OH observations of IRS 1 in NGC 7538

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Summary. The OH masers associated with IRS 1 in NGC 7538 have been observed with the Very Large Array at a spatial resolution of 1.2 arcsec and a velocity resolution of 0.65 km s\(^{-1}\). At 1720 MHz, two components with radial velocities of \(-57.4\) and \(-59.3\) km s\(^{-1}\) are found to lie on the southern edge of the ultracompact H\(\text{II}\) region. They are separated by \(0.24 \pm 0.07\) arcsec in a direction roughly perpendicular to the line from the centre of IRS 1. An upper limit of 0.3 arcsec is obtained for the sizes. These masers are not coincident with the two H\(_2\)CO masers with similar velocities. Three spatial components are measured at 1665 MHz: one with \(V = -59.0\) km s\(^{-1}\) is on the northern edge of IRS 1 close to the H\(_2\)CO masers, one with \(V = -60.1\) km s\(^{-1}\) is on the western edge and the third with \(V = -57.9\) km s\(^{-1}\) is midway between the centre and the 1720-MHz OH masers to the south.

The 1720-MHz and 1665-MHz OH masers, together with the two H\(_2\)CO masers, lie roughly on a ring which is centred on IRS 1 and whose outer radius is \(\sim 0.4\) arcsec (\(\sim 2 \times 10^{16}\) cm for an assumed distance of 3.5 kpc). The positions and velocities of the maser spots are interpreted in terms of a simple shell model. Without knowing the H\(\text{II}\) systemic velocity, it is not possible to distinguish whether the shell is expanding or contracting.

1 Introduction

The nebular complex NGC7538 (\(l=111^\circ.5, b=0^\circ.8\)) is a region of active star formation. Several centres of activity exist within the molecular cloud which contains the diffuse optical H\(\text{II}\) region NGC 7538. One of these centres contains the compact H\(\text{II}\) regions IRS 1, 2 and 3 seen at infrared and radio wavelengths (Wynn-Williams, Becklin & Neugebauer 1974;
Martin 1973). The observations to be presented here pertain to IRS 1, which is the most compact of these H II regions and has associated OH and H2O masers (Wynn-Williams, Werner & Wilson 1974; Norris, Booth & Davis 1980; Forster et al. 1978). An H2O emission line at 6 cm was detected near IRS 1 by Downes & Wilson (1974), and subsequent WSRT observations (Forster et al. 1980) showed it to be non-thermal — the first known H2O maser. Further observations of the H2O source with the VLA (Rots et al. 1981) showed that the two velocity-components, at -57.7 and -59.9 km s⁻¹, are spatially separated by 0.11 arcsec and lie within the northern boundary of the brighter of the two H II regions which make up IRS 1. Each H2O spot is unresolved (FWHM < 0.15 arcsec), yielding a lower limit of 5 x 10⁹ K for the equivalent brightness temperature of the maser emission.

The H2O masers are near the 1665-MHz OH position measured by Norris et al. (1980) and the 1720-MHz OH position measured by Wynn-Williams et al. (1974), although the positional uncertainties in these latter measurements are large. The purpose of the current observations is to measure the positions and sizes of the 1665-MHz and 1720-MHz OH masers accurately in order to compare them with the H2O masers and the H II region IRS 1.

2 Observations

We observed the OH masers associated with IRS 1 in NGC 7538 at 18 cm with the VLA (Very Large Array) of the National Radio Astronomy Observatory (operated by Associated Universities, under contract with the National Science Foundation) on 1980 November 8. Thirteen antennae were used with 78 baselines, giving roughly uniform uv coverage between 0.8 and 32 km. The shortest baseline corresponds to a fringe spacing of about 50 arcsec; larger-scale features are not present in the maps. The synthesized beamwidth is 1.2 x 1.2 arcsec and the sidelobe level is ~ 5 per cent.

During a 6-hr period we observed the source at 1665.4018 MHz for 1.5 hr and at 1720.530 MHz for 1.5 hr. These observations were made in left-hand circular polarization. They were calibrated every 30 min by observing the nearby point source 2352 + 495. This was the calibrator used in the H2O observations of Rots et al. (1981). The flux density of 2352 + 495 is 2.5 Jy at 18 cm and the uncertainty in its position is ~ 0.05 arcsec. The passband of the spectral line system was calibrated during a 70-min observation of 3C48 (40 min at 1665 MHz and 30 min at 1720 MHz).

A total of 64 frequency-channels were correlated, with a channel separation of 3 kHz and a resolution of 3.6 kHz. This corresponds to a separation of 0.52 km s⁻¹ and a velocity resolution of 0.63 km s⁻¹ at 1720 MHz (the corresponding values for 1665 MHz are 0.54 and 0.65 km s⁻¹). The rms noise in the unsmoothed channel maps is 50 mJy beam⁻¹. For the 1665-MHz observations it was necessary to smooth the data to a velocity resolution of 1.1 km s⁻¹ by the Hanning method.

3 Results

3.1 CONTINUUM MAPS

Continuum maps at both 1665 and 1720 MHz were made by averaging 46 frequency-channels which showed no line radiation. In order to improve the signal-to-noise ratio, a map was made with a beamwidth of 1.6 x 1.5 arcsec including both the 1665-MHz and 1720-MHz continuum channels. The extended source IRS 2 (Martin 1973) is detected 8 arcsec north of IRS 1 with a peak of ~ 40 mJy beam⁻¹ and total flux density of 0.7 ± 0.1 Jy. IRS 1 is detected as a
slightly extended source with total flux density $25 \pm 8 \text{ mJy}$ (compared to $111 \pm 9 \text{ mJy}$ at 4830 MHz measured by Rots et al. 1981). Its position $[\alpha(500) = 23^{h} 11^{m} 36^{s}.66 \pm 0^{s}.03$, $\delta(500) = 61^{\circ} 11' 50'' .1 \pm 0''.2]$ is close to the mean position of the two continuum components mapped at 6 cm (Fig. 1). This can be explained if both components are optically thick at 18 cm and have about the same size.

### 3.2 Line Channel Maps

A total of 12 line-channel maps were made for each observation (1665 and 1720 MHz), covering the velocity range $-56$ to $-62 \text{ km s}^{-1}$. A field of view of $50 \times 50$ arcsec was synthesized, centred on IRS 1. The maps were cleaned and restored with a circular Gaussian beam of half-power width 1.2 arcsec.

At 1720 MHz the two separate features at $-57.4$ and $-59.3 \text{ km s}^{-1}$ appear as unresolved spots with upper limits to their size of 0.3 arcsec. The positions and intensities of the maser emission were obtained by fitting the antenna pattern to the data. At 1665 MHz, the maser emission appears to arise from three separate positions, although the actual number is uncertain due to the low velocity-resolution of 1.1 km s$^{-1}$. With the velocity resolution it is not possible to give accurate limits to the source size, because of blending of components from different positions. At 1720 MHz the two positions are summarized in Table 1 (part a) while the three positions at 1665 MHz are given in Table 1 (part b). These five positions are indicated on the 6-cm continuum map of IRS 1 in Fig. 1. The OH relative position errors are as follows: at 1720 MHz $\sigma = 0.05$ arcsec and at 1665 MHz $\sigma = 0.1$ arcsec. The absolute positional accuracy for both is 0.1 arcsec. This latter uncertainty is relevant when comparing the positions of these OH masers with those listed in Table 1 (part c) for the H$_2$CO masers (Rots et al. 1981). The OH/H$_2$O maser source NGC 7538 S, at velocities of $-54$ to
Table 1. Observations.

(a) 1720-MHz OH components with velocity resolution 0.6 km s\(^{-1}\).

<table>
<thead>
<tr>
<th>(\alpha)</th>
<th>(\delta)</th>
<th>(V) (km s(^{-1}))</th>
<th>(p) (arcsec)</th>
<th>(S) (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(23^h\ 11^m\ 36.651)</td>
<td>61° 11' 49&quot;.02</td>
<td>-57.4</td>
<td>0.42</td>
<td>7.9</td>
</tr>
<tr>
<td>(23\ 11\ 36.623)</td>
<td>61 11 49 .15</td>
<td>-59.3*</td>
<td>0.37</td>
<td>3.6*</td>
</tr>
</tbody>
</table>

(b) 1665-MHz OH components with velocity resolution 1.1 km s\(^{-1}\).

<table>
<thead>
<tr>
<th>(\alpha)</th>
<th>(\delta)</th>
<th>(V) (km s(^{-1}))</th>
<th>(p) (arcsec)</th>
<th>(S) (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(23^h\ 11^m\ 36.655)</td>
<td>61° 11' 49&quot;.22</td>
<td>-57.9</td>
<td>0.23</td>
<td>1.3</td>
</tr>
<tr>
<td>(23\ 11\ 36.637)</td>
<td>61 11 49 .86</td>
<td>-59.0</td>
<td>0.42</td>
<td>1.0</td>
</tr>
<tr>
<td>(23\ 11\ 36.599)</td>
<td>61 11 49 .57</td>
<td>-60.1</td>
<td>0.41</td>
<td>1.1</td>
</tr>
</tbody>
</table>

(c) \(\text{H}_2\text{CO}\) components (Rots et al. 1981) with velocity resolution 0.4 km s\(^{-1}\).

<table>
<thead>
<tr>
<th>(\alpha)</th>
<th>(\delta)</th>
<th>(V) (km s(^{-1}))</th>
<th>(p) (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(23^h\ 11^m\ 36.645)</td>
<td>61° 11' 49&quot;.82</td>
<td>-57.7</td>
<td>0.37</td>
</tr>
<tr>
<td>(23\ 11\ 36.637)</td>
<td>61 11 49 .74</td>
<td>-59.9</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Positional errors: OH absolute = 0.1 arcsec, relative = 0.05 arcsec (1720 MHz), 0.1 arcsec (1665 MHz).
\(\text{H}_2\text{CO}\) absolute = 0.05 arcsec, relative = 0.02 arcsec.

* Flux densities and velocity refer to the average of two adjacent channels.

-56 km s\(^{-1}\) (cf. Genzel & Downes 1977; Forster et al. 1978), is 80 arcsec to the south of IRS 1 and is outside the field of view of the present observations.

In addition to the observations in the left-hand circular polarization described above, we obtained short observations of both the 1665-MHz and 1720-MHz lines in right-hand circular polarization. The integration times were about 18 min at each frequency. The synthesized beam is \(\sim 4 \times 1\) arcsec at a position angle of 45°. The noise is much higher in the channel maps (\(\sim 220\) mJy beam\(^{-1}\)) and the positional accuracy is poorer. Within the larger errors, the positions agree with those given in Table 1. No measurement of position was attempted for \(V = -60.1\) km s\(^{-1}\) at 1665 MHz. Spectra for the \(\text{H}_2\text{CO}\) and OH masers are shown in Fig. 2 for both right-hand and left-hand circular polarization. The values plotted represent the peak line flux density in the corresponding channel maps.

### 3.3 Maser Positions

The seven maser features whose positions have been determined are shown in Fig. 1. The circles represent the two \(\text{H}_2\text{CO}\) masers, the squares represent the two 1720-MHz OH masers and the triangles represent the three 1665-MHz OH masers. Filled symbols indicate the more positive velocities. Contrary to our expectations based on the similarity of the \(\text{H}_2\text{CO}\) and 1720-MHz OH spectra, the two components of the 1720-MHz OH maser do not coincide with the two \(\text{H}_2\text{CO}\) components. Instead they lie about the same distance from the centre of IRS 1 but on the opposite side. (Here and in the discussion which follows, by the term
Figure 2. Right- and left-hand circularly polarized spectra for the H$_2$CO, 1720-MHz OH and 1665-MHz OH masers taken with the VLA. The velocity resolution is indicated in the upper left-hand corner of each spectrum.

'centre' we are referring to the position of the peak emission of the southern component of IRS 1 which is seen on the 6-cm contour map shown in Fig. 1.) The two 1720-MHz maser spots are separated by 0.24 ± 0.07 arcsec along a line roughly perpendicular to the radius vector from the centre of IRS 1. For both H$_2$CO and 1720-MHz OH, the more positive velocities are found slightly farther from the centre.

The three 1665-MHz OH maser spots are also distributed around the centre of IRS 1. The position of our −60.1 km s$^{-1}$ component is displaced by 0.1 ± 0.2 arcsec from the position given by Norris et al. (1980) at −59.9 km s$^{-1}$ (velocity resolution 0.15 km s$^{-1}$). Our 1665-MHz positions are in reasonable agreement with the more detailed measurements of Norris (private communication), although changes in the relative intensities of the features are apparent in the 3-yr interval between the observations.

Six out of seven of the observed maser spots in OH and H$_2$CO (Fig. 1) appear to lie roughly on a ring centred at the 6-cm peak of the ultra-compact H II region IRS 1. The outer radius of the ring is 0.4 arcsec (2 × 10$^{16}$ cm at a distance of 3.5 kpc). Rots et al. (1981)
measured the deconvolved Gaussian full-width of the 6-cm continuum emission from IRS 1 to be 0.6 arcsec. Since the H II region is optically thick at 6 cm, and we may thus approximate it as a uniformly bright disc, the true diameter is 0.85 ± 0.1 arcsec (Panagia & Walmsley 1978). Thus the maser spots are projected onto the H II region. Due to the large continuum optical depth of IRS 1 at both 6 and 18 cm, the maser sources must lie in front of IRS 1 and probably amplify the continuum radiation of the H II region.

4 Discussion

The OH and H$_2$CO maser emission near IRS 1 occurs preferentially near the projected edge of the H II region; this pattern suggests that the masers are located in a shell for which the maximum coherence length occurs along a line of sight where both a long pathlength and a minimum gradient in radial velocity exist. The shell must be relatively thin and/or have significant differential motion to keep the masers from appearing across the entire face of the compact H II region. In W3 (OH) the 1665-MHz OH masers are also confined to the face of the continuum source, and the brightest spots appear on a ring of radius 1.3 arcsec (~ 4 × 10$^{16}$ cm at a distance of 2.2 kpc), so there is a strong resemblance between W3 (OH) and NGC7538 in their maser emission. As discussed by Reid et al. (1980), the absence of a complete ring could be due to narrow beaming if the masers are saturated.

The mean radial velocity of the maser source is −58.8 km s$^{-1}$ with a spread of ±1.3 km s$^{-1}$. For comparison, the recombination-line velocity of the H II region IRS 2, which is only 8 arcsec to the north, is −67.6 ± 1.5 km s$^{-1}$ (from unpublished WSRT data of Goss, Forster & van Gorkom 1981). Typical velocities of molecules in this direction are about −57.5 km s$^{-1}$ near IRS 1 to about −56 km s$^{-1}$ at a position 1.5 arcmin to the south near NGC7538 S (Dickel, Dicker & Wilson, in preparation). Since there is no measurement of the systematic velocity of IRS 1, we can only assume that it lies in the range −56 to −68 km s$^{-1}$.

The small radius (~ 0.01 pc) and high emission measure (~ 5 × 10$^8$ cm$^{-6}$ pc) of the ultracompact H II region suggests that IRS 1 is a very young object. The age found by assuming constant expansion at the speed of sound is of the order of 500 yr. Another indicator of a very early evolutionary stage is the large ratio of infrared to Lyman-continuum luminosity which may imply the presence of a pre-main sequence star (see Thompson 1981; Thronson & Harper 1979; Willner 1976; Simon, Simon & Joyce 1979). The strong 20-μm emission implies heated dust mixed in with the ionized gas ($T_d$~370 K and gas/dust ~ 75 according to Wynn-Williams et al. 1974; Willner 1976). The extremely deep 10-μm absorption feature suggests a dusty cool envelope of mass between 2 and 20 $M_\odot$ (Willner 1976).

It has been suggested that the masers are located in the expanding, shock-compressed zone just outside the ionization front (Cook 1968; Elitzur & de Jong 1978), but in W3 (OH) the OH masers are all redshifted with respect to the H II region and therefore must be part of a contracting shell. Since the velocity of the ionized gas in IRS 1 is unknown, the relative velocity of the masers with respect to the H II region cannot be determined directly.

In order to explore the possibility of a shell surrounding IRS 1, we will assume that the masers are located in a shell which is centred on IRS 1 and has a constant radial motion which, as viewed from the outside, is positive for collapse and negative for expansion. For IRS 1 the range in observed velocities should be small, since all the masers are at nearly the same projected distance from the centre of IRS 1. This model implies that the 1665-MHz and 1720-MHz masers, as well as the H$_2$CO masers, arise in the same shell. The H$_2$CO and 1720-MHz OH masers are expected to exist in regions of comparable molecular hydrogen densities ($n_{H_2}$~10$^4$ cm$^{-3}$ and 10$^3$–10$^5$ cm$^{-3}$ respectively; cf. Boland & de Jong 1981; Elitzur 1976), whereas the 1665-MHz OH masers probably arise in a higher density zone or
in dense fragments \((n_{\text{H}_2} \sim 10^6 - 10^8 \text{ cm}^{-3}; \text{cf. Reid et al. 1980})\). A further complication is introduced by the possibility that kinematical effects are confused by frequency shifts due to Zeeman splitting. This is particularly important at 1665 MHz where the Zeeman splitting is 0.59 km s\(^{-1}\) mG\(^{-1}\). At 1720 MHz the splitting is only 0.12 km s\(^{-1}\) mG\(^{-1}\). The H\(_2\)CO velocities are not affected by Zeeman splitting, since H\(_2\)CO is diamagnetic and therefore has a \(g\) factor three orders of magnitude less than OH. Although a single-shell model may be an oversimplification, more complicated models are not merited at present.

The radial velocity, \(V\), observed at a projected distance, \(p\) (see Table 1), from the centre of IRS 1 is:

\[ V(p) = V_{\text{sys}} + V_{\text{shell}} \left[ 1 - \left( p/r_{\text{shell}} \right)^2 \right]^{1/2}, \]

where \(V_{\text{sys}}\) is the systemic velocity of IRS 1, \(V_{\text{shell}}\) is the shell velocity, and \(r_{\text{shell}}\) is the radius of the shell. We consider two simple cases based on two possibilities for the unknown \(V_{\text{sys}}\) of IRS 1.

(1) The fact that the more negative velocity components of the H\(_2\)CO and 1720-MHz OH masers are closer to the centre of IRS 1 suggests that an expanding thin shell \((V_{\text{shell}} < 0)\) is appropriate. A reasonable fit to the H\(_2\)CO and 1720-MHz OH data can be achieved with an \(r_{\text{shell}}\) close to that of the radius of the H\(\text{II}\) region \((\sim 2.2 \times 10^{16} \text{ cm})\). Values of \(V_{\text{shell}}\) in the range \(-3.5\) to \(-6 \text{ km s}^{-1}\), with corresponding values \(V_{\text{sys}}\) in the range \(-57.5\) to \(-55.5 \text{ km s}^{-1}\), are indicated. These values of \(V_{\text{sys}}\) are close to the velocities observed in the large molecular cloud near NGC 7538. Two of the three 1665-MHz masers easily fit into the expanding shell picture. They are located farther out in the shell at a radius of \(-3 \times 10^{16} \text{ cm}\).

These parameters can be compared to models calculated for the expansion of dust-bounded H\(\text{II}\) regions by Cochran & Ostriker (1977) for a star of luminosity \(\sim 10^5 L_\odot\) embedded in an initially uniform cloud of density \(\sim 2 \times 10^5 \text{ cm}^{-3}\). At the stage where the expansion of the H\(\text{II}\) region has reached \(\sim 2 \times 10^{16} \text{ cm}\), the shell has a density of \(3 \times 10^8 \text{ cm}^{-3}\) (suitable for the 1665-MHz OH masers) and a column density of \(7 \times 10^{22} \text{ cm}^{-2}\) (approaching that inferred from the 10-\(\mu\)m absorption feature). Such high densities are well above the narrow range \((1-3) \times 10^4 \text{ cm}^{-3}\) allowed if the H\(_2\)CO masers are radiatively pumped according to the model of Boland & de Jong (1981).

There are several potential difficulties with the expanding model. First, it does not explain the velocity of the 1665-MHz emission at \(-57.9 \text{ km s}^{-1}\). Secondly, the systemic velocity of \(-56.5 \text{ km s}^{-1}\) is more representative of the molecular velocity found deeper in the molecular cloud about 1.5 arcmin to the south, as opposed to the value of \(-68 \text{ km s}^{-1}\) found for the H\(\text{II}\) region IRS 2 only 8 arcsec to the north.

(2) If we assume that the systemic velocity of IRS 1 is close to \(-68 \text{ km s}^{-1}\), a contracting model must be considered. Following the contracting model for W3 (OH) proposed by Reid et al. \((V \propto r^{-1/2}\), in the case of gravitationally collapsing envelope), a reasonable fit for a thicker shell is possible. The shell has an outer radius of \(4 \times 10^{16} \text{ cm}\) and a thickness of \(\sim 2 \times 10^{16} \text{ cm}\). The collapse velocity, \(V_{\text{shell}} \sim 8 \text{ km s}^{-1}\), requires a high mass (perhaps \(100 M_\odot\)) for the central star. The \(V_{\text{sys}}\) is \(-66 \text{ km s}^{-1}\), in close agreement with the recombination-line velocity of IRS 2. The collapse parameters for IRS 1 are quite similar to the values that Reid et al. (1980) propose for W3 (OH): \(\sim 6 \text{ km s}^{-1}\) and a radius of \(5 \times 10^{16} \text{ cm}\).

5 Conclusions

The 1665-MHz and 1720-MHz OH, as well as the 4830-MHz H\(_2\)CO, maser spots mapped with the VLA toward NGC7538 (IRS 1) all lie within the projected boundary of the background H\(\text{II}\) region and probably amplify its radiation. The spots appear roughly along a ring
surrounding IRS 1. The two maser species having similar double-peaked line profiles (1720-MHz OH and H2CO) lie on opposite sides of the ring. The maser velocities and positions have been compared to expanding and contracting shell models. For the expanding model, the masers are located in a thin dense shell which surrounds the H II region and expands with a velocity in the range 3.5–6 km s⁻¹. For the contracting model, the H2CO and 1720-MHz masers arise from an accreting envelope around a massive pre-main sequence star and the newly formed compact H II region. The 1665-MHz OH emission probably comes from high-density fragments embedded in the shell which is gravitationally collapsing with a velocity of ~8 km s⁻¹. This shell is somewhat thicker and less dense than in the case of the expanding model. A high-frequency measurement of the recombination-line velocity of IRS 1 is required to discriminate between expansion and contraction.

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References