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VLA DETECTION OF THE EXCITING SOURCES OF THE HH 288 AND HHL59 OUTFLOWS

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RESUMEN

Presentamos observaciones hechas con el VLA a 3.6 cm hacia tres campos conteniendo flujos moleculares, incluyendo a la región de HHL59, cuyo flujo molecular en CO se reporta en este artículo. Detectamos candidatos para las fuentes excitadoras de los flujos moleculares en los tres campos observados: L1287, HH 288 y HHL59. La fuente excitadora de L1287 se ha reportado anteriormente, pero aquellas hacia HH 288 y HHL59 se presentan aquí por vez primera. Discutimos los parámetros de estas fuentes, así como su relación con fuentes detectadas a otras longitudes de onda.

ABSTRACT

We present VLA observations at 3.6 cm of three fields containing molecular outflows, including the HHL59 region, whose CO molecular flow is reported here. We detected candidates for the exciting sources of the molecular outflows in the three fields observed: L1287, HH 288, and HHL59. The exciting source of L1287 has been reported previously, but those toward HH 288 and HHL59 are her presented for the first time. We discuss the parameters of these sources, and their relation with sources detected at other wavelengths.

Key Words: **ISM: JETS AND OUTFLOWS — STARS: FORMATION — STARS: MASS LOSS — RADIO CONTINUUM: STARS**

1. INTRODUCTION

Radio continuum emission at centimeter wavelengths is frequently found in association with young stellar objects (YSOs) that power outflows. This emission is, in general, weak and compact and can be angularly resolved only through subarcsecond observations, which typically reveal that the sources are elongated in the direction of the large-scale outflow. This radio continuum emission is believed to have a free-free nature and to trace the origin of the ionized outflow very close ($\leq$ 100 AU) to the star. These compact jets travel through space and at larger physical scales (about 0.1 pc) energize the molecular outflows and the Herbig-Haro objects.

The study of these thermal jets is of importance in our understanding of the star formation process. Usually, the exciting sources of molecular outflows are heavily obscured (e.g., Anglada, Sepúlveda, & Gómez 1997; Sepúlveda 2001) and their detection and study has to be undertaken at wavelengths longer than several microns. In particular, sensitive observations at centimeter wavelengths made with interferometers toward these compact jets provide accurate positions and flux densities for these sources and allow subsequent and more refined studies. Also, while molecular observations of high velocity gas at the 0.1 pc scale trace the time-integrated effect of the outflow over the last 10^2–10^5 years (e.g., Fukui et al. 1993), the subarcsecond observations of the exciting sources in the centimeter radio continuum reveal the presence of ionized gas that has left the star within the last several months or years (e.g., Anglada 1996; Rodríguez 1997).

In this paper we present a search for radio continuum sources, made at 3.6 cm, toward three fields with molecular outflows. Our observations detect candidates for the exciting sources of the outflows in all three fields, two of which are new detections.

In § 2 we describe the observations; in § 3 we comment on each individual field, while in § 4 a brief discussion and our main conclusions are given.

2. OBSERVATIONS

The continuum observations of L1287 and HHL59 were made during 2001 June 17 using the VLA of the NRAO[1] in the CnB configuration. On-source integration times of about 30 minutes were obtained for the observed fields. The absolute amplitude calibrator was 0542+498 (B1950 coordinates), with an adopted flux density of 4.81 Jy. The observations of HH 282 were made during 1996 May 12, with the VLA in the DnC configuration and an on-source integration time of about 35 minutes. The absolute amplitude calibrator was 0134+329 (B1950 coordinates), with an adopted flux density of 3.29 Jy. The names of the regions and the positions of the phase centers observed, as well as the phase calibrators used and their bootstrapped flux densities, are given in Table 1. The observations were made in both circular polarizations with an effective bandwidth of 100 MHz. The data were edited and calibrated following the standard VLA procedures and using the software package AIPS. We made cleaned, natural-weight images of the regions. The rms noise at the center of the fields and the dimensions of the synthesized beam of these maps are given in Table 1. The positions and flux densities of the sources detected are given in Table 2. We considered as detections only those signals above 5-σ. In this table we also give proposed counterparts to some of the centimeter sources.

[1]NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

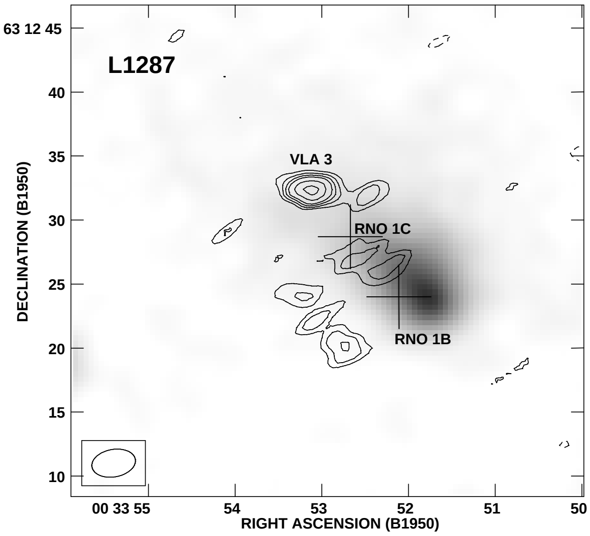

Fig. 1. VLA map of the 3.6 cm continuum emission from the central region of the molecular outflow in L1287, superposed on a greyscale representation of the red image from the second generation Digital Sky Survey. Contour levels are −3, 3, 4, 5, 6, 8, and 10 times 26 μJy beam^{-1}, the rms noise of the image. In this and the following maps the half-power contour of the synthesized beam is shown in the bottom left corner of the map. The positions of RNO 1B and RNO 1C, taken from Staude & Neckel (1991), are indicated with a cross and a label.

3. COMMENTS ON INDIVIDUAL REGIONS

3.1. *L1287*

The Lynds 1287 dark cloud contains, among other objects, the peculiar nebulosity HHL3, also known as PP6 and GM 1-33. One of the two radio sources detected by us corresponds to source VLA 3 in Anglada et al. (1994). For consistency, we refer to this source as L1287 VLA 3. The faint extended component to the south of L1287 VLA 3 is most probably the combination of sources VLA 1, 2, and 4 of Anglada et al. (1994). Part of this southern radio component seems to be associated with the faint near-IR nebulosities RNO 1B and RNO 1C, as can be seen in Figure 1. L1287 VLA 3 is associated with IRAS 00338+6312 and has been proposed by Anglada et al. (1994) as the exciting source of the bipolar molecular outflow in the region; it is discussed extensively by these authors. The flux density measured by us (0.35±0.03 mJy) seems to be smaller than that reported by Anglada et al. (0.49±0.02 mJy) at the same wavelength. However, given the presence of additional emission to the south of the source and that the Anglada et al. (1994) image has a different angular resolution, we cannot conclude confidently that time variability is present.

TABLE 1

REGIONS OBSERVED AT 3.6 cm[a]

Region	Phase Center[b]		Phase	Bootstrapped Flux	rms Noise	Synthesized Beam	
	α(B1950)	δ(B1950)	Calibrator	Density (Jy)	(μJy)	Size (arcsec)	PA (deg)
L1287	00 33 54.0	+63 12 00	0059+581	1.340±0.004	26	3.4×2.2	−80
HH 288	00 34 17.9	+63 47 44	0059+581	1.749±0.002	23	9.2×4.9	+53
HHL59	17 55 30.0	−26 07 00	1748−253	0.273±0.001	28	3.6×2.1	+37

[a]The observations of L1287 and HHL59 were made on 2001 June 17, while those of HH 288 were made on 1996 May 12.

[b]Units of right ascension are hours, minutes, and seconds and units of declination are degrees, arcminutes, and arcseconds.

TABLE 2

SOURCES DETECTED AT 3.6 cm

Region	VLA Source	Position[a]		Flux Density (mJy)	Counterpart	References
		α(B1950)	δ(B1950)			
L1287	3	00 33 53.11	+63 12 32.4	0.35±0.03 [b]	IRAS 00338+6312	1
	5	00 34 09.45	+63 12 54.1	0.34±0.05		
HH 288	1	00 34 14.46	+63 47 52.8	0.12±0.02		
	2	00 34 18.24	+63 47 45.1	0.40±0.03	IRAS 00342+6347,mm	2,3
	3	00 34 19.76	+63 47 21.6	0.38±0.03		
HHL59	1	17 55 26.54	−26 06 45.6	0.34±0.03		
	2	17 55 27.50	−26 06 44.5	0.36±0.04[c]	HHL59, IR	4,5
	3	17 55 34.94	−26 06 12.8	0.20±0.05		

[a]Units of right ascension are hours, minutes, and seconds and units of declination are degrees, arcminutes, and arcseconds.

[b]This compact source has a faint, extended component to the south that is associated with sources VLA 1, 2, and 4 of Anglada et al. (1994).

[c]May be extended or double. It could also form part of a multiple system with VLA 1.

References: (1) Anglada et al. 1994; (2) Gueth et al. 2001; (3) Dent et al. 1998; (4) Gyulbudaghian et al. 1987; (5) Dutra & Bica 2000.

The second radio source detected by us has no reported counterpart in the literature and we tentatively identify it as an extragalactic background source. To continue with the nomenclature of Anglada et al. (1994), we name it L1287 VLA 5.

3.2. *HH 288*

This region contains the spectacular HH 288 bipolar outflow that has been imaged in H_2 (McCaughrean & Dent 2002) and in CO (Gueth, Schilke, & McCaughrean 2001). The source VLA 2 is located at the center of the outflow and coincides within $0\farcs3$ with the position of the 2.6 mm continuum source observed by Gueth et al. (2001). As can be seen in Figure 2, it is also inside the error ellipsoid of IRAS 00342+6347 and we propose that it is associated with the powering source of the outflow. The HH 288 outflow is now believed to be quadrupolar, so images with higher angular resolution may show VLA 2 to be double. The sources VLA 1 and VLA 3 have no counterpart in the literature and we tentatively propose that they are extragalactic background sources.

In Figure 3 we plot the mm and cm spectrum of the central source of the HH 288 outflow. The mm spectrum is well described by the power law $S_\nu \propto \nu^{4.0\pm0.4}$, as expected for dust emission (Beckwith & Sargent 1991). The flux density at 3.6 cm greatly

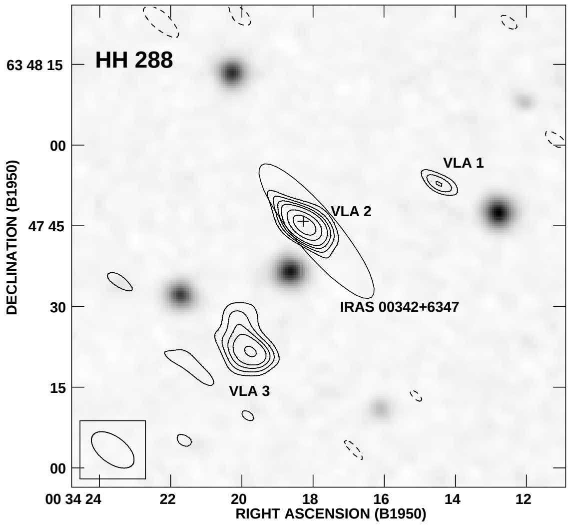

Fig. 2. VLA map of the 3.6 cm continuum emission from the central region of the molecular outflow in HH 288, superposed on a greyscale representation of the red image from the second generation Digital Sky Survey. Contour levels are −3, 3, 4, 5, 6, 8, and 10 times 23 μJy beam^{-1}, the rms noise of the image. The position of the mm source of Gueth et al. (2001) is marked with a cross. The error ellipsoid of IRAS 00342+6347 is also shown.

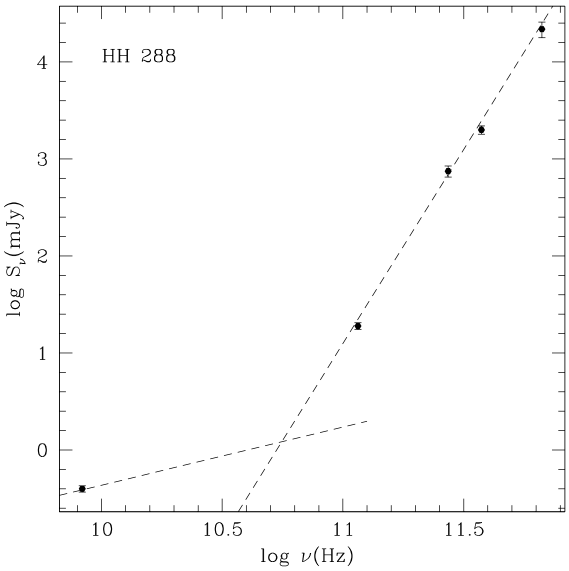

Fig. 3. Centimeter and millimeter spectrum of the central source of the molecular outflow HH 288. The millimeter spectrum is fitted to a power law, $S_\nu \propto \nu^{4.0}$. A power law $S_\nu \propto \nu^{0.6}$ that plotted through the 3.6 cm data point is also shown. Data from Dent et al. (1998), Gueth et al. (2001), and this paper.

exceeds the value extrapolated from this power law, suggesting that it is free-free emission from ionized gas. In Fig. 3 we have also plotted through the 3.6 cm data point the power law $S_\nu \propto \nu^{0.6}$, characteristic of an ionized outflow.

3.3. *HHL59*

This nebulosity, also known as G1–19 (Gyulbudaghian 1983), is located in the Lynds 133 dark cloud (Gyulbudaghian, Rodríguez, & Mendoza-Torres 1987) and has received little attention. It is located in a zone of obscuration (see Figure 4). Torrelles et al. (1984) detected CO emission toward this object at a v_{LSR} of +10.4 km s^{-1}. This radial velocity implies a near/far kinematic distance of 3.5/13.4 kpc. The fact that the cloud is evident in optical images (see Fig. 4) favors the nearer kinematic distance. In addition to HHL59, there are two additional nebulosities in the optical image, to the north and south, that spread over 6′. The southern nebulosity is associated with IRAS 17554–2609.

Our CO observations indicate the presence of a molecular outflow in this region. The observations of the ^{12}CO $J = 1$–0 line emission were carried out with SEST (Swedish-ESO Submillimetre Telescope) at La Silla, Chile, in September 1999. The telescope beam size at 115 GHz is 45″ and the beam efficiency is 0.70. The positions toward HHL59 were observed with a spacing of 40″ in frequency-switched mode, with a frequency throw of 10 MHz.

The telescope was equipped with an SIS detector and a high-resolution acousto-optical spectrometer with 1000 channels and a velocity resolution of 0.112 km s^{-1}. The map with high velocity redshifted and blueshifted CO is shown in Fig. 5.

The observations of high velocity CO toward the inner galaxy are difficult, because there is abundant line-of-sight CO that can be confused with high velocity gas. To be certain of the presence of high velocity CO one needs to search for the characteristic line wings observed in outflowing gas. In Figure 6 we show CO spectra with blueshifted and redshifted emission, taken at the high velocity lobes.

Our sources VLA 1 and 2 are shown in Figure 7. As can be seen in Fig. 5, the CO outflow is centered close to VLA 1 and 2, suggesting that it is powered by one of these two sources. However, since the outflow is better centered with respect to VLA 1, we favor this source as the exciting one. Source VLA 2 seems to have a protuberance to the SE (see Fig. 7) and may turn out to be a double source. However, observations of higher angular resolution are needed to test this possibility. The source VLA 2 coincides within 1″ with the brightest member of a small infrared cluster of stars detected with 2MASS (Du-

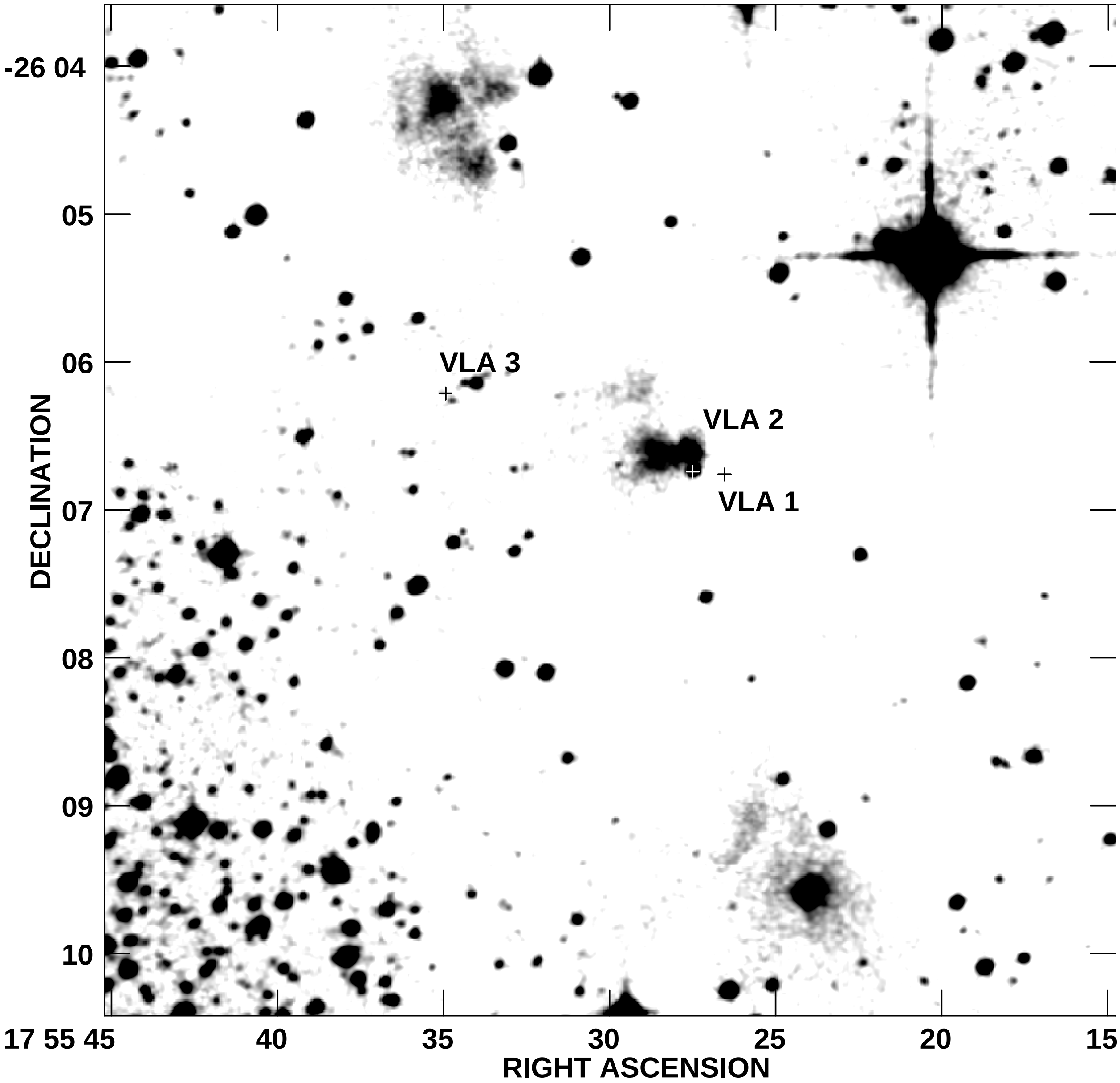

Fig. 4. Positions of the sources VLA 1, 2, and 3 (marked with crosses) in the HHL59 region, superposed on a greyscale representation of the red image from the second generation Digital Sky Survey. HHL59 is the nebulosity to the east of VLA 1 and 2.

tra & Bica 2000). In Figure 8 we show the K-band 2MASS image with the positions of sources VLA 1 and 2. VLA 1 could be associated with a fainter member of the cluster and, as noted above, seems to be better centered with respect to the CO outflow. The nature of the radio emission from VLA 1 and 2 is unclear, but we tentatively propose that it is due to free-free emission from outflowing gas.

Our source VLA 3 has no reported counterpart and we tentatively propose it is an extragalactic background source. However, it seems to be associated with a faint nebulosity (see Fig. 4) and may also be an object embedded in the molecular cloud. These three radio sources are reported here for the first time.

4. DISCUSSION AND CONCLUSIONS

In the three fields mapped, we have detected a total of 8 sources above a 5-σ level, which was typically 0.13 mJy at the center of the field. Using eq. (A11) of Anglada et al. (1998), the expected number of background sources in the four fields is 4 ± 2. Thus,

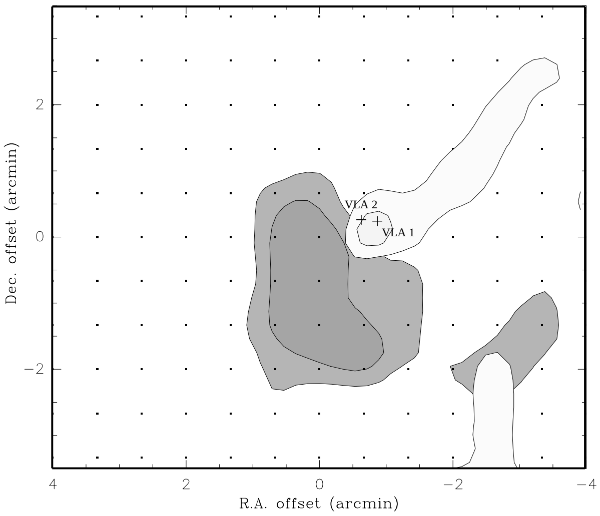

Fig. 5. SEST map of the high velocity ^{12}CO toward the HHL59 region. The center of the map is at $\alpha(1950) = 17^{\rm y}\ 55^{\rm m}\ 30^{\rm s}$; $\delta(1950) = -26^\circ\ 07'\ 00''$. The blueshifted emission (with contours at 10 and 12 K km s^{-1}) is marked by the dark shaded region and was integrated from +6 to +10 km s^{-1}, while the redshifted emission (with contours at 8 and 10 K km s^{-1}) is marked by the light shaded region and was integrated from +12 to +16 km s^{-1}. The positions of VLA 1 and 2 are indicated with large crosses. The small dots indicate the positions observed.

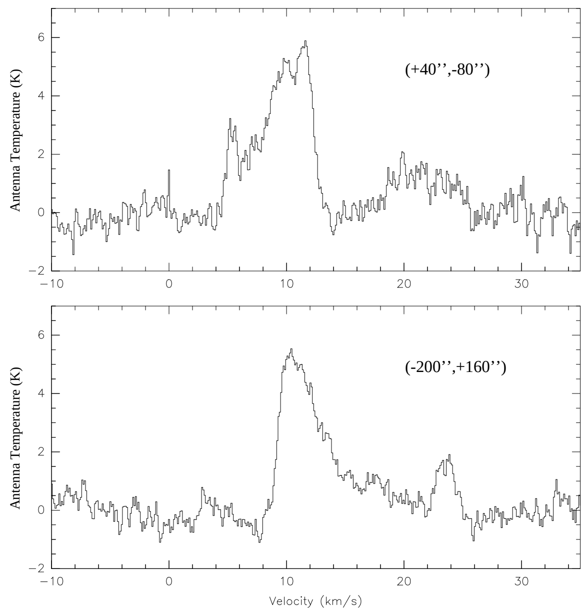

Fig. 6. CO spectra toward the offset position indicated in parenthesis (with respect to $\alpha(1950) = 17^{\rm y}\ 55^{\rm m}\ 30^{\rm s}$, $\delta(1950) = -26^\circ\ 07'\ 00''$), showing blueshifted (top) and redshifted (bottom) wing emission.

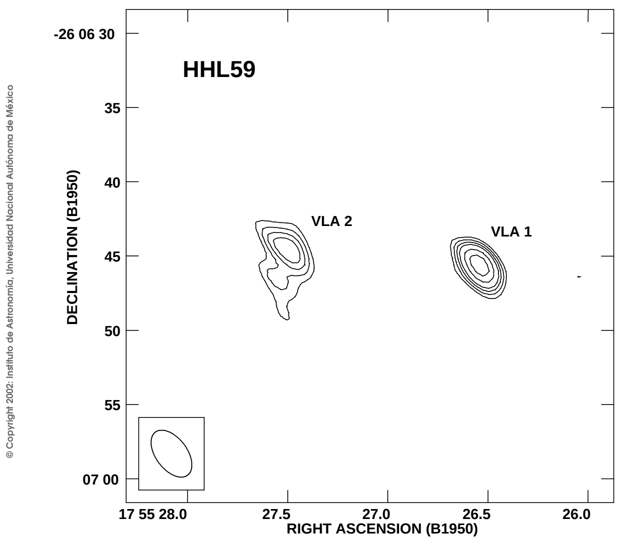

Fig. 7. VLA map of the 3.6 cm continuum emission from the central region of the HHL59 outflow. Contour levels are −3, 3, 4, 5, 6, 8, and 10 times 28 μJy beam^{-1}, the rms noise of the image. Note that VLA 2 appears to be double.

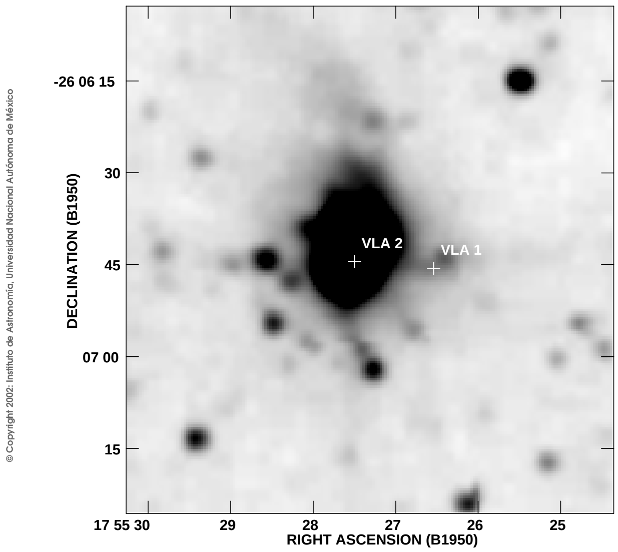

Fig. 8. Position of the sources VLA 1 and 2 (marked with crosses) in the HHL59 region, superposed on a greyscale representation of the 2MASS K-band image. Source VLA 2 coincides with a brightest member of this small infrared cluster (Dutra & Bica 2000).

about one half of the sources are expected to be related to the star-forming regions studied and the other half to be background sources. Indeed, three of the sources detected (L1287 VLA 3, HH288 VLA 2, HHL59 VLA 1) are considered to be candidates to excite their associated outflows.

Future observations with higher sensitivity and higher angular resolution, such as those that could be performed with the Expanded Very Large Array (EVLA), are needed to study the morphology of these sources and to further test their probable nature as thermal jets.

Our main conclusions are:

(1) In HH 228 we detected three sources, of which VLA 2 is associated with IRAS 00342+6347 and with the 2.6 mm continuum source observed by Gueth et al. (2001). This object is most probably related to the exciting source of the molecular outflow. The HH 288 outflow is now believed to be quadrupolar, so images with higher angular resolution may show VLA 2 to be double. Analysis of its cm and mm spectrum indicates that the 3.6 cm emission is dominated by free-free emission.

(2) In HHL59 we present maps of high velocity CO that suggest the presence of a bipolar molecular outflow. The source VLA 1 is found to be located close to the centroid of this outflow and is proposed as its exciting source. VLA 2 coincides within $1''$ with the brightest member of a small infrared cluster of stars detected with 2MASS (Dutra & Bica 2000).

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REFERENCES

Anglada, G. 1996, in ASP Conf. Ser. 93, Radio Emission from the Stars and the Sun, eds. A. R. Taylor & J. M. Paredes (San Francisco: ASP), 3

Anglada, G., Rodríguez, L. F., Girart, J. M., Estalella, R., & Torrelles, J. M. 1994, ApJ, 420, L92

Anglada, G., Sepúlveda, I., & Gómez, J. F. 1997, A&AS, 121, 255

Anglada, G., Villuendas, E., Estalella, R., Beltrán, M. T., Rodríguez, L. F., Torrelles, J. M., & Curiel, S. 1998, AJ, 116, 2953

Beckwith, S. V. W., & Sargent, A. I. 1991, ApJ, 381, 250

Dent, W. R. F., Matthews, H. E., & Ward-Thompson, D. 1998, MNRAS, 301, 1053

Dutra, C. M., & Bica, E. 2000, A&A, 359, L9

Fukui, Y., Iwata, T., Mizuno, A., Bally, J., & Lane, A. P. 1993 in Protostars and Planets III, eds. E. H. Lay & J. I. Lunine, p. 603

Gueth, F., Schilke, P., & McCaughrean, M. J. 2001, A&A, 375, 1018

Gyulbudaghian, A. L. 1983, Sov. Astron. Lett., 8, 123

Gyulbudaghian, A. L., Rodríguez, L. F., & Mendoza-Torres, E. 1987, RevMexAA, 15, 53

McCaughrean, M. J., & Dent, W. R. F. 2002, in preparation

Rodríguez, L. F. 1997, in IAU Symp. 182, Herbig-Haro Flows and the Birth of Stars, eds. B. Reipurth & C. Bertout (Dordrecht: Reidel) 83

Sepúlveda, I. 2001, Ph.D. thesis, University of Barcelona

Staude, H. J., & Neckel, Th. 1991, A&A, 244, L13.

Torrelles, J. M., Rodríguez, L. F., Cantó, J., Marcaide, J., & Gyulbudaghian, A. L. 1984, RevMexAA, 8, 149

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