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THE W3 IRS 5 CLUSTER: RADIO CONTINUUM AND WATER MASER OBSERVATIONS

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ABSTRACT

High sensitivity and angular resolution observations of the radio continuum toward W3 IRS 5, along with observations of strong water masers, have been made with the VLA. At least seven distinct radio continuum sources have been discovered, which are most likely a cluster of B0.5–B0 stars with ionized stellar winds. This is in contrast to previous interpretations of observational data, which suggested that IRS 5 is a single massive protostar with bolometric luminosity of $2 \times 10^5\ L_\odot$. The spatial distribution of the water masers roughly follows that of the radio sources; and these masers show a gradient in radial velocity similar to that found in a larger scale molecular outflow. We suggest that previously observed, multicomponent absorption in CO infrared transitions traces outflows from the several stellar wind sources, rather than episodic outbursts from a single source.

Subject headings: H II regions — masers — radio continuum: ISM — stars: formation

1. INTRODUCTION

W3 is a well-studied star formation complex in the Perseus arm at a distance of 2.3 kpc (Georgelin & Georgelin 1976), which contains sites in different evolutionary states. The so-called core of the W3 region contains, within an area approximately 2′ (1.3 pc) in diameter, at least 12 radio components (Colley 1980), seven embedded infrared sources (Wynn-Williams, Becklin, & Neugebauer 1972), compact molecular clouds (CO, Claussen et al. 1984; HCN, Wright, Dickel, & Ho 1984; NH_3, Zeng et al. 1984), and both OH and H_2O masers (Forster, Welch, & Wright 1977; Gaume & Mutel 1987; Wynn-Williams, Werner, & Wilson 1974). The radio components are obviously in different stages of evolution, from ultracompact H II regions (W3M associated with IRS 5, W3C associated with IRS 4) to compact H II regions with possible shell structure (W3B/IRS 3), and evolved sources (W3A/IRS 1 and IRS 2).

Detailed results from our comprehensive, high-resolution study of the radio continuum, ammonia, OH and H_2O masers, and high-frequency recombination lines using multifrequency, multiconfiguration observations of the Very Large Array of the NRAO[1] will be presented elsewhere. In this *Letter*, we concentrate on high-resolution radio continuum and H_2O maser emission studies of the very young "protostar" IRS 5. This infrared source has been recognized previously as a candidate high-mass protostar, based on its high luminosity, infrared energy distribution, and relatively weak radio continuum emission. It has total luminosity of more than $2 \times 10^5\ L_\odot$, making it one of the most luminous of this type of object (Ladd et al. 1993, Campbell et al. 1993, Werner et al. 1980). Near-IR measurements of IRS 5 (Howell, McCarthy, & Low 1981; Neugebauer, Becklin, & Mathews 1982) suggests the existence of two peaks separated by 1″, each having similar size and luminosity. Aperture synthesis maps of high-velocity CO ($J = 1 \rightarrow 0$) emission with 7″ resolution (Claussen et al. 1984) show the red and blue line wings separated by about 2″.5. Single-dish millimeter spectroscopy of CO $J = 2 \rightarrow 1$ (Mitchell, Hasegawa, & Schella 1992) demonstrates that a larger bipolar outflow (lobe separation of 30″) is also present with similar orientation as the $J = 1 \rightarrow 0$ aperture synthesis observations. Observations of the CO $J = 3 \rightarrow 2$ line (Choi, Evans, & Jaffe 1993) show the presence of an extremely high velocity flow ($\Delta V_{FWZP} \approx 70$ km s^{-1}). High-resolution (aperture size of 2″.5) infrared spectroscopy reported by Mitchell, Maillard, & Hasegawa (1991) shows blueshifted absorption features in the lines of the fundamental band of CO, which was interpreted as episodic outbursts of mass loss from a single central source similar to an FU Orionis object. Radio continuum emission (W3M; Colley 1980) has been previously detected at 15 GHz at a level of 7 mJy, coincident with the position of IRS 5; such a measurement is difficult to make because of the nearby strong sources W3A and W3B. To discover the radio continuum structure of IRS 5 and to test the single massive protostar model, 0″.15 angular resolution observations of W3 IRS 5, along with 0″.7 resolution observations of the strong water masers near IRS 5 were carried out.

2. DATA

We report here on observations of the radio continuum at 15 and 22 GHz, using a combination of configurations of the VLA. The 15 GHz map presented in Figure 1 was made from data taken only in the A configuration (1989 January). The data were edited and calibrated in the usual manner, using the source 3C 286 as an absolute flux density standard (assuming $S = 3.50$ Jy at 14.9 GHz), and the source 3C 84 as a phase reference. The data represent about 3 hr of on-source time using 27 antennas of the array, and two IF channels, for an

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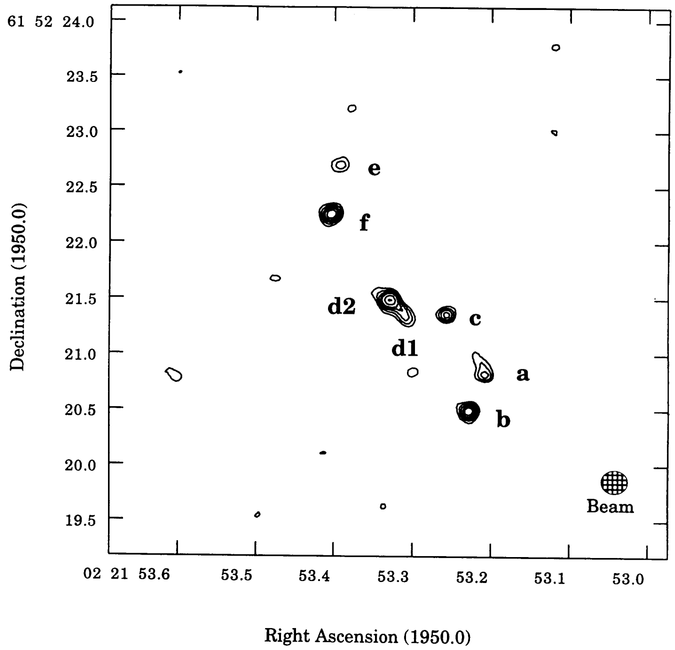

FIG. 1.—Contour map of a 15 GHz image of the W3 IRS 5 region, with a FWHM beam size of 0″.15 × 0″.12, p.a. −83°. The map was made from natural weighting of the *u*,*v* data with a cell size of 0″.03. The seven continuum components discovered in this work are labeled a, b, c, d1, d2, e, and f. The contours are drawn at 200, 300, 400, 500, 600, 800, and 1000 μJy beam^{-1}.

equivalent bandwidth of 100 MHz. This map was made with natural weighting of the visibility data and a cell size of 0″.03. Residual effects of the beam were removed with the CLEAN algorithm. The fitted full width at half-maximum (FWHM) beam is 0″.15 × 0″.12 at a position angle of −83° (measured N of E); the rms noise is 63 μJy beam^{-1}. At least seven distinct radio sources are discernible in this image with signal-to-noise ratios greater than 7. We have designated these sources as W3 IRS 5a–f, in order of increasing right ascension. In Table 1 we give the positions and flux density as determined by fitting two-dimensional Gaussians to the emission.

We observed the W3 region in the radio continuum at 22 GHz, using the B (1989 April) and C (1989 September) configurations of the VLA. Again, the data were edited and calibrated, using the source 3C 48 as an absolute flux density standard (assuming $S = 1.15$ Jy at 22.5 GHz) and the source 3C 84 as a phase reference. Because of low sensitivity, IRS 5 was not detected at 22 GHz in the highest resolution array (B configuration). Thus, we combined the data from the C and B configurations after these were calibrated. The combined data represent about 3 hr of on-source time using 27 antennas of the array, and two IF channels, for an equivalent bandwidth of 100 MHz. A CLEANed map (not shown) of the 22 GHz data was made, using uniform weighting of the visibility data and a cell size of 0″.07. The fitted FWHM beam is 0″.43 × 0″.42, p.a. −40°. The rms noise in this map was 320 μJy beam^{-1}.

We convolved the 15 GHz image to the same resolution as the 22 GHz image in order to identify sources between the two images and to determine radio spectral indices. In the 22 GHz map, we can clearly identify three sources which correspond to sources a and b, c and d, and e and f. Table 2 gives the results of fitting two-dimensional Gaussians to the six sources from the convolved 15 GHz image and to the three identifiable sources in the 22 GHz map. We have estimated the spectral index (given in Table 2) of the three 22 GHz sources by summing the 15 GHz fluxes for each pair (a-b, c-d, and e-f). The indices are all consistent with 0.6, the canonical value for a constant, isothermal, spherical, ionized stellar wind.

Water masers ($6_{16} \rightarrow 5_{23}$) were measured using the C configuration. These were interspersed with the continuum observations to provide better *u*-*v* coverage. We used 127 channels with a spectral resolution of 0.33 km s^{-1} centered at a velocity of −43.5 km s^{-1} with respect to the LSR. Thus our velocity coverage was about ±21 km s^{-1} from the central velocity. The beam size for these observations was 0″.7 by 0″.6; the rms noise in channel maps was about 20 mJy beam^{-1}. Maser features were determined by fitting Gaussian profiles in both spatial position and velocity. Forty-nine distinct features were detected. The positions of the features are displayed in Figure 2 as crosses, overlaid on the full-resolution 15 GHz contour map (with only one contour displayed). The sizes of the crosses correspond to the strength of the masers; velocities of different groups of masers are indicated in the figure. Maser emission was detected from −23.4 km s^{-1} to −56.3 km s^{-1}. The overall distribution of most of the maser spots resembles the distribution of the continuum emission. However, there are at least four spatially distinct groups of masers that are clearly not associated with any continuum emission. The strongest masers seem to be associated with source c, although a strong feature is found in a group almost 2″ directly south of source d.

3. DISCUSSION

We have detected at least seven separate continuum sources in the IRS 5 region. All of the sources have about the same brightness (within a factor 3) and broad-band radio spectrum. Thus it seems reasonable to conclude that the radio sources are all similar kinds of objects, and that a single massive protostar model cannot explain the radio emission. It is possible that some of the ionized regions are not internally heated but are fragments ionized by a wind from IRS 5. The average value of the spectral indices is ~0.6, consistent with an ionized stellar

TABLE 1

W3 IRS 5 POSITIONS AND FLUX DENSITIES

Designation	α(B1950) (1 σ error)	δ(B1950) (1 σ error)	$S_{15\,\mathrm{GHz}}$ (μJy beam^{-1})
a	02^{h}21^{m}53^s.208 (0.014)	61°52′20″.83 (0.1)	520
b	02 21 53.229 (0.014)	61 52 20.50 (0.1)	780
c	02 21 53.258 (0.014)	61 52 21.37 (0.1)	560
d1	02 21 53.309 (0.014)	61 52 21.37 (0.1)	480
d2	02 21 53.331 (0.014)	51 52 21.49 (0.1)	1020
e	02 21 53.394 (0.014)	61 52 22.69 (0.1)	360
f	02 21 53.403 (0.014)	61 52 22.27 (0.1)	720

TABLE 2

IRS 5 Derived Properties

Source	$S_{15\,\mathrm{GHz}}$ (μJy beam^{-1})	$S_{22\,\mathrm{GHz}}$ (μJy beam^{-1})	α_{15}^{22} (error)	N_i (10^{44} photons s^{-1})
a and b	1480	2000	1.07 (0.47)	4.0
c and d	2000	2500	0.56 (0.37)	6.2
e and f	1010	1400	0.80 (0.67)	3.1

wind. However, the errors are rather large, and shock ionization cannot be ruled out. If sources a, b, c, e, and f are clumps ionized by shock waves from source d (the strongest, and "central" source), a J-type shock is required. If this shock had a speed of $\sim$30–50 km s^{-1}, neutral gas clumps would be ionized (e.g., Draine & McKee 1993, and references therein). Near-infrared imaging at high resolution is necessary to definitively answer this question.

If we assume that these radio sources are photoionized and that a single star provides the required Lyman-continuum flux (N_i), we calculate N_i for each pair of sources (Table 2) following the methods of Fey et al. (1992) with $T_e = 10^4$ K. The emission measure from each pair of sources is approximately the same and of order 3×10^7 pc cm^{-6}. Assuming that the spectral index for each individual source is similar to that derived for the pair, each radio continuum source would thus contain a B2–B3 star (Panagia 1973). The infrared luminosity of 2×10^5 $L_\odot$ requires more than 50 B2–B3 main-sequence stars. Since it is unlikely that 50 B2–B3 stars reside in the IRS 5 region, we must look elsewhere for the source of the infrared luminosity.

Our derived spectral indices for the IRS 5 sources are all consistent with the spectral index of an isothermal, homogeneous, constant velocity, spherical, ionized stellar wind. Panagia & Felli (1975), Felli & Panagia (1981), and Wright & Barlow (1975) have derived formulae which describe the ionization of extended envelopes around luminous objects that are losing mass. They show that the Lyman-continuum flux derived from radio observations using the formalism described above may be largely underestimated. If we assume that the radio sources in W3 IRS 5 are such objects, then the Lyman-continuum flux from each of the IRS 5 sources is 6–30 $\times 10^{46}$ photons s^{-1}, which suggests that they have earlier spectral type than given in Table 2—more like B0.5–B0 stars. Thus the total bolometric luminosity for the seven detected radio sources is about 1–2 $\times 10^5$ $L_\odot$, essentially the same as measured by far-infrared and submillimeter observations (Ladd et al. 1993, Campbell et al. 1993).

Our observations show that the position angle made by the radio continuum sources b, d, and f is the same as that of the infrared double. Because the infrared measurements do not have absolute position measurements, we cannot relate our positions with those of the IR double. Since the separations of b and d, or d and f are both about 1″, either pair could correspond to the infrared double. However, since all seven of the detected radio sources are roughly similar in size, flux density, and spectral index between 15 and 22 GHz, it is not clear which pair is a good candidate for identification with the infrared double.

The water masers plotted in Figure 2 show a tendency to follow the distribution of continuum sources, although there are several features that do not overlap with a continuum source. Most of the strongest maser features are found to be near or directly toward a continuum source. This suggests that the masers are excited near the radio continuum sources. Water masers in star-forming regions are quite often found at shocked interfaces between outflows and the surrounding, quiescent molecular cloud. Thus, we suspect that the masers in the W3 IRS 5 region trace the flow from the stellar wind sources where they meet the dense molecular gas. Although the velocities delineated by the water masers show a large scatter, there is a general trend for a gradient from SW to NE across the field. The more blueshifted velocity features are found to the NE, and the more redshifted velocity features are found to the SW. This is roughly the same orientation as found for the molecular outflow by Claussen et al. (1984), Mitchell, Hasegawa, & Schella (1992), and Choi et al. (1993).

The continuum data for IRS 5 sources seem to lead to the conclusion that they are all B0.5–B0 stars undergoing an ionized stellar wind outflow and the water maser data lend support to this picture. The presence of seven B stars in such a small region is unusual, but the total stellar density may be very large in this region. A decision between the scenarios of stars and shocked gas would require near-infrared imaging data. If seven B stars are present, each should be found in the near-IR if the extinction is no larger than 20 mag in the

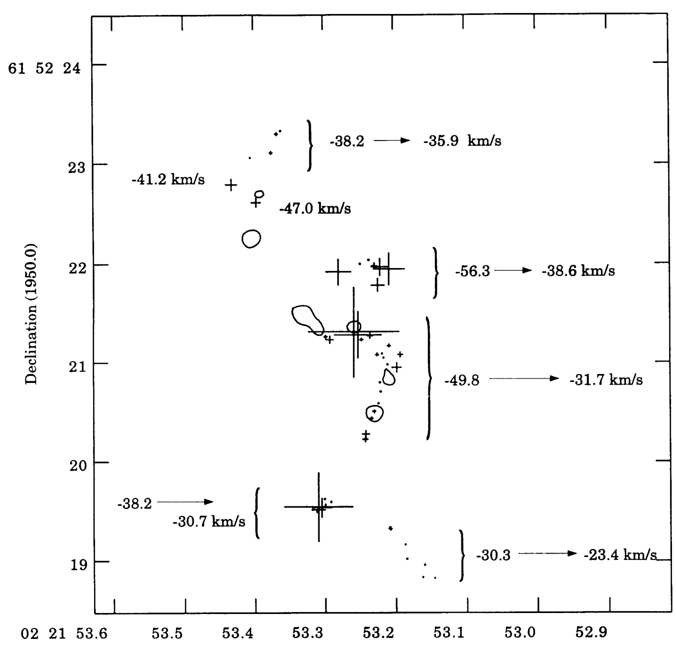

Fig. 2.—Location of water masers as described in the text. Contours are from the full-resolution 15 GHz image and drawn at 300 μJy beam^{-1} to show the location of the continuum sources. The size of each cross gives an indication of the strength of the water maser feature. Groups of water masers are labeled as to their velocity (ranges) with respect to the local standard of rest.

visual. If there is only one outflow region, perhaps source d, then only this source would show up as a near-IR source.

If all the radio sources are B stars, how can more than one star power what seems to be a simple bipolar outflow? The near-IR absorption observations of the fundamental band of CO toward W3 IRS 5 by Mitchell et al. (1991) may well hold the answer. At least three blueshifted absorption features were detected at velocities of 11, 31, and 42 km s^{-1} with respect to the infrared source with an aperture size of 2"5. Mitchell et al. interpret these features as similar to FU Ori–type outbursts in which gas is ejected from the source; we suggest that the absorption features in the near-IR toward IRS 5 are explained not by episodes in the temporal domain, but rather "episodes" in the spatial domain. That is, the absorption features are tracing the stellar wind from the different radio continuum sources in the cluster, with outflows at different velocities, instead of from a single source with episodic outbursts over time. This argument also suggests that collimation of the larger scale bipolar outflow is a result of an interstellar rather than circumstellar-sized confinement. Related evidence for large-scale collimation has been found in other young stellar objects by Mundt, Ray, & Raga (1991). The IR spectroscopy for W3 IRS 5 may well be tracing gas that is channeled from the several stellar winds into the larger scale molecular outflow. Although the angular resolution of millimeter or IR spectroscopy is coarse compared to that in the radio, the IR spectroscopy has perhaps enough resolution to see significant changes if the aperture were placed at several overlapping positions. It might also be useful to search for higher velocity water masers in this region, since high-velocity molecular gas is apparent in both the millimeter and IR spectroscopy.

4. CONCLUSIONS

1. We find seven distinct radio sources in the W3 IRS 5 region in a region 2"5 (8.6×10^{16} cm) in size. All seven sources have similar radio spectra between 15 and 22 GHz, consistent with the expected index of a spherical, constant velocity, ionized wind.

2. The stronger radio sources (b, d, and f) lie along a line whose position angle is coincident with the position angle of the near-IR double as measured by Howell et al. (1981) and Neugebauer et al. (1982). The separation of the radio sources is also similar to that of the IR double.

3. Strong water masers appear in the same general area as the radio continuum sources, but there is not a clustering of water masers directly toward each of the continuum sources. The water masers have a general velocity trend which is in the same directional sense as the molecular outflow toward the region.

4. We interpret the radio continuum sources as being stellar winds from embedded B0.5–B0 stars; the stars are probably part of a forming cluster.

5. Absorption features seen in near-infrared molecular spectra may be tracing outflows toward different stellar wind sources in the cluster.

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