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THE EXCITING SOURCE OF THE BIPOLAR OUTFLOW IN L1448

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ABSTRACT

A fast (± 70 km s^{-1}), highly collimated CO bipolar outflow has been recently detected in the L1448 molecular cloud. No optical or infrared object has been found near the center of the outflow, implying a bolometric luminosity less than 3 $L_\odot$ for the exciting source. With the VLA we detected at 2 cm wavelength a radio continuum source at the center of this outflow. This radio source may be the exciting source of the bipolar outflow. We failed to detect the radio source at 6 cm wavelength, implying that it has a spectral index of $\alpha \geq 1.1$, which may mean it is a partially thick H II region. We also detected at 6 and 2 cm wavelength a double radio continuum source ($\sim 8''$ component separation) that is associated with the source IRS 3, about $1\overset{'}{.}4$ to the north of the outflow center. The spectral index of the main component is $\alpha \simeq 0.2$, similar to that expected for a thermal jet. The second component has a spectral index of $\alpha \simeq 1.0$, consistent with that of a partially thick H II region.

Subject headings: infrared: sources — nebulae: general — radio sources: general — stars: pre–main-sequence

I. INTRODUCTION

The core region of the L1448 cloud appears to be the site of very recent star formation as it is indicated by the presence of a strong ($S_\nu \sim 700$ Jy) H_2O maser and a compact radio continuum source (Anglada *et al.* 1989), three *IRAS* sources, several high-velocity CO outflows (Levreault 1988; Bachiller *et al.* 1990), and an ammonia condensation (Bachiller and Cernicharo 1986; Anglada *et al.* 1989). The radio continuum source, the H_2O maser and one of the *IRAS* sources (IRS 3) coincide in position, within the measurement uncertainties, and are near the peak of the high-density molecular condensation (Anglada *et al.* 1989). Recently, Bachiller *et al.* (1990) observed that the ammonia emission has two components, one of them peaking close to IRS 3 and the other offset to the south. We refer to these two regions as L1448 North (L1448N) and L1448 Center (L1448C), respectively. Bachiller *et al.* (1990) have interpreted the observed high-velocity CO wings in terms of a superposition of two molecular outflows: one having a low degree of collimation in L1448N and excited by IRS 3, and the other having a high degree of collimation in L1448C and excited by an unseen source located $\sim 80''$ south of IRS 3. The proposed position for the exciting source of this highly collimated bipolar outflow does not appear to be associated with any optical or infrared source.

One of the most difficult aspects in the study of the outflow phenomenon is the identification of the powering sources. Several studies have shown that molecular outflows are frequently associated with high-density molecular condensations, and that their exciting sources are commonly embedded in these dense gas cores (Torrelles *et al.* 1985). Therefore, the exciting soures are usually undetectable at optical wavelengths and are found only as IR or radio continuum sources. Radio continuum observations have, in many cases, revealed the presence of embedded compact sources in regions with molecular outflows (e.g., Pravdo *et al.* 1985; and Rodríguez and Curiel 1989). In an attempt to identify the exciting sources of the molecular outflows associated with L1448, we undertook matching-beam observations at 6 and 2 cm wavelength of this region with the Very Large Array (VLA) of the NRAO.[3] We also measured the position of the H_2O maser with the VLA, known to be near IRS 3. We describe the observations in § II, our results and discussion in § III, and our conclusions in § IV.

II. OBSERVATIONS

We observed L1448 at 6 cm (1989 July 26) and 2 cm wavelength (1990 January 26) using the VLA. The 6 cm wavelength observations were made in the C configuration, and the 2 cm wavelength ones were made in the D configuration, so that the angular resolution was $\sim 5''$ for natural weighting at both wavelengths. The observations were made with the phase center at $\alpha = 03^{\mathrm{h}}22^{\mathrm{m}}32\overset{\mathrm{s}}{.}7$; $\delta = 30°34'12''$, a position between L1448N and L1448C, and with a total bandwidth of 100 MHz. The absolute amplitude calibrator was 3C 286 and the phase calibrator was 0336+323 for both wavelengths. The data were edited and calibrated following standard VLA procedures. In Figure 1 we show the 6 and 2 cm wavelength maps made with the task MX of AIPS. We made maps of $9' \times 9'$ (6 cm) and $3' \times 3'$ (2 cm) with natural weighting to identify sources in the field. At 2 cm wavelength we detected three radio sources whose positions, flux densities, and spectral indexes are listed in Table 1.

Using the VLA in the A configuration during 1989 January 30, we observed the 6_{16}–5_{23} transition of H_2O (with a rest frequency of 22235.080 MHz). The spectrum consisted of a single feature at $v_{\mathrm{LSR}} \simeq 3.0$ km s^{-1}. We measured a flux density of ~ 410 Jy, with a velocity resolution of 0.66 km s^{-1}, in the right circular polarization channel. This flux density was significantly smaller than the value of 730 Jy obtained by Anglada *et al.* (1989). There was no other maser source within $\pm 30''$ at a level of 6 Jy ($5\ \sigma$). Using the 37 m radio telescope at the Haystack Observatory[4] during 1990 July 15, we searched for H_2O maser emission from the central region of the highly collimated

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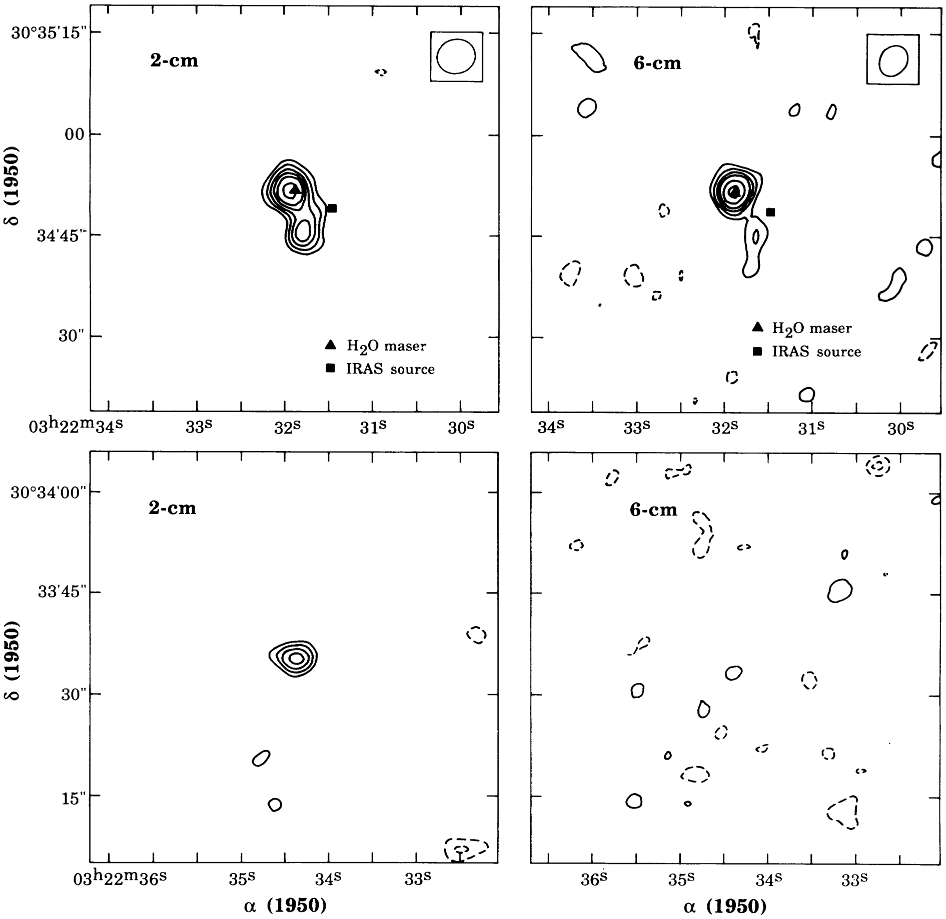

FIG. 1.—VLA maps of the continuum sources in the L1448 region. *Left:* natural-weighted 2 cm wavelength maps (*top*, L1448N; *bottom*, L1448C). Contours are −4, −3, 3, 4, 5, 6, 7, and 9 times 72 μJy beam^{-1}. *Right:* natural-weighted 6 cm wavelength maps. Contours are −4, −3, −2, 2, 3, 4, 5, 7, and 9 times 63 μJy beam^{-1}. The half-power contour of the beams are also shown. The filled triangle and square indicate the position of the H_2O maser and the *IRAS* source IRS 3, respectively. The position of IRS 3 (IRAS 03225+3034) is $\alpha = 03^h22^m31^s.5$, $\delta = 30°34'49''$, and the *IRAS* ellipsoid error is 48″ × 10″ with a position angle PA = 72°. The maser position is $\alpha = 03^h22^m31^s.92 \pm 0^s.01$; $\delta = 30°34'51''.8 \pm 0''.1$. The rms noise levels are 43 and 52 μJy at 6 and 2 cm wavelength, respectively.

molecular outflow. We did not detect new masers at this position or any other position within the area of the CO contours of Figure 2 to a 5 σ upper limit of ~8 Jy.

III. RESULTS AND DISCUSSION

We detected three radio sources in L1448 (Figs. 1 and 2). Two of them are located in the L1448N region, while the other is located in the L1448C region. We discuss these regions separately.

a) L1448C

We detected at 2 cm wavelength a radio continuum source ~82″ south of IRS 3, near the center of the highly collimated molecular outflow detected by Bachiller *et al.* (1990) (see Fig. 2). It seems to be associated with a local maximum of $NH_3(1,1)$ and $NH_3(2,2)$ emission, and does not appear to be associated with any *IRAS* source. The source is unresolved and has a flux density of 0.56 ± 0.05 mJy. We did not detect it at 6 cm wavelength, to a 4 σ upper limit of 0.17 mJy. The spectral index is

TABLE 1

OBSERVATIONS AT 6 AND 2 CENTIMETERS OF L1448

Source Component	α(1950)[a]	δ(1950)[a]	Flux Density[b] 6 cm (mJy)	Flux Density[b] 2 cm (mJy)	Spectral Index
L1448N(B)	$03^h22^m31^s.85$	30°34′45″.0	0.23 ± 0.04[c]	0.67 ± 0.05	1.0 ± 0.2
L1448N(A)	03 22 31.93	30 34 51.0	0.92 ± 0.04	1.15 ± 0.05	0.2 ± 0.1
L1448C	03 22 34.40	30 33 35.0	≤0.17[d]	0.56 ± 0.05	≥1.1

[a] From 2 cm wavelength data. Positional errors are 1″.0.

[b] Integrated flux densities corrected for primary beam response.

[c] Marginal detection (with a peak flux ~5 σ).

[d] 4 σ upper limit.

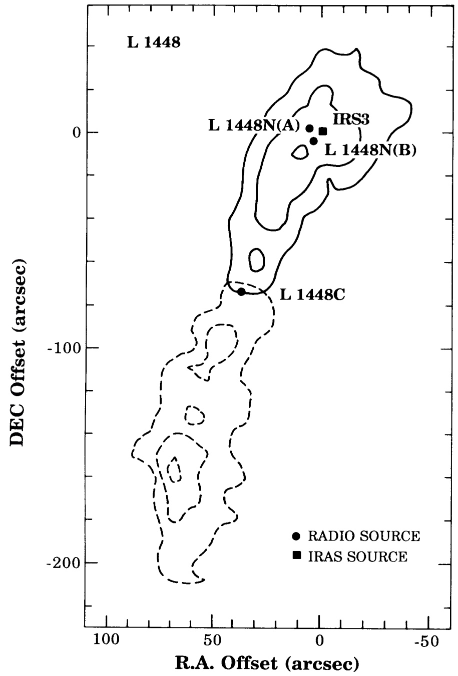

FIG. 2.—Contour map of the redshifted (*solid line*) and blueshifted (*dashed line*) high-velocity CO emission from L1448C, adapted from Bachiller *et al.* (1990). The filled circles indicate the position of the radio continuum sources. The filled square indicates the position of the infrared source IRS 3.

$\alpha \geq 1.1$ ($S_\nu \propto \nu^\alpha$), consistent with that of a partially thick homogeneous H II region. The location and the spectral index of this continuum source suggest that it is associated with the energy source of this highly collimated bipolar outflow. Other energy sources of molecular outflows have been first detected at radio frequencies, e.g., the energy sources of HH 1–2 (Pravdo *et al.* 1985) and NGC 2264G (Rodríguez and Curiel 1989). High-resolution ammonia observations with the VLA and sensitive IR studies are required to confirm that this radio continuum source is exciting the outflow.

The highly collimated bipolar outflow in L1448C is remarkable in that its mechanical luminosity, $L_{\rm mech} \sim 2\ L_\odot$, is comparable with the limit on the bolometric luminosity of the exciting source, $L_{\rm bol} \leq 3\ L_\odot$ (Bachiller *et al.* 1990). Another outflow source with $L_{\rm mech}/L_{\rm bol} \sim 1$, NGC 2264G, has been discussed by Margulis, Lada, and Snell (1988) and Rodríguez and Curiel (1989). Bipolar outflows typically have $L_{\rm mech}/L_{\rm bol} \simeq 10^{-2}$ to 10^{-3} (Rodríguez *et al.* 1982; Lada 1985). In both L1448C and NGC 2264G, the outflows are very fast, highly collimated, and have radio continuum emission associated with the exciting source, which appears to be a heavily obscured, low-luminosity object. The acceleration mechanism of molecular outflows remain unclear, even in the case of typical bipolar outflows. Sources like L1448C and NGC 2264G suggest that the mechanism must be extraordinarily efficient (see discussion below).

b) L1448N

One of the two radio continuum sources associated with this northern region, L1448N(A), is located at the same position given by Anglada *et al.* (1989) from their lower angular resolution 6 cm wavelength map, and is associated with the infrared source IRS 3 and the H_2O maser. This continuum source appears unresolved, is coincident with the maser, and has an integrated flux density of 0.92 ± 0.04 mJy at 6 cm wavelength and 1.15 ± 0.05 mJy at 2 cm wavelength. L1448N(A) has a rising spectrum with $\alpha = 0.2 \pm 0.1$, significantly smaller than the value of 0.6 expected for an isothermal spherical ionized stellar wind. A similar spectral index has been found for the exciting sources of L1551 ($\alpha = 0.0 \pm 0.2$; Rodríguez *et al.* 1989*a*), HH 1–2 ($\alpha = 0.3 \pm 0.1$; Rodríguez *et al.* 1990), and L1489 ($\alpha = 0.3 \pm 0.2$; Rodríguez *et al.* 1989*b*). This value of spectral index has been interpreted in terms of a "confined" thermal jet model as described by Reynolds (1986) (see discussion in Rodríguez *et al.* 1990). The exact nature of these continuum sources remains unclear, but the hypothesis of a thermal confined jet could explain several of the characteristics of the outflow phenomenon. However, it is necessary to make high-angular resolution observations of L1448N(A) to find whether or not this source has a jetlike morphology, as observed in the energy source of the HH 1–2 system. The spectral index of L1448N(A) and its association with IRS 3, the H_2O maser, and a local molecular maximum strongly suggest, as proposed by Anglada *et al.* (1989), that this radio source is associated with the powering source of the weakly collimated molecular outflow in this region.

The second source in this region, L1448N(B), is located 8″ SW of L1448N(A) (see Fig. 1 and Table 1). It is easily seen at 2 cm wavelength and marginally detected at 6 cm wavelength. Its spectral index is $\alpha = 1.0 \pm 0.2$, consistent with that of a partially thick H II region. The total 6 cm wavelength flux density from L1448N(A) and L1448N(B), about 1.2 mJy, agrees with that given by Anglada *et al.* (1989), about 1.3 mJy, derived from a low angular resolution map.

c) Radiative Mechanism of the Radio Sources

Due to the low bolometric luminosity of the region, it is difficult to explain the radio emission observed in these sources in terms of photoionized gas. If we assume that the emission arises from optically thin H II regions at a distance of 300 pc, ionizing flux rates of $N_{\rm UV} \sim 5\text{–}10 \times 10^{42}\ {\rm s}^{-1}$ are required. This ionizing rate can be provided by a B3 ZAMS star with a luminosity of $\sim 10^3\ L_\odot$ (Panagia 1973). However, the bolometric luminosity of the central region is $\leq 3\ L_\odot$ (Bachiller *et al.* 1990), and the IR luminosity of the northern region is about 10 $L_\odot$ (Bachiller and Cernicharo 1986). An alternative ionization mechanism has been proposed by Torrelles *et al.* (1985) and Rodríguez *et al.* (1986). In their model, an exciting star has a strong neutral wind with a mass-loss rate of 10^{-5} to $10^{-7}\ M_\odot\ {\rm yr}^{-1}$ and a velocity of a few hundred km s^{-1} (typical of protostellar objects). The neutral wind creates a shock when it encounters surrounding clumps or perhaps a circumstellar disk, producing enough UV photons to ionize the shocked wind (see Table 2). The thermal radio continuum spectrum produced by a shock wave is very similar to that expected from a photoionized H II region (Curiel, Cantó, and Rodríguez 1987). The opacity and flux density for a shock-ionized region are approximately given by the equations (Curiel *et al.* 1989)

$$\tau_\nu \simeq 4.13\left(\frac{\dot{M}_*}{10^{-7}\ M_\odot\ {\rm yr}^{-1}}\right)\left(\frac{V_*}{100\ {\rm km\ s}^{-1}}\right)^{0.68} \times\left(\frac{R}{10^{-5}\ {\rm pc}}\right)^{-2}\left(\frac{T_e}{10^4\ {\rm K}}\right)^{-0.55}\left(\frac{\nu}{5\ {\rm GHz}}\right)^{-2.1}, \quad (1)$$

$$S_\nu \simeq \Omega\,\frac{R^2}{D^2}\,B_\nu(T_e)(1 - e^{-\tau_\nu})\,, \quad (2)$$

TABLE 2

PARAMETERS OF THE SHOCK EXCITATION MODEL[a]

Source	S(2 cm) (mJy)	τ_ν	$\Omega/4\pi$	$\dot{M}_* V_*^{0.68}$	$\dot{M}_*$ (10^{-7} $M_\odot$ yr^{-1})	L_w ($L_\odot$)	$N_{\rm UV}$[c] (10^{43} s^{-1})	R (10^{-5} pc)
L1448N(B)	0.67	~0.4	1	2.1	1.3	0.4	5.9	1.5
			0.1	21	13	4.2	5.9	4.6
L1448N(A)	1.15	~0.1	1	3.1	1.9	0.6	8.8	3.5
			0.1	31	19	6.2	8.8	11
L1448C[b]	0.56	≥0.4	1	1.7	1.1	0.3	5.0	1.3
			0.1	17	11	3.5	5.0	2.2

[a] Wind speed = 200 km s^{-1}, electron temperature = 10^4, and distance = 300 pc.

[b] Parameters calculated for τ(2 cm) = 0.4.

[c] Ionizing rate calculated from equation given by Torrelles *et al.* 1985.

where $\dot{M}_*$ and V_* are the mass-loss rate and the terminal velocity of the wind, D is the distance to the source, R is the distance to the obstacle, T_e is the electron temperature of the emitting region, B_ν is the Planck function, and the factor $(\Omega/4\pi)$ is the fraction of the stellar wind that is shocked. From the spectrum given by equations (1) and (2) (e.g., $\alpha = 2$ in the optically thick and -0.1 in the optically thin regions), we can deduce the opacity of the sources from the spectral indices under the assumption that they are partially optically thick in the frequency range of the observations. We obtain $\tau(2\ \mathrm{cm}) \geq 0.4$ for L1448C, $\tau(2\ \mathrm{cm}) \sim 0.4$ for L1448N(B), and $\tau(2\ \mathrm{cm}) \sim 0.1$ for L1448N(A). Using the parameters of the sources detected (Table 1) in the equations above, we obtain the parameters of the required stellar wind, which are listed in Table 2. Adopting a wind velocity of 200 km s^{-1}, an electron temperature of 10^4, a filling factor between 0.1 and 1, and a distance of 300 pc, we find that a mass-loss rate between 10^{-7} and 10^{-6} $M_\odot$ yr^{-1} is required to provide the observed rates of ionizing photons. The mechanical luminosity of a wind, $L_w \sim \dot{M}_* V_*^2/2$, with this mass-loss rate and velocity is comparable to the infrared luminosity of IRS 3, the bolometric luminosity of the central region and the mechanical luminosity of the highly collimated bipolar outflow obtained by Bachiller *et al.* (1990), all of which are ~ 1 $L_\odot$. The predicted distance between the star and the obstacle (i.e., the blackbody size) is a few tens of astronomical units (see Table 2), similar to the separation between the two components of the radio continuum source associated with L1551 IRS 5 (Rodríguez *et al.* 1986). This proposed separation might be confirmed by observing these radio sources with high angular resolution, $\sim 0\farcs1$.

IV. CONCLUSIONS

We have detected a 2 cm radio continuum source at the center of the highly collimated molecular outflow in L1448. This radio source, L1448C, has a spectral index consistent with that of an H II region, and appears to be associated with a local maximum of $NH_3(1,1)$ and $NH_3(2,2)$ emission. These characteristics strongly suggest that this radio continuum source is associated with the energy source of this highly collimated bipolar outflow. The bipolar outflow in L1448C is very similar to that in NGC 2264G; both are very fast, highly collimated, have radio continuum emission associated with the exciting source, and have an unusually large ratio of mechanical to bolometric luminosity, $L_{\rm mech}/L_{\rm bol} \sim 1$. The radio continuum source associated with IRS 3 has two components, one associated with IRS 3 and the H_2O maser, L1448N(A), and the other, L1448N(B), located 8″ to the SW of these sources. The spectral index of L1448N(A) and its spatial association with the H_2O maser suggest that this radio source is associated with the source that powers the weakly collimated molecular outflow in this region. The emission from these sources may be generated by shock ionization.

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Note added in proof.—P. André has recently detected the central source of the L1448C outflow at 1 mm.

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