\(^{-1}\) at 6.669 GHz. The HPBW (half-power beam width) of the synthesised beam at 8.590 GHz was approximately 1.2 arcsec.

Each program source was observed twelve times for a 16-min period over the 13-h observing session and was preceded by a 4-min observation of a calibration source. The observing frequency of the 8-MHz band was changed to the alternate frequency at the end of each observing cycle (an observation of each program and calibration source). As a result, the maser and recombination line observations consist of six 16-min scans, while the continuum observations consist of 12 scans.

The data were calibrated and imaged using the AT AIPS (Astronomical Image Processing System), which is based on the NRAO software package of the same name. 1934-638 was used as the primary flux calibrator, which we assumed to have flux densities of 3.92 Jy and 2.86 Jy at 6.669 GHz and 8.590 GHz respectively. 1414-59, 1740-517 and 1744-312 were used as secondary calibrators and their positions and flux densities, calculated by comparing them with 1934-638 are listed in Table 1.

After the initial calibration, the continuum emission for each source was imaged and CLEANed using the AIPS task MX. The spectral resolution of our 6.7-GHz methanol maser observations is four times lower than that of Norris et al. (1993). Because of this we did not try to determine the relative positions of the 6.7-GHz methanol masers from these data, but rather used the positions determined by Norris et al. We independently imaged only the reference maser feature.

We used three different techniques to determine the offset between the position of the 8.5-GHz continuum peak and the reference feature from the 6.7-GHz methanol maser spectrum. The first and simplest technique was to measure independently the absolute positions of the continuum peak and the reference maser. The second technique was to reference the phase of all the channels in the 6.7-GHz methanol maser observations to a channel containing a strong unresolved maser feature (the reference feature). We then formed a continuum image from the channels which did not contain maser emission, and determined the position of the peak. This method works only if the radio continuum emission from the UCH\(\text{ii}\) region is strong. The final technique was to reference the phase of the 8.5-GHz continuum channels to the 6.7-GHz reference feature. If we assume that the same region of the atmosphere causes the phase errors at both 6.7 and 8.5 GHz, then we can correct the 8.5-GHz phase simply by multiplying the 6.7-GHz correction by the ratio of the frequencies. Scaling the phase corrections causes a discontinuity if the reference phase wraps. For these observations we found that after calibration the reference phase did not wrap for many of the baselines. For those where the phase did wrap, it did so only once and we flagged these data before phase referencing the 8.5-GHz data.

To assess the accuracy with which we could measure the offset between a reference maser feature and the 8.5-GHz continuum peak, we calculated the offset for NGC 6334F using each of the above methods. In addition, we calculated the offset for several datasets which had not been fully calibrated, or contained small deliberate errors in the calibration. In all cases the measured offset was very similar, with the rms being 0.2 arcsec. The offsets quoted below are the mean of the offsets calculated from each of the methods outlined above (for G339.88-1.26 only the first and third methods were used). We adopt 0.2 arcsec as a conservative estimate of the standard error.

### 3 RESULTS

Images of the 8.5-GHz radio continuum with the positions of the 6.7-GHz methanol maser emission are shown in Figs 1 and 2. Five separate sites of 6.7-GHz methanol maser emission were observed in the three sources, but we detected radio continuum emission associated with only two. The observed parameters of the radio continuum emission toward each of the sites of maser emission are summarized in Table 2. Two of the sites without continuum emission lie in the NGC 6334 star formation region. The upper limits on the peak flux density we obtained for them (see Table 2) are quite large, due to the presence of nearby strong diffuse sources, which severely limited the dynamic range we were able to achieve for images of this region. The resulting upper limits are not significantly smaller than the peak flux measured for G339.88-1.26. The entire NGC 6334 region was imaged with the VLA by Rodríguez, Cantó & Moran (1982), but they were able to set only an upper limit of 20 mJy for other compact sources in the region. Gaume & Mutei (1987) also imaged NGC 6334F with the VLA and report no additional compact emission with a 5-\(\sigma\) limit of 6.5 mJy for their 15-GHz image.

#### 3.1 G318.95-0.20

We are able to set a 5-\(\sigma\) upper limit of 0.82 mJy beam\(^{-1}\) for any radio continuum emission from G318.95-0.20. UCH\(\text{ii}\) regions with peak flux densities less than our upper limit have been detected. However, the large-scale, high-resolution studies of UCH\(\text{ii}\) regions which have been made so far (Wood & Churchwell 1988; Garay et al. 1993; Kurtz, Churchwell & Wood 1994; Miralles, Rodríguez & Scalise 1991), typically have sensitivity comparable to, or worse than, our observation of G318.95-0.20. Thus there is little information on whether UCH\(\text{ii}\) regions with peak fluxes less than 1 mJy are common.

The depth to which we could CLEAN the image toward G318.95-0.20 was limited by the presence of a confusing source with a peak flux density of 29.5 mJy beam\(^{-1}\) ∼ 160 arcsec west and 34.5 arcsec north of the reference maser position. The confusing source we detected is approximately...
Table 1. Positions and measured flux at 6.7 and 8.5 GHz, of the secondary calibrators used

| Source Name (J2000) | Right Ascension (J2000) | Declination (J2000) | 6.7-GHz Flux Density (Jy) | 8.5-GHz Flux Density (Jy) |
|--------------------|-------------------------|---------------------|--------------------------|--------------------------|
| 1414−59            | 14:17:41.640            | -59:50:37.53        | 1.16                     | 1.08                     |
| 1740−517           | 17:44:25.454            | -51:44:43.77        | 3.03                     | 2.51                     |
| 1744−312           | 17:43:59.640            | -31:07:38.45        | 0.40                     | 0.40                     |

Figure 1. Radio continuum image of G339.88-1.26 at 8.59 GHz. The contours are at -1, 1, 2, 4, 8, 16, 32, 64, and 90 per cent of the peak flux (6.14 mJy beam$^{-1}$). The rms noise level in the image is approximately 0.04 mJy beam$^{-1}$. The positions of the 6.7-GHz methanol masers as measured by Norris et al. (1993) are marked as open circles. The position of the OH masers as measured by Caswell, Vaile & Forster (1995) and the H$_2$O masers as measured by Forster & Caswell (1989) are marked as squares and a triangle respectively. The error bar above the clean beam plot represents the 3-$\sigma$ error for the relative offset between the methanol masers and the continuum. The error in the relative position of the methanol masers with respect to each other is smaller than the size of the symbols used to plot them. The width of the synthesised beam at the half power points is 1.04 arcsec in Right Ascension and 1.36 arcsec in Declination.

coincident with the IRAS source 14567-5846, which has been identified as an HII region. The radio continuum emission appears to be a cometary HII region with a major axis of $\sim$10 arcsec. Two groups have reported maser emission toward 14567-5846 (Cohen, Baart & Jonas 1988; Kemball, Gaylard & Nicolson 1988). In both cases they report the position to be consistent with the OH maser position measured by Caswell & Haynes (1987), which, in turn, is coincident with the 6.7-GHz CH$_3$OH masers. Therefore, it appears that all the maser emission reported in this region to date is from the same site, which is more than 2 arcmin away from the IRAS source 14567-5846.
3.2 G339.88-1.26

Our 8.5-GHz image of G339.88-1.26 is shown in Fig. 1. This is the first image to be produced of this UCH\textsc{ii} region. We measured it to have a peak brightness of 6.1 mJy beam\(^{-1}\) at 8.5 GHz, but it was too weak to image from our 6.7-GHz spectral-line observations. The bulk of the continuum emission is unresolved in our 1.2-arcsec synthesised beam, but shows some low-level extension to the north-east, suggesting a possible cometary morphology.

The reference maser (-38.7 km s\(^{-1}\)) is the most south-eastern of the spots and is offset from the continuum peak by 0.6±0.2 arcsec. The methanol masers lie in a line approximately across the centre of the continuum emission, perpendicular to the direction of the extended emission. The positions of two of the OH maser spots have been observed by Caswell et al. [1995], and they straddle the line of 6.7-GHz methanol masers. The position of one of the H\textsubscript{2}O masers spots was measured with the VLA by Forster & Caswell [1989]. They quote an absolute positional accuracy of 0.5 arcsec, but as G339.88-1.26 was the most southerly source in their sample, the maser position is probably less well determined than for the majority of sources. The H\textsubscript{2}O maser positions they quote is approximately 1 arcsec south of the 6.7-GHz methanol masers.

3.3 NGC 6334F (G351.42+0.64)

This source was previously imaged at 4.9 and 15 GHz using the VLA [Rodríguez et al. 1982; Gaume & Mutel 1987]. Our 8.5-GHz image, shown in Fig. 2, agrees with theirs. Making sensitive high-resolution images of the NGC 6334F region is difficult because of the presence of the sources NGC 6334D and E, two nearby strong, diffuse H\textsc{ii} regions. We measure a peak brightness of 585 mJy beam\(^{-1}\) for NGC 6334F at 8.5 GHz and 606 mJy beam\(^{-1}\) at 6.7 GHz. We also produced an 8.5-GHz image using a restoring beam with the same dimensions as the 6.7-GHz beam and measured the spectral

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Radio continuum image of NGC 6334F at 8.59 GHz. The contours are at -1, 1, 2, 4, 8, 16, 32, 64, and 90 per cent of the peak flux (585 mJy beam\(^{-1}\)). The rms noise level in the image is approximately 1.0 mJy beam\(^{-1}\). The open circles are the positions of the 6.7-GHz methanol masers (Norris et al. 1993), the dots are the positions of the OH masers (Gaume & Mutel 1987) and the crosses mark the positions of two 20-\mu m infrared sources (Harvey & Gatley 1983). The error bar above the clean beam plot represents the 3-\sigma error for the relative offset between the methanol masers and the continuum. The error in the relative position of the methanol masers with respect to each other is smaller than the size of the symbols used to plot them. The width of the synthesised beam at the half-power points is 1.04 arcsec in Right Ascension and 1.73 arcsec in Declination.}
\end{figure}
Continuum emission associated with 6.7-GHz methanol masers

Table 2. Positions of observed sites of 6.7-GHz methanol maser emission and some parameters of any associated continuum emission. For the first three sources the positions are those of the reference maser in each source. For NGC 6334F (NW) the position is the centroid of the four maser spots in that region and for G351.54+0.66 the position is that of the -2.5 km s\(^{-1}\) feature. The upper limits for sources with no detected continuum emission are 5 times the rms noise level in the final image.

| Source Name | Right Ascension (J2000) | Declination (J2000) | 8.5-GHz Peak Flux Density (mJy) | 8.5-GHz Integrated Flux Density (mJy) | Major Axis (arcsec) | Minor Axis (arcsec) |
|-------------|-------------------------|---------------------|-------------------------------|--------------------------------------|-------------------|-------------------|
| G318.95−0.20 | 15:00:55.332            | -58:58:42.04        | < 0.82                        |                                      |                   |                   |
| G339.88−1.26 | 16:52:01.682            | -46:08:34.42        | 6.14                          | 14.0                                 | 6.3               | 3.4               |
| NGC 6334F (C) | 17:20:53.454            | -35:47:00.52        | 585                          | 2780                                 | 8.8               | 6.5               |
| NGC 6334F (NW) | 17:20:53.240            | -35:46:57.92        | < 4.8                        |                                      |                   |                   |
| G351.54+0.66 | 17:20:54.621            | -35:45:07.38        | < 3.3                        |                                      |                   |                   |

index (\(\alpha\)) of the peak to be 0.95 (\(S_\nu \propto \nu^{\alpha}\)) between 6.7 and 8.5 GHz. This implies that the centre of the H\(\text{ii}\) region is still optically thick at 8.5 GHz.

Toward NGC 6334F, three centres of 6.7-GHz methanol maser emission are within the primary beam of the ATCA antennas. We have labelled the three sites NGC 6334F (C) (all those masers which lie in projection against the H\(\text{ii}\) region), NGC 6334F (NW) (the masers to the north-west of NGC 6334F (C)) and G351.54+0.66. G351.54+0.66 is not shown in Fig. 2, as it is offset 14.0 arcsec east and 114.2 arcsec south of NGC 6334F (C) (see Table 3). The northern clump of masers in NGC 6334F (C) is approximately coincident with the position of the OH masers determined by Gaume & Mutel (1987). No OH masers have been detected at the locations of either NGC 6334F (NW) or G351.54+0.66. The latter is in the same general region as the infrared source NGC 6334I(N), but does not appear to be closely associated with any known radio or infrared sources.

4 DISCUSSION

4.1 The Energizing star

By making some simplifying assumptions about the nature of the H\(\text{ii}\) regions observed, we can calculate some of the physical parameters (see Table 3). We calculated the electron density (\(n_e\)), emission measure (EM) and mass of ionized hydrogen (\(M_{\text{H}\text{II}}\)) using the equations of Panagia & Walmsley (1972). These equations assume that the H\(\text{ii}\) region is optically thin, spherically symmetric and has an electron temperature of 10\(^4\) K. In neither case are the H\(\text{ii}\) regions we observe spherically symmetric. Instead, we calculate the linear radius of the H\(\text{ii}\) region using the method outlined in Panagia & Walmsley independently for Right Ascension and Declination and use the geometric mean of the two. We also calculate the excitation parameter using the formula of Schraml & Mezger (1969). Using this we estimate the Lyman continuum photon flux (\(N_\alpha\)) and the spectral class of the exciting star (Panagia 1972). As the excitation parameter (\(U\)) depends only upon the flux density and the distance to the source, we were also able to calculate upper limits for the spectral class of the exciting star where we did not detect any continuum emission. For NGC 6334F, the spectral index we calculate for the central peak of the source between 6.7 and 8.5 GHz indicates that it is optically thick at these frequencies. The equations we have used to calculate the H\(\text{ii}\) region parameters assume that they are optically thin. The effect of the violation of this assumption is to reduce our estimate of the ionizing flux of the exciting star, effectively making it a lower limit. So for the H\(\text{ii}\) region NGC 6334F, which has a central core that appears to be optically thick from our spectral index calculations, the stellar types we derive are a lower limit. However, the effect is small since Gaune & Mutel (1987) derive similar parameters from observations at 15 GHz where the optical depth effect will be much smaller.

4.2 Morphology

Norris et al. (1993) observed 15 sites of 6.7-GHz methanol maser emission and found that a large fraction of their sample of 6.7- and 12.2-GHz methanol maser sources have a simple curved or linear spatial distribution. Based on their spatial distribution, we can divide all 6.7-GHz methanol maser sources into one of two classes: those with a simple linear or curved morphology (e.g. G339.88-1.26), and those with a more complex morphology (e.g. NGC 6334F). We have radio continuum observations associated with only two sites of 6.7-GHz methanol maser emission, one from each class of spatial morphology. No models have been suggested to explain the methanol masers with complex spatial distributions. They may represent a different evolutionary phase of the star formation process, as suggested by Forster & Caswell (1983) for complex OH and H\(_2\)O maser distributions. Three possibilities have been suggested to explain the curved/linear spatial morphology: shocks fronts, collimated jets, and circumstellar discs (Norris et al. 1993; Norris et al. 1997). For each of these, Norris et al. (1992) make a specific prediction about the relationship between the methanol masers and the H\(\text{ii}\) region. If the methanol masers form in the shocks at the interface between the ionized and molecular gas, then we expect to see them near the edge of H\(\text{ii}\) regions, as is often observed for OH. If the methanol masers form in jets or collimated outflows, then we would expect to observe them distributed radially to the H\(\text{ii}\) region. However, if the methanol masers form in the circumstellar discs of young stars, then we would expect to observe them approximately coincident with the continuum peak for the H\(\text{ii}\) region.

4.2.1 G339.88-1.26

G339.88-1.26 is one of the strongest sources of both 6.7- and 12.2-GHz methanol maser emission. The only published
Table 3. Derived parameters for H\textsc{ii} regions and the exciting stars associated with them. The distance estimates are from: 1 = Caswell & Haynes (1983), 2 = Neckel (1978), 3 = Haynes (1987), 2 = Caswell & Haynes (1983), 3 = Neckel (1978).

| Source        | Distance (kpc) | $n_e$ (cm$^{-3}$) | EM (pc cm$^{-6}$) | $M_{HII}$ (M$_\odot$) | U (pc cm$^{-2}$) | Log $N_L$ (s$^{-1}$) | Spectral Type |
|---------------|----------------|-------------------|------------------|----------------------|----------------|----------------------|---------------|
| G318.95−0.29  | 2.0$^1$        | 2.6×10$^4$        | 5.9×10$^3$       | 0.001                | <2.1          | <45.73               | <B2           |
| G339.88−1.26  | 3.0$^2$        | 2.6×10$^4$        | 9.6×10$^3$       | 0.025                | 7.2           | 46.32                | B0.5          |
| NGC 6334F (C) | 1.7$^3$        | 9.5×10$^4$        | 9.6×10$^3$       | 0.025                | 25.7          | 47.98                | O9            |
| NGC 6334F (NW)| 1.7$^3$        | 9.5×10$^4$        | 9.6×10$^3$       | 0.025                | 7.2           | 45.73                | B1            |
| G351.54+0.66  | 1.7$^3$        | 9.5×10$^4$        | 9.6×10$^3$       | 0.025                | 7.2           | 45.73                | B1            |

4.2.2 NGC 6334F

The NGC 6334 region is the most active known region of OB star formation in the Galaxy (Harvey & Gatley 1983). The region has been the subject of several surveys at radio and infrared wavelengths (McBreen et al. 1971, Rodriguez et al. 1982, Loughran et al. 1984, Straw, Hyland & McGregor 1989). These observations show six main sites of radio emission and a similar number of clusters of infrared emission. Unfortunately, the nomenclature of the region is rather confusing. The main site of 6.7-GHz methanol maser emission, called G351.42+0.64 in the methanol maser literature, is associated with the radio source NGC 6334F, which is designated NGC 6334-I at infrared wavelengths.

The NGC 6334F (C) star formation region is often compared to W3(OH). Both these regions show maser emission in many molecular transitions which are rarely detected toward other H\textsc{ii} regions. For example, very strong maser emission from many class II methanol transitions, along with thermal emission from class I transitions, has been detected toward NGC 6334F (C) (Batrla et al. 1987, Haschick & Baan 1989, Haschick, Baan & Menten 1989, Menten & Batrla 1989, Menten 1991). This suggests that W3(OH) and NGC 6334F (C) have some special characteristics not generally shared with other massive star-formation regions. Therefore it may not be valid to infer general characteristics of molecular emission, or star formation, from observations of NGC 6334F (C) or W3(OH) alone.

It is well established that 6.7-GHz methanol maser emission is common toward star formation regions which show main-line OH maser emission (Menten 1991, MacLeod & Gaylard 1992, Gaylard, MacLeod & van der Walt 1994, Caswell et al. 1993). However, recent observations by Ellingsen et al. (1995) have detected many new 6.7-GHz methanol masers in a region of the Galactic Plane previously surveyed for OH maser emission by Caswell, Haynes & Goss (1988). This suggests that in some sources the conditions are favourable for methanol maser emission, but not OH. Menten et al. (1992) found OH masers situated in, or near, all but one of the clumps of methanol maser emission in W3(OH). However, within the clumps there appears to be an anticorrelation between the positions of the OH and methanol masers. For NGC 6334F (C) we find, in agreement with Menten et al., that the OH masers appear to be associated with methanol maser emission. However, unlike the case for W3(OH) there are two clumps of 6.7-GHz methanol maser emission which have no reported OH emission. This, combined with the large scale observations of Ellingsen et al. (1995), suggests that 6.7-GHz methanol masers are more widespread than OH masers in star formation regions.

Infrared observations at a large number of wavelengths by Harvey & Gatley (1983) found the strongest emission in all bands to be coincident with the radio continuum peak (which they designated IRS 1). At 20 and 30 \textmu m the emission is extended to the North-west indicating the presence of a second source (IRS 2) separated from IRS 1 by approximately 6 arcsec. They suggest that IRS 1 and 2 may form a double source. 2.2-\textmu m (K-band) images of the same region by Stray et al. (1989) detected a cluster of sources in the general region of NGC 6334F, including a counterpart to IRS 1, but no counterpart to IRS 2.

Observations of CO, NH$_3$ and recombination lines probe large-scale outflows and the velocity of the ionized gas, and so provide additional information on star formation regions. Two lobes of NH$_3$ and CO emission have been observed to be associated with methanol maser emission. However, the distribution of the masers is highly linear and they do not have a wide velocity range as might be expected if they emanated from a high-velocity outflow. Further, we also require a double-sided jet, which is almost never seen in stars.

From our radio continuum images we estimate that a B0.5 star is required to produce the observed H\textsc{ii} region. However, as the model we used does not take into account the absorption of UV photons by dust, this is a lower limit on the spectral class of the exciting star. Norris et al. (1993) used simple modelling to show that the observed spatial and velocity distribution of the masers is consistent with Keplerian motion, but were unable to derive a mass for the star. We find that the position of the masers with respect to the parent H\textsc{ii} region also supports the hypothesis that the masers lie in circumstellar discs.

4.2.2 NGC 6334F

The NGC 6334 region is the most active known region of OB star formation in the Galaxy (Harvey & Gatley 1983). The region has been the subject of several surveys at radio and infrared wavelengths (McBreen et al. 1971, Rodriguez et al. 1982, Loughran et al. 1984, Straw, Hyland & McGregor 1989). These observations show six main sites of radio emission and a similar number of clusters of infrared emission. Unfortunately, the nomenclature of the region is rather confusing. The main site of 6.7-GHz methanol maser emission, called G351.42+0.64 in the methanol maser literature, is associated with the radio source NGC 6334F, which is designated NGC 6334-I at infrared wavelengths.

The NGC 6334F (C) star formation region is often compared to W3(OH). Both these regions show maser emission in many molecular transitions which are rarely detected to-
The lobes are approximately perpendicular to the major-axis of the continuum emission and both show a velocity gradient. A rotating molecular disc around IRS 1 (Jackson, Ho & Haschick 1988) and bipolar outflow from IRS 1 (Bachiller & Cernicharo 1990) have been proposed as explanations for the observed distribution of the molecular gas. The detection of shock-excited H$_2$ in the general vicinity of NGC 6334F (Straw & Hyland 1989) and shock-excited NH$_3$ (3,3) masers at the interface between the molecular gas and ambient medium (Kraemer & Jackson 1995), support the outflow hypothesis. Recent recombination-line observations also show a velocity gradient in the ionized gas, in approximately the same directions as the molecular gas, but are inconsistent with molecular outflow from IRS 1 (De Pree et al. 1995). De Pree et al. suggest instead that IRS 2 may be the source of the observed molecular outflow.

The orientation of IRS 1 and 2 is in the same direction, and the separation roughly the same distance, as the two main clusters of 6.7-GHz methanol masers near NGC 6334F which we have labelled NGC 6334F (C) and (NW). Norris et al. (1995) have shown that the observed spatial and velocity distribution of the two clusters of methanol masers is consistent with Keplerian motion about two separate stars. If IRS 2 is the source of the molecular outflow then we would expect it to have a circumstellar disc perpendicular to the direction of the outflow. The 6.7-GHz methanol masers NGC 6334F (NW) have a spatial and velocity structure consistent with Keplerian motion and are aligned perpendicular to the molecular outflow. This leads us to speculate that NGC 6334F (NW) may be associated with the infrared source IRS 2. If we can show that IRS 2 is coincident with the masers, and that it is the source of the molecular outflow, then this source provides circumstantial evidence for the circumstellar disc model of methanol masers. This requires higher resolution observations in the mid- to far-infrared and of the molecular outflow, particularly at its origin.

In Table 3 we present some calculated physical parameters of the HII regions and exciting stars. Our values are all comparable with those calculated by Rodriguez et al. (1983) and Gaume & Mutel (1987). From their model of the 6.7-GHz methanol masers, Norris et al. (1995) calculate a mass of 70 M$_\odot$ for IRS 1 and 13 M$_\odot$ for IRS 2. These masses are approximate but, encouragingly both are roughly consistent with the spectral types inferred from the radio continuum observations.

5 CONCLUSION

We have detected 8.5-GHz continuum emission toward two of the five sites of 6.7-GHz methanol maser emission detected. For G339.88-1.26 we find the position of the 6.7-GHz methanol masers to be consistent with the hypothesis that these masers occur in circumstellar discs of massive stars. The maser emission toward NGC 6334F has a more complex distribution, with one of the clusters of methanol maser emission being approximately coincident with the OH emission detected by Gaume & Mutel (1987). We also argue that the 6.7-GHz methanol maser cluster we call NGC 6334F (NW) may be in a circumstellar disc of the young stellar object IRS 2 (Harvey & Gatley 1983).

ACKNOWLEDGMENTS

This research has made use of the Simbad database, operated at CDS, Strasbourg, France.
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