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VLA OBSERVATIONS OF THE $^{15}NH_3$ MASER ASSOCIATED WITH NGC 7538 IRS 1

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ABSTRACT

Emission in the $(J, K) = (3, 3)$ inversion line of ortho-$^{15}NH_3$ associated with NGC 7538 IRS 1 has been found to be coincident with the continuum peak emission. The brightness temperature of the most intense feature, at -60 km s^{-1}, is >5200 K. This maser emission may be due to amplification of the background H II region. The maser emission arises from many discrete sources distributed over a north-south extent of $\approx 0\overset{''}{.}3$. The $^{15}NH_3$, H_2CO, and OH (1665 MHz) emission probably all originate in a common highly clumped compact region that is in front of the H II region. The H II region appears to be optically thick at centimeter wavelengths and maser emission from these molecules may be a good probe of neutral gas near ultracompact H II regions.

Subject headings: interstellar: molecules — masers — nebulae: H II regions

I. INTRODUCTION

Maser emission has been detected near compact H II regions in various lines of OH, H_2O, and CH_3OH (see, e.g., Reid and Moran 1981; Menten *et al.* 1986). The relationship of the maser emission to the compact H II region and its role in star formation is unclear. Masers appear to occur in individual clouds surrounding the compact H II region and describe the kinematics of star-forming regions.

Maser emission from the metastable (3, 3) inversion levels of $^{15}NH_3$ has been found *only* toward NGC 7538. This region shows maser emission from more molecules than any other (see, e.g., a collection of data in Wilson *et al.* 1983; also Batrla *et al.* 1987). The evidence for maser emission is based on 100 m data (40″ beam) for the $(J, K) = (1, 1)$ and (2, 2) absorption lines, the (3, 3) emission line, and limits for the (4, 4) line of $^{15}NH_3$. In order to map the spatial distribution of the $^{15}NH_3$ (3, 3) emission, to verify that it is indeed maser emission, and to determine the peak line optical depth, observations were made with the VLA[1].

II. OBSERVATIONS AND RESULTS

Observations were made on 1986 December 31, using the C configuration of the VLA which has a maximum baseline length of 3 km. Thirty-two spectrometer channels were used with a total bandwidth of 1.5 MHz. The center velocity was -60 km s^{-1} with respect to the local standard of rest. The line frequency was assumed to be 22.789421 GHz. On-line Hanning-weighting was used which gave an effective spectral resolution of 48.8 kHz or 0.64 km s^{-1}. The data were obtained by alternatively observing NGC 7538 and 3C 84. The flux density scale was established by assuming a flux density of 42 Jy for 3C 84.

[1] The Very Large Array (VLA) is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under contract to the National Science Foundation.

The data were calibrated using the amplitude and phase of 3C 84 to remove the instrumental effects. Maps were made with a cell size of $0\overset{''}{.}3$ and 256 pixels. The resulting synthesized beam was $1\overset{''}{.}21$ by $1\overset{''}{.}18$, p.a. $-73°$. The data were processed using the Astronomical Image Processing System (AIPS). The standard procedures were used to "self-calibrate" the data using a model of the source based upon the inner $\frac{3}{4}$ of the 1.5 MHz band. The maps in the velocity range -63.2 to -67.7 km s^{-1} were averaged and cleaned to make a continuum map shown in Figure 1. The final resulting clean continuum map was subtracted from all the cleaned channel maps. After subtracting the continuum map in each velocity channel, we found only unresolved point sources in each velocity channel. The IR maxima are located near the peak of the continuum emission of IRS 1. The spectrum of the line emission is given in Figure 2. This was obtained by summing the emission in a box with size of $\sim 3''$ centered on NGC 7538 IRS 1. Summing the flux density over a square of 40″ on a side did not give a reasonable flux density for the line, due to an inadequate subtraction of the continuum emission which occurs over the wide area shown in Figure 1. Also shown in Figure 2 are the spectra obtained with the 100 m telescope on 1983 March 9–10 and 1988 July 22–24. The signal-to-noise ratio was lower than in 1983, but to within the errors the line shape and intensity were the same. The data acquisition and calibration followed the procedure used by Mauersberger *et al.* (1986). There are no significant differences between the two profiles taken with the 100 m telescope in 1983 and 1988 and thus do not provide conclusive evidence for time variability.

The flux density and size of the continuum emission are given in Table 1 as measured from a Gaussian fit to this emission. The emission in the line channels was also fitted with a Gaussian at -60.0 and 55.5 km s^{-1}. The positions of the line features and their intensities are also listed in Table 1. The sizes of the line emission features vary between $<0\overset{''}{.}5$ and $<0\overset{''}{.}9$, but are approximately $<0\overset{''}{.}5$ in the strongest channels near the two peaks. For the most luminous feature, near -60 km s^{-1}, this

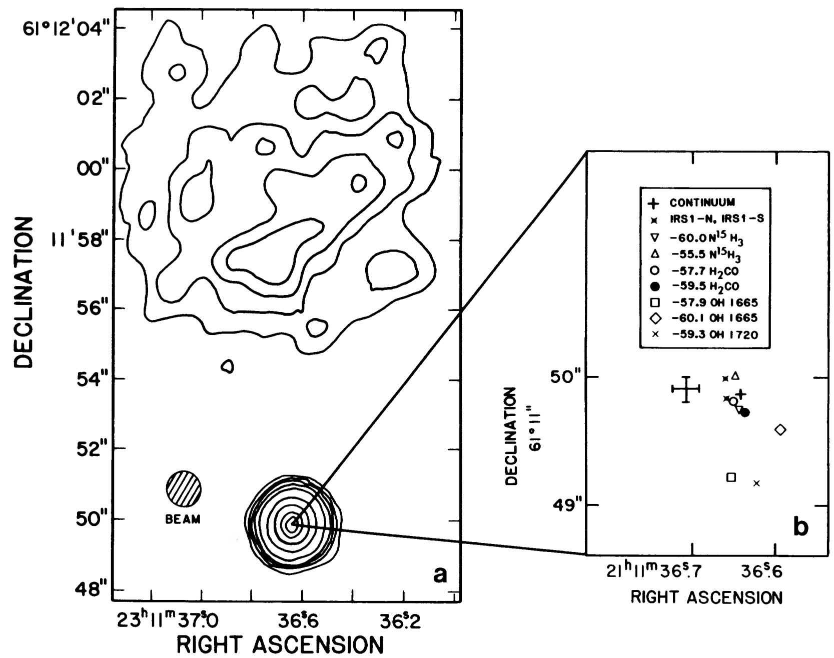

FIG. 1.—(*a*) Continuum map of the NGC 7538 region. This map was obtained from the velocity range −63.2 to −67.7 km s^{-1} of $^{15}NH_3$. The contour levels are 7.5, 10, 12.5, 20, 40, 60, 80, and 100% of the peak flux density which is 432 mJy beam^{-1}. The restoring beam is 1″.20 by 1″.18, p.a., −73°. Note that this *Letter* deals only with NGC 7538 IRS 1 which is the southern compact source. (*b*) The peak positions of the continuum source (measured with a 1″.2 by 1″.13 beam) and molecular masers associated with NGC 7538 IRS 1. The relative positions of the emission of the same molecular transition are of order 0″.03 while the absolute positions are of order 0″.01. The error bars correspond to a ±0″.1 error. Within the observational errors, the NH_3 and H_2CO masers coincide with the continuum emission peaks.

corresponds to a brightness temperature of >5200 K. Since this region is unresolved, this is a lower limit to the actual peak line temperature. The relative positions, shown in Figure 3, were all measured from the self-calibrated maps. The features appear to cluster about two positions. Those between −54.2 and −56.1 km s^{-1} are located north of the continuum peak while those between −57.4 and −61.3 km s^{-1} are south of this peak. The separation of these two regions is 0″.25. The individual spectral channels appear to be individual masers. The velocities of these masers become more positive with distance from the position of the continuum source.

The position of the continuum emission was measured from the non–self-calibrated map and is listed in Table 1. The positions of the line emission were found by adding the offsets from the self-calibrated maps to the continuum position in Table 1. In Table 1, we also list the positions of other molecular masers and of the NH_3 absorption found near IRS 1. The spectral resolution of the formaldehyde observations was 0.4 km s^{-1} (Rots *et al.* 1981). The spectral resolution for the 1720 and 1665 MHz OH observations (Dickel *et al.* 1982) was 0.6 and 1.1 km s^{-1}, respectively.

Continuum maps of IRS 1 show an intense H II region which becomes optically thin at frequencies above 22 GHz (Henkel, Wilson, and Johnston 1984). Continuum emission is found over an area of at least 1″ near IRS 1. Inspection of the 6 cm continuum map by Rots *et al.* (1981) shows a peak intensity at a position ∼0″.5 from the ammonia emission. VLA continuum maps at 2 cm (Campbell 1984; Turner and Mathews 1989) show that there are two emission peaks separated by 0″.17 along a north-south line which are coincident within the

TABLE 1

POSITIONS OF EMISSION NEAR NGC 7538 IRS 1

Parameter	R.A. (1950)	Decl. (1950)	Flux Density (mJy)	Size	Comments
Continuum	23ʰ11ᵐ36ˢ.643 ± 0ˢ.01	61°11′49″.85 ± 0″.1	523 ± 20	0″.66 × 0″.35, p.a. = 174° ±0.02 ± 0.02 ±10	
$^{15}NH_3$ −60.0 km s^{-1}	23 11 36.644 ± 0.001	61 11 49.78 ± 0.1	323 ± 30	<0″.5	
$^{15}NH_3$ −55.5 km s^{-1}	23 11 36.648 ± 0.001	61 11 49.99 ± 0.1	271 ± 30	<0″.5	
H_2CO −57.7 km s^{-1}	23 11 36.645 ± 0.014	61 11 49.82 ± 0.1	...	...	Rots *et al.* 1981
H_2CO −59.9 km s^{-1}	23 11 36.637 ± 0.014	61 11 49.74 ± 0.1	...	...	Rots *et al.* 1981
OH (1665 MHz):					
−57.9 km s^{-1}	23 11 36.655 ± 0.014	61 11 49.22 ± 0.1	...	...	Dickel *et al.* 1982
−59.0 km s^{-1}	23 11 36.637 ± 0.014	61 11 49.86 ± 0.1	...	...	Dickel *et al.* 1982
−60.1 km s^{-1}	23 11 36.599 ± 0.014	61 11 49.57 ± 0.1	...	...	Dickel *et al.* 1982
OH (1720 MHz):					
−57.4 km s^{-1}	23 11 36.651 ± 0.014	61 11 40.02 ± 0.1	...	...	Dickel *et al.* 1982
−59.3 km s^{-1}	23 11 36.623 ± 0.014	61 11 49.15 ± 0.1	...	...	Dickel *et al.* 1982
NH_3 absorption:					
−60.0 km s^{-1}	23 11 36.64	61 11 49.8	...	...	Henkel *et al.* 1984

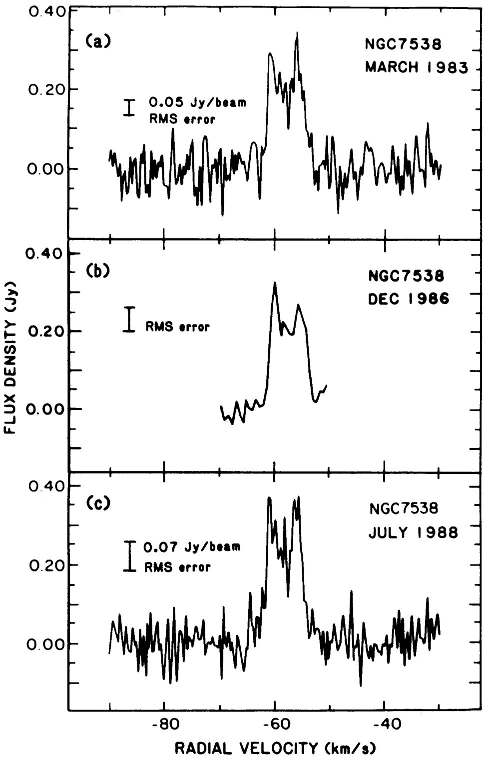

FIG. 2.—(*a*) The spectrum of the $(J, K) = (3, 3)$ inversion line of $^{15}NH_3$ in the direction of NGC 7538 IRS 1. A 100 m spectrum obtained on 1983 March 9–10 with a spectral resolution of 0.3 km s^{-1}. The rms flux density of the measurements is shown by the error bar. The velocity is with respect to the local standard of rest, and the assumed line frequency was 22789.421 MHz. (*b*) VLA spectrum obtained 1986 December 31 with a spectral resolution of 0.6 km s^{-1}. This spectrum was obtained by summing the flux density in a 3″ box centered on the continuum peak position of NGC 7538 IRS 1 after the continuum emission had been subtracted from the maps. (*c*) A spectrum obtained with the 100 m telescope on 1988 July 22–24. The spectral resolution is 0.5 km s^{-1}.

measurement error with the $^{15}NH_3$ masers. The positions reported in these two publications differ in right ascension by 0″.1, with an error of 0″.1 from that reported in Table 1. These have been denoted as IRS 1-N and IRS 1-S by Campbell (1984). The positions of the $^{15}NH_3$ emission associated with IRS 1, continuum emission, and other maser emission are illustrated in Figure 1.

III. DISCUSSION

The claim made by Mauersberger *et al.* (1986) that the emission in the metastable $(J, K) = (3, 3)$ inversion line of $^{15}NH_3$ is due to maser emission has been confirmed. The brightness temperature of the most intense spectral feature is >5200 K as seen with 0.48 km s^{-1} resolution and thus cannot be due to thermal excitation. In fact at temperatures of this magnitude, the ammonia molecule would dissociate.

Figure 1 shows that within the errors of measurement, the maser emission coincides with the peaks on the continuum emission of the H II region. The NH_3 masers probably amplify the continuum background, since (1) the continuum source is optically thick at the line frequency, so that if behind the continuum source, the line emission would be attenuated; and (2) the two peaks in the continuum map of Campbell (1984) coincide with the two groups of NH_3 masers, if the continuum positions are appropriately adjusted.

There is a particularly simple scheme for maser excitation in the (3, 3) levels of ammonia (see Guilloteau *et al.* 1983) which involves the transfer of population between the $K = 0$ and $K = 3$ ladders of ortho-ammonia. This is basically due to the Pauli exclusion principle which requires that one-half of the levels in the $K = 0$ ladder are missing. For a much lower column density of NH_3, appropriate to the present case, Mauersberger, Henkel, and Wilson (1988) find that inversion occurs over the H_2 density range 10^4–10^7 cm^{-3} and a T_k of 220 K. These collision rates used in the maser excitation schemes were taken from Green (1981). From this and the "apparent" optical depth of the $^{15}NH_3$ and $^{14}NH_3$ lines, Mauersberger, Wilson, and Henkel (1986) derived a density of $10^{6.5}$ cm^{-3}. Recently, some doubt has been cast on the theoretical collision rates. Excitation schemes involving the transfer of population to vibrationally excited NH_3 levels are an alternative, and absorption in the 2 mm line of vibrational excited NH_3 (see Mauersberger, Henkel, and Wilson 1988 for a level diagram) has been found toward NGC 7538 IRS 1.

From a detailed analysis of single-dish NH_3 absorption-line profiles, Wilson *et al.* (1983) had concluded that the core of the NH_3 emission region has a kinetic temperature of ≥ 170 K. This has recently been confirmed by an analysis of HDO absorption lines which probably are from the same volume of gas and for which a rotation temperature of 185 ± 15 K was obtained. $N(NH_3)$ is 2.5–$3.0 \times 10^{+18}$ cm^{-3} (Wilson *et al.*; Mauersberger *et al.*; Wilson and Henkel 1986). With $(NH_3)/(H_2) = 10^{-5}$ (Wilson *et al.* 1983) or $10^{-5.5}$ (Mauersberger, Wilson, and Henkel 1986) we obtain $N(H_2) = 0.25$–$1. \times 10^{24}$ cm^{-3}, i.e., somewhat smaller values than toward the Orion hot core. Toward NGC 7538 IRS 1 there may be indications for even higher column density peaks. Jacq *et al.* (1988) derive an HDO column density of the order of 10^{18} cm^{-2}, a value which is comparable to that of the main species

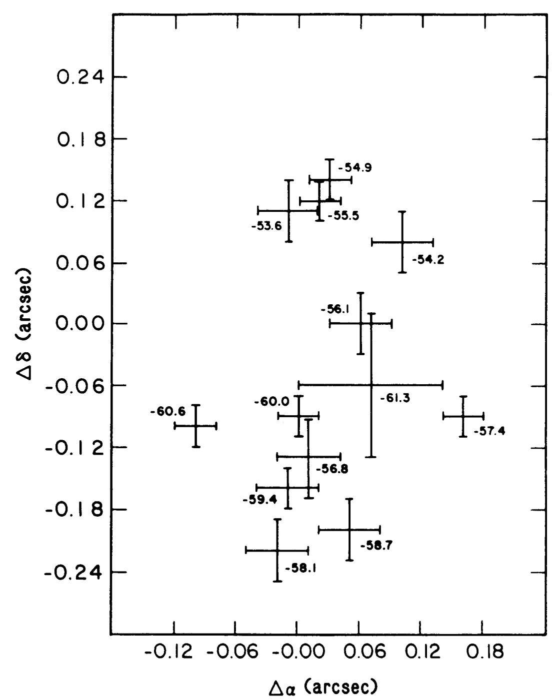

FIG. 3.—The relative position of the spectral features with respect to the continuum emission. Note that the spectral emission is found in two areas separated by about 0″.3. There also appears to be a velocity gradient away from the central continuum source which may indicate an outflow.

of ammonia. With $(HDO)/(H_2O) = 10^{-3}$ (Jacq *et al.* 1988) and $H_2O/H_2 = 10^{-5}$ (Jacq *et al.* 1988), this would imply an H_2 column density of 10^{26} cm^{-2}. This and the line shape of the NH_3 transitions (see Henkel, Wilson, and Johnston 1984) indicates a high degree of clumping within the compact cloud with the masers presumably arising from regions with small velocity gradients. From the line-to-continuum ratio in optically thick transitions, it was deduced that 50% of NGC 7538 IRS 1 was covered by the cloud. Applying a virial analysis, Wilson *et al.* (1983) obtained an H_2 density of $\sim 2 \times 10^7$ cm^{-3}. It is possible that the $^{15}NH_3$ maser lines are emitted from the lower density envelope of a number of clumps which have different velocities and positions. The spatial distribution is shown in Figure 3. Another NH_3 maser, from the (9, 6) lines, has been discovered by Madden *et al.* (1986). This maser has a line width of ≤ 0.5 km s^{-1}, and $V_{LSR} = -60$ km s^{-1}. Presumably this maser arises near our cluster of masers at $V_{LSR} = -60$ km s^{-1} (Fig. 1). The population of the (9, 6) levels are ~ 1000 K above the NH_3 ground state and may be inverted by population of vibrationally excited levels via the absorption of broad-band and IR radiation (Mauersberger, Henkel, and Wilson 1988). The FWHP of the (9, 6) inversion line is <1 km s^{-1}. This implies that the higher excitation NH_3 is located in the southern cluster of NH_3 maser sources in Figure 3.

From our map, the brightness temperature of the continuum emission is estimated to be 6900 K. This may be a lower limit as the size of the emission region was measured with a beam of approximately 1″.2. The 2 cm measurements of Turner and Matthews (1984) and Campbell (1984) show the emission to contain two peaks with sizes of approximately 0″.2. From our data, the emission for the -60 km s^{-1} feature requires an average line optical depth of -0.5. The linewidths appear to be unresolved at a resolution of 0.48 km s^{-1} indicating that the foreground clouds have thermal temperatures of ~ 50 K provided the maser amplification is not large enough to significantly narrow the lines. If the sizes of these clouds are of order $<0''.5$ at a distance of 2.8 kpc this would correspond to a radius of <500 AU and mass of $<2.5 \times 10^{-4}$ $M_\odot$. The virial mass for a region of this size and linewidth 0.5 km s^{-1} is 0.4 $M_\odot$; the Jeans mass for an H_2 density of 10^5 cm^{-3} and kinetic temperature of 100 K is 18 $M_\odot$. Unless these clouds are contained by external pressure, which is unlikely, they will expand on a time scale of 10^4 yr.

There appears to be a gradient in the velocity of the emission going from the central position of the continuum source as determined with a 1″.2 beam at 1.3 cm. Both the ammonia and formaldehyde masers show an increase in radial velocity with more northerly position. The positions of the -60 km s^{-1} feature of H_2CO and -59.9 km s^{-1} of $^{15}NH_3$ are coincident. This may be interpreted as an outflow from a central source (Campbell 1984) or turbulence in a dense region that is the site of active star formation. The line profiles in Figure 2 show that there are probably many individual maser clouds which are in the velocity range -60 to -52 km s^{-1}. The sensitivity of these observations was not adequate to map those features with velocities greater than -53 km s^{-1}. Since the masers map the velocity range of the foreground clouds, we can gain insight into the kinematics of the region surrounding an area of immediate star formation. More detailed and sensitive measurements made with the A configuration of the VLA should yield a more detailed description of this velocity field, indicating whether it is due to organized motion, i.e., and outflow of turbulence.

IV. CONCLUSIONS

The maser emission in the $(J, K) = (3, 3)$ inversion line of $^{15}NH_3$ (3, 3) associated with NGC 7538 IRS 1 has been found to be coincident with the continuum peak and to be found over a north-south extent of $\approx 0''.3$. The brightness temperature of the strongest feature at -60 km s^{-1} exceeds 5200 K, directly confirming that this emission is due to weak maser emission. The $^{15}NH_3$, H_2CO, and OH (1665) emission probably all originate in a common region in front of the H II region. The $^{15}NH_3$ maser emission amplifies the continuum H II region emission. The H II region appears to be optically thick at centimeter wavelengths, and maser emission from these molecules may be a good probe of neutral gas near ultracompact H II regions.

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