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VLA-D OBSERVATIONS OF THE CANDIDATE RARE 23.1 GHZ METHANOL MASER TOWARD NGC 7538 IRS1

Roberto Galván-Madrid, Edgar A. Ramírez-Alonso, Gabriela Montes, and Stan Kurtz

Centro de Radioastronomía y Astrofísica
Universidad Nacional Autónoma de México, Morelia, Michoacán, México

and
Peter Hofner and Esteban Araya

New Mexico Institute of Mining and Technology & NRAO

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RESUMEN

Reportamos observaciones hechas con el VLA de la transición a 23.1 GHz del metanol (CH_3OH) hacia la región de formación de estrellas masivas NGC 7538 IRS1. Nuestro espectro muestra las dos componentes de velocidad (nombradas aquí S por *strong* y W por *weak*) previamente detectadas por Wilson et al. (1984). Obtuvimos límites inferiores para las temperaturas de brillo de $T_{\rm B,S} > 545$ K y $T_{\rm B,W} > 214$ K, y anchos de línea de $\Delta V_{\rm S} = 0.83$ km s^{-1} y $\Delta V_{\rm W} = 1.77$ km s^{-1}. Favorecemos la interpretación de que ambas son maseres, aunque nuestros datos no permiten una conclusión definitiva. Las posiciones de S y W son las mismas y ambas son no resueltas para nuestra resolución angular de $\sim 3''$. La emisión a 23.1 GHz coincide en posición y velocidades con máseres de metanol a 6.7 GHz y 12.2 GHz y con un raro maser de formaldehído (H_2CO) a 4.8 GHz. Por lo tanto, si nuestra detección es confirmada como maser, IRS1 podría ser el único objeto conocido que posea ambos máseres raros. Lo anterior sugiere que las condiciones físicas que producen estas dos poco entendidas transiciones podrían estar relacionadas.

ABSTRACT

We report VLA observations of the 23.1 GHz methanol (CH_3OH) transition toward the massive star forming region NGC 7538 IRS1. Our spectrum shows the two velocity components (labeled here as S and W for strong and weak, respectively) previously reported by Wilson et al. (1984). We obtain lower limits to the brightness temperatures of $T_{\rm B,S} > 545$ K and $T_{\rm B,W} > 214$ K, and linewidths of $\Delta V_{\rm S} = 0.83$ km s^{-1} and $\Delta V_{\rm W} = 1.77$ km s^{-1}. We favor a maser interpretation for both components, although the data do not permit a definitive conclusion. The S and W positions coincide within the uncertainties, and they are unresolved by our $\sim 3''$ beam. The 23.1 GHz emission coincides in position and velocity with 6.7 GHz and 12.2 GHz methanol masers and with a rare 4.8 GHz formaldehyde (H_2CO) maser. Thus, if the maser nature is confirmed, then IRS1 would be the only known object that harbors these two rare masers. This suggests that the physical conditions that give rise to these two poorly understood maser transitions may be related.

Key Words: **H II REGIONS — ISM: INDIVIDUAL (NGC 7538) — ISM: MOLECULES — MASERS — RADIO LINES — STARS:FORMATION**

1. INTRODUCTION

NGC 7538 is a Galactic star forming region located at the edge of the Sharpless 158 HII region, at a distance of about 3 kpc (Blitz et al. 1982). It hosts both ultracompact and hypercompact H II regions (Gaume et al. 1995). The hypercompact region IRS1 was first found in the infrared by Wynn-Williams et al. (1974), and later its free-free emission was clearly resolved at centimeter wavelengths by Campbell (1984), showing that it has a remarkable bipolar structure. IRS1 also presents unusually broad (250 km s^{-1} FWZI) recombination line emission (Gaume et al. 1995).

NGC 7538 IRS 1 is known to be an exceptionally rich maser source. Maser emission has been detected in OH, H_2O, NH_3, CH_3OH, and H_2CO (e.g., Gaume et al. 1991; Minier et al. 1998; Hutawarakorn & Cohen 2003; Hoffman et al. 2003, and references therein). Methanol emission at 23.1 GHz, from the $9_2 - 10_1 A^+$ transition, was reported by Wilson et al. (1984) (hereafter W84), who concluded that the emission was probably maser in nature. Since that time, other methanol masers, most notably the well-known 6.7 GHz and 12.2 GHz masers, have also been detected (Minier et al. 2000). The 23.1 GHz class II methanol maser has proven to be quite rare. At present, only two such masers have been confirmed — W3(OH) and NGC 6334F (W84; Menten & Batrla 1989). Cragg et al. (2004) searched 50 southern star-forming regions and detected 23.1 GHz maser emission in only one, the previously known NGC 6334F.

Formaldehyde (H_2CO) emission at 4.8 GHz from NGC 7538 was first reported by Downes & Wilson (1974). The emission was isolated at the position of IRS1 and confirmed as a maser by Forster et al. (1980). Milliarcsecond resolution observations of the maser were recently reported by Hoffman et al. (2003). The 4.8 GHz formaldehyde maser has also proven to be quite rare; at present, only five have been found in the Galaxy (Araya et al. 2006). Although ammonia is a ubiquitous molecule in massive star forming regions, it is much rarer to encounter masing of ammonia. At present, only five sources are known to mase in ammonia lines — including NGC7538 IRS1 and NGC6334 (see Zhang & Ho 1995, and references therein).

Because the original methanol detection by W84 was never pursued at higher angular resolution, and because of the coincidence in IRS1 of not one but three rare maser species, we chose to undertake a pilot observation of NGC 7538 IRS1 at moderate (3″) angular resolution. In this article we report new observations of the 23.1 GHz methanol emission toward IRS1. In § 2 we describe the observations and the data reduction procedure. We present the results in § 3, a discussion in § 4, and give our conclusions in § 5.

2. OBSERVATIONS

We performed student-time observations of the CH_3OH $9_2 - 10_1 A^+$ transition at 1.3 cm (ν_0 = 23.121024 GHz) toward NGC 7538 IRS1 with NRAO's VLA[1]. We observed for one hour on 2005 December 8. The array was in the D-configuration, providing an angular resolution of $\sim 3''$ at 1.3 cm. The pointing center was α(J2000) = $23^{\rm h}\ 13^{\rm m}\ 46\overset{\rm s}{.}0$, δ(J2000) = $61^\circ\ 28'\ 11\overset{''}{.}0$. Reference pointing was performed to minimize sensitivity losses. On-source integration time was approximately 25 minutes; the remaining time was used in primary, secondary, and bandpass calibration. Table 1 gives the calibrator flux densities.

We used the 1A normal correlator mode, measuring right circular polarization and without on-line Hanning smoothing. A 3.125 MHz bandwidth with 255 channels of 12.207 kHz each provided a spectral resolution of 0.16 km s^{-1} and a velocity coverage of 40 km s^{-1}. The central 75% of the 3.125 MHz bandwidth was recorded as a broad-band, continuum channel.

The data were reduced following standard spectral line procedures with the Astronomical Image Processing System (AIPS) of NRAO. Phase-only self-calibration was performed on the broad-band data and the solutions were passed to the line data. A continuum level of $\simeq$ 300 mJy was subtracted in the *uv* plane. The final image cube was made with a ROBUST parameter of 0, resulting in a synthesized beam of $2\overset{''}{.}98 \times 2\overset{''}{.}35$. The per-channel noise level of the CLEANed image cube was 9 mJy beam^{-1}.

3. RESULTS

3.1. *Sizes and Positions*

Our spectrum shows two velocity components, as originally reported by W84. We denote them by S (for strong) and W (for weak), respectively. Although our D-array resolution of $2\overset{''}{.}98 \times 2\overset{''}{.}35$ is 15 times higher than the $43''$ resolution of W84, the emission remains spatially unresolved (see Fig. 1). We fit a 2-D Gaussian to the peak channel of each spectral component. There was no beam-broadening

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

TABLE 1

CALIBRATION SUMMARY

Calibrator type	Calibrator	Flux density (Jy)
Primary	J0137 + 331	1.08[a]
Secondary	J2322 + 509	0.85 ± 0.01[b]
Bandpass	J0319 + 415	11.0 ± 0.3[b]

[a]Calculated using 1999.2 VLA values.

[b]Bootstrapped flux density.

for the S component and very slight beam broadening for the W component. We adopt one-half the beam size ($1''.5 \times 1''.2$) as an upper limit for the size of both components. The actual source size may be somewhat smaller; limits from the Gaussian fits are given in Table 2.

The spatial positions of the two spectral components coincide within the uncertainty. The 2-D Gaussian fits yield J2000 positions of $\alpha_S = 23^{\rm h}\ 13^{\rm m}\ 45^{\rm s}.37 \pm 0^{\rm s}.02$, $\delta_S = 61^\circ\ 28'\ 10.3'' \pm 0.1''$ and $\alpha_W = 23^{\rm h}\ 13^{\rm m}\ 45^{\rm s}.36 \pm 0^{\rm s}.04$, $\delta_W = 61^\circ\ 28'\ 10.2'' \pm 0.3''$ for the S and W components, respectively.

3.2. *Spectral line parameters*

We fit a two-component Gaussian to the spectrum (see Fig. 2), to obtain the line-center velocities, line-widths, and peak fluxes listed in Table 2. Our results are similar to those of W84; however, they reported S to be wider than W, while we find the opposite. Our velocity resolution of 0.16 km s^{-1} is four times better than their 0.6 km s^{-1}, and our SNR (~ 50 for S and ~ 20 for W) is significantly better, hence we feel that the linewidths reported here are the more accurate ones. We note that our component S linewidth is in agreement with the 1.1 ± 0.5 km s^{-1} reported for this component by Kurtz et al. (2004). Their observations were not sensitive enough to distinguish component W, which they thought to be a plateau of width 7.7 ± 1.5 km s^{-1}.

4. DISCUSSION

4.1. *Nature of the emission*

W84 did not have sufficient angular resolution to place a useful limit on the source brightness temperature. Nevertheless, they argued that the emission was of maser nature, based on absorption in the CH_3OH $10_1 - 9_2\, A^-$ transition. This absorption implied that the excitation temperature of the CH_3OH $9_2 - 10_1\, A^+$ line was greater than the background temperature of at least 10^3 K.

The brightness temperatures we obtain, 545 K

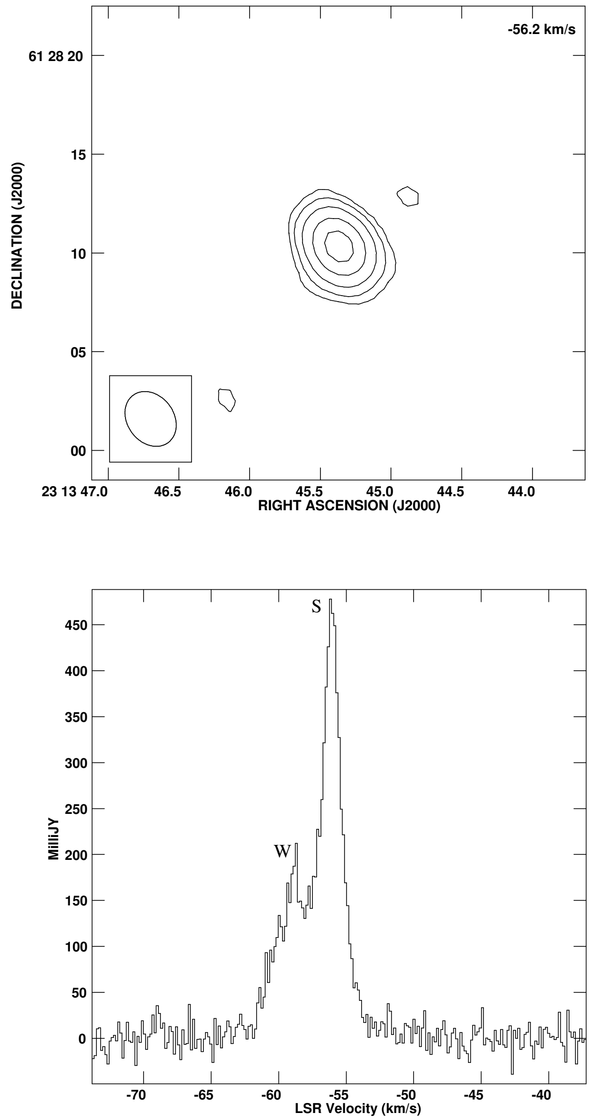

Fig. 1. *Above*: Contour plot of the 23.1 GHz CH_3OH emission toward NGC 7538 IRS1. The emission is unresolved by our $2''.98 \times 2''.35$ D-array beam. Levels are 3, 6, 12, 24 and 40 times 9.6 mJy beam^{-1}, the rms noise of peak channel (-56.2 km s^{-1}). *Below*: 23.1 GHz CH_3OH spectrum toward NGC 7538 IRS1. Two velocity components are clearly seen. We use S to denote the stronger line, while W indicates the weaker feature. Velocities coincide within a few km s^{-1} with those reported for a rare 4.83 GHz formaldehyde maser and 6.7 GHz and 12.2 GHz methanol masers (see Table 3). A continuum level of $\simeq 300$ mJy was subtracted before imaging the line emission.

and 214 K, are not high enough to rule out the possibility of thermal emission. We note, however, that they are conservative estimates. By using the up-

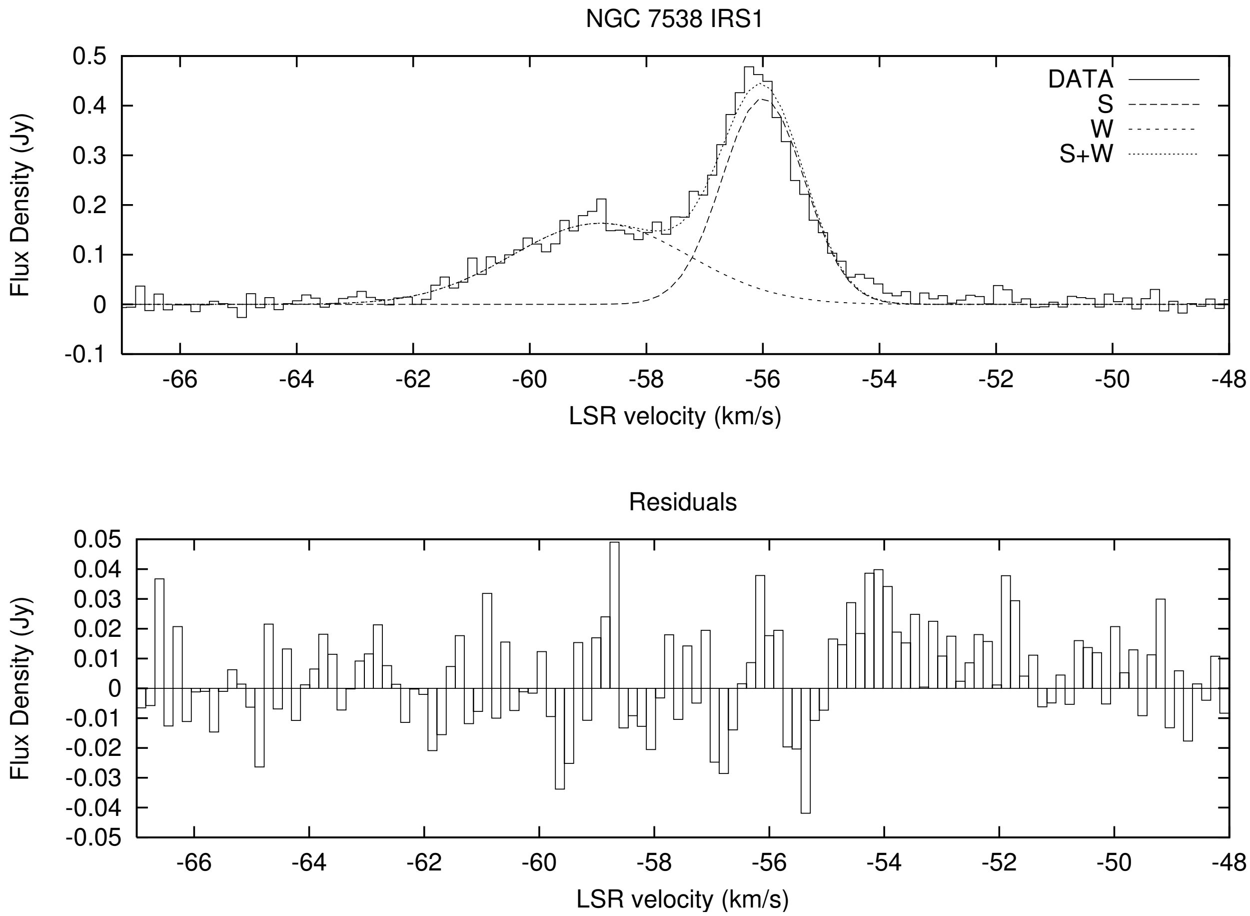

Fig. 2. *Above*: Two-component Gaussian fit of the observed spectrum. S and W are the best-fit functions for the Strong and Weak components respectively. Fitting was done using GNUPLOT 3.7 software.
Below: Velocity distribution of fit residuals, plotted as observed spectrum minus fitting function. The indication of a weak line-wing is seen slightly redshifted from the S centroid, at $\simeq -54$ km s^{-1}.

per limit from the Gaussian fit rather than half the synthesized beamwidth, for example, component S would have $T_{\rm B} \simeq 2800$ K, which would confirm the maser nature of the emission. Hence, we concur with the conclusion of W84 that component S is probably a maser; nevertheless, we reserve final judgment until higher angular resolution data are available.

Thermal linewidths for methanol, corresponding to 545 K and 214 K, are $\Delta V = 0.88$ km s^{-1} and $\Delta V = 0.55$ km s^{-1}. Comparison with the linewidths reported in Table 2 shows that the observed values are consistent with thermal emission at these temperatures. Nevertheless, we consider that these relatively narrow lines are probably indicative of maser emission. In massive star formation regions molecular line widths are typically several kilometers per second. For IRS1, in fact, Pratap et al. (1989) report HCN linewidths of 2–3 km s^{-1}. That the methanol lines are narrower than this suggests they are of maser origin.

The spectrum of component S shows evidence for a weak line wing slightly redshifted from the centroid (see Fig. 2). We do not have the spectral or spatial resolution, however, to discern the nature of the putative wing. A similar weak wing is seen in the $^{15}NH_3$ (3,3) maser spectrum reported by Gaume et al. (1991).

From Table 2, we see that component W is broader, weaker, and probably more extended than S. It may be the case that S is a maser, while W is thermal. Higher resolution observations are needed to confirm this.

4.2. *Comparison with other masers*

Within our positional uncertainty, components S and W coincide spatially (see Fig. 3) and in velocity (see Table 3) with the 6.7 GHz and 12.2 GHz

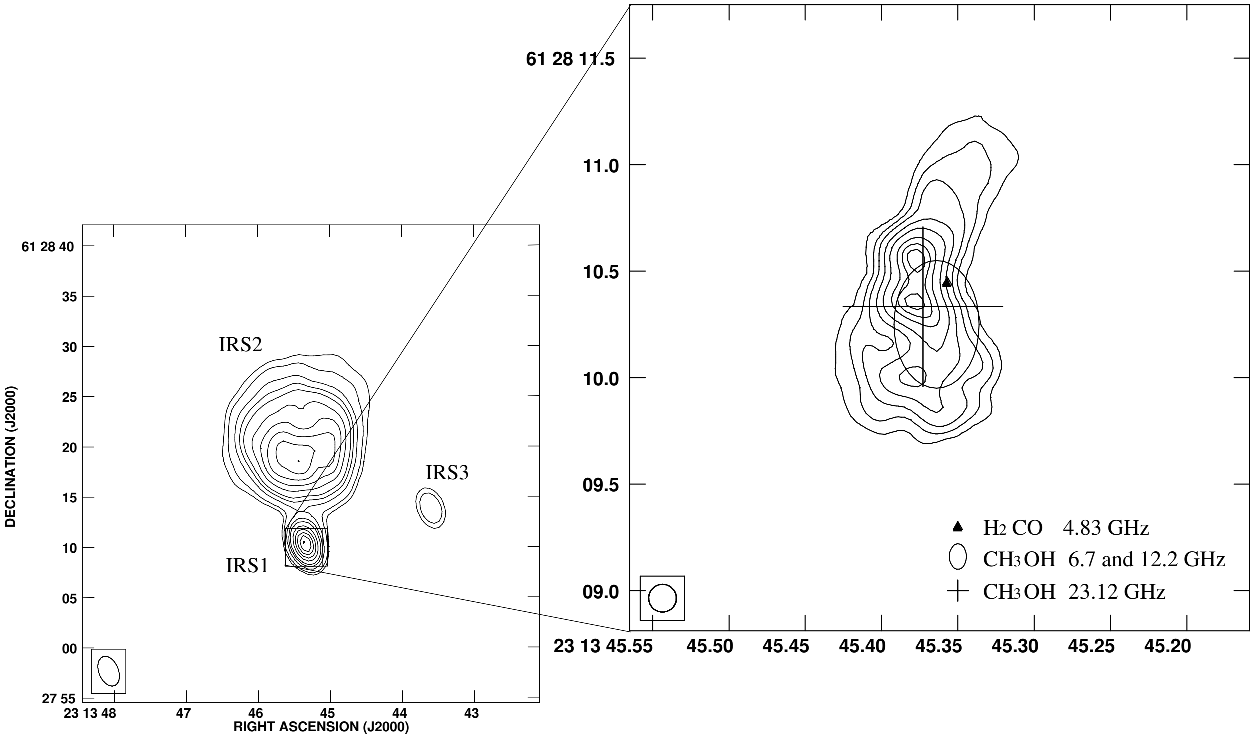

Fig. 3. *Left*: A low resolution 3.6-cm continuum image of NGC 7538. The hypercompact H II region IRS1 is seen immediately south of the ultracompact H II region IRS2. Taken from Sewilo et al. (2004).
Right: Maser positions overlaid on a 2-cm continuum image of the hypercompact H II region IRS1. Taken from Franco-Hernández & Rodríguez (2004). Our detection coincides (the uncertainty cross is one-fourth the beamsize) with the formaldehyde maser position reported by Hoffman et al. (2003). It also coincides with 6.7 GHz and 12.2 GHz methanol masers (Minier et al. 2000); the ellipse represents the region of their many detections (see Fig. 1 of their paper).

methanol masers reported in the literature. The 23.1 GHz emission also coincides spatially with the rare 4.8 GHz formaldehyde (H_2CO) maser reported by Hoffman et al. (2003), although the line velocities are slightly different. Also present within the same region are H_2O, NH_3 and OH masers (for clarity, these are not shown in Figure 3; see, for example, Harvey-Smith & Cohen (2005), Pratap et al. (1992), and Johnston et al. (1989)).

NGC 7538 IRS1 is already an unusual maser source, for the large number of maser species it presents. It is even more special because it is one of the five known Galactic 4.8 GHz formaldehyde maser emitters and one of five known ammonia maser emitters. If the 23.1 GHz emission is also of a maser nature, then IRS1 would be the third confirmed 23.1 GHz maser and the *only* known object with both 4.8 GHz formaldehyde and 23.1 GHz methanol masers.

The pumping mechanism of methanol masers is better understood than that of formaldehyde (Sobolev et al. 1997a, 1997b; Boland & de Jong 1981). Even the former, however, is still poorly understood. For example, the Sobolev et al. (1997a) model predicts 23.1 GHz maser intensities 3 to 7 orders of magnitude lower than for 6.7 GHz masers. However, the known 23.1 GHz masers are rather stronger than this prediction indicates: for W3(OH) and NGC 6334F the ratios are of order 10–100 and ~ 60, respectively (W84; Menten et al. 1992; Menten & Batrla 1989; Norris et al. 1993). For NGC 7538 IRS1, the candidate 23.1 GHz maser is a factor of ~ 500 fainter than the 6.7 GHz maser.

Both the methanol and formaldehyde maser models base the pumping mechanism on background continuum emission (more precisely, for methanol models the pumping arises from warm dust in front of the H II region). Thus, variations in the background continuum should be reflected in the maser intensities. This is the case for IRS1, for which

TABLE 2

SPECTRUM PARAMETERS

	S	W
Peak[a] (mJy)	415 ± 11	163 ± 5
$V_{\rm LSR}$[a] (km s^{-1})	-56.0 ± 0.1	-58.8 ± 0.1
$\Delta V_{\rm FWHM}$[a] (km s^{-1})	0.8 ± 0.1	1.8 ± 0.1
$\theta_{\rm max}$[b] (arcsec)	0.7×0.5	1.5×0.8
$T_{\rm B}$[c] (K)	> 545	> 214

[a]From the 2-component Gaussian fit.

[b]Diameters are upper limits from a 2-D Gaussian fit using the IMFIT task of AIPS.

[c]Assuming a source size of $1''.5 \times 1''.2$; i.e., one-half the synthesized beam.

TABLE 3

MASER VELOCITIES TOWARD NGC 7538 IRS1

Molecule	$V_{\rm LSR,S}$(km s^{-1})	$V_{\rm LSR,W}$(km s^{-1})
CH_3OH (23.1 GHz)[a]	-56.0 ± 0.1	-58.8 ± 0.1
CH_3OH (6.7 GHz)[b]	$\simeq -56$	$\simeq -58$
CH_3OH (12.2 GHz)[b]	$\simeq -56$	not detected
H_2CO (4.8 GHz)[c]	-58.05 ± 0.01	-60.22 ± 0.08
NH_3 (9,6)[d]	not detected	-60.10 ± 0.02
$^{15}NH_3$ (3,3)[d]	-55.9 ± 0.1	-59.8 ± 0.1

[a]This paper

[b]Minier et al. (2000)

[c]Hoffman et al. (2003)

[d]Schilke et al. (1991); see also Gaume et al. (1991)

Franco-Hernández & Rodríguez (2004) report a decrease of 20–30% in the 2 cm continuum emission of the bipolar lobes between 1983 and 1995. They also note two regions of *increasing* emission located at the "waist" of bipolar structure. The western region coincides with the 4.8 GHz H_2CO maser (compare our Figure 3 with Figure 1 of Franco-Hernández & Rodríguez 2004). Hoffman et al. (2003) report a systematic increase in this maser between 1977 and 2001. Comparing our flux densities with those of W84, there seems to be a decrease of $\sim$ 10% in the component S flux density and a decrease of $\sim$ 20% in the W component between 1983 and 2005. We lack the angular resolution to determine if the methanol emission coincides with the decreasing bipolar lobes or the increasing "waist" regions. Instrumental differences and distinct calibration and fitting procedures may contribute to the variations seen in the flux densities. We do not claim a significant correlation, but rather note the trend, which is intriguing.

A detailed consideration of the various maser pumping mechanisms is beyond the scope of this paper. Nevertheless, the discussion above suggests that the very special physical conditions that give rise to the 4.8 GHz H_2CO maser, the ammonia masers, and the 23.1 GHz CH_3OH maser may be related.

5. CONCLUSIONS

Our conclusions may be summarized as follows:

- Our data strongly suggest that component S is a maser, while the nature of W is unclear.
- If the maser nature of component S is confirmed, then NGC 7538 IRS1 would be the third known 23.1 GHz methanol maser, and the only known object with both 23.1 GHz methanol and 4.8 GHz formaldehyde masers.
- The 23.1 GHz methanol emission coincides in position and velocity 4.8 GHz formaldehyde masers and $^{15}NH_3$ (3,3) masers, suggesting that the physical conditions required to pump these rare maser species may be related.

We have requested VLA-B observation time to confirm the maser nature of the emission in NGC 7538 IRS1, and to search for this transition in the known 4.8 GHz H_2CO masers. If the formaldehyde (and ammonia) masers and the 23.1 GHz methanol masers are found to co-exist, then the relation between the two will have to be explored in detail. In particular, important clues concerning the physical conditions that give rise to these two rare maser species may become evident if they are found to co-exist.

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Roberto Galván-Madrid, Edgar André Ramírez-Alonso, Gabriela Montes and Stan Kurtz: Centro de Radioastronomía y Astrofísica, UNAM, Apartado Postal 3-72, (Xangari), 58089 Morelia, Michoacán, México (r.galvan, e.ramirez, g.montes, s.kurtz@astrosmo.unam.mx)

Peter Hofner: Physics Department, New Mexico Institute of of Mining and Technology, 801 Leroy Place, Socorro, NM 87801, & National Radio Astronomy Observatory, P.O. Box 0, Socorro, NM 87801 (phofner@nrao.edu)

Esteban Araya: Physics Department, New Mexico Institute of of Mining and Technology, 801 Leroy Place, Socorro, NM 87801 (earaya@nmt.edu)