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VLA DETECTION OF A DOUBLE RADIO SOURCE AT THE CENTER OF THE HH 288 QUADRUPOLAR OUTFLOW

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RESUMEN

Presentamos observaciones de alta resolución angular ($\sim 0\farcs3$) hechas con el VLA a 3.5 cm hacia la región del flujo cuadrupolar HH 288. Observaciones anteriores hechas con el VLA a baja resolución angular ($\sim 7''$) habían revelado la presencia de la fuente VLA 2, la cual es coincidente con la fuente IRAS 00342+6347. Encontramos que VLA 2 es una fuente doble, con separación angular de $\sim 4''$ entre sus componentes. La componente sur (llamada VLA 2a) de esta fuente doble está alargada aproximadamente en la dirección del gran flujo norte-sur de la región. Desafortunadamente, la otra componente (VLA 2b) no está resuelta y no la podemos asociar de manera concluyente con el pequeño flujo este-oeste.

ABSTRACT

We present high angular resolution ($\sim 0\farcs3$) VLA observations at 3.5 cm toward the region of the quadrupolar outflow HH 288. Previous VLA observations made at low angular resolution ($\sim 7''$) had revealed the presence of the source VLA 2, that is associated with the source IRAS 00342+6347. We find that VLA 2 is a double source with an angular separation of $\sim 4''$. The southern component of this double (named VLA 2a) is elongated approximately along the direction of the large north-south outflow in the region. Unfortunately, the other component (VLA 2b) is unresolved and we cannot associate it unambiguously with the small east-west outflow.

Key Words: **ISM: INDIVIDUAL (HH 288) — 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 stellars objects (YSOs) that power outflows. This emission is, in general, weak and compact and can be spatially resolved only through subarcsecond observations, which typically reveal that the sources are elongated in the direction of the large scale outflow. The 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 (e.g., Anglada 1996; Rodríguez 1997). These compact jets travel through space and, at larger physical scales (about 0.1 pc), energize molecular outflows and 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 that several microns. In particular, sensitive observations at cm wavelengths made with interferometers toward these compact jets provide accurate positions and flux densities of these sources and allow future, 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 outflow 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.

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In the last decade several sources have been found to have two outflows apparently emanating from the same region, presenting a quadrupolar morphology, e.g., L723 (Goldsmith et al. 1984; Avery, Hayashi, & White 1990), Cepheus A-HW2 (Torrelles et al. 1993), Cepheus E/IRAS 23011+6126 (Ladd & Hodapp 1997), IRAS 20050+2027 (Bachiller, Fuente, & Tafalla 1995), HH 111 (Cernicharo & Reipurth 1996), HH 288 (Gueth, Schilke, & McCaughrean 2001), IRAS 16293−2422 (Hirano et al. 2001) and IRAS 05358+3543 (Beuther et al. 2002). Various interpretations have been proposed to explain the mechanism that produces such a morphology (Anglada, Rodríguez, & Torrelles 1996; Rodríguez 1997): (1) the four lobes correspond to the limb-brightened walls of the evacuated cavities of a single wide-angle outflow (e.g., Avery et al. 1990); (2) a single outflow is split in two as the result of the interaction with some dense interstellar material located on the flow axis (Mizuno et al. 1990; Torrelles et al. 1993); (3) multiple ejection events in the same protostellar system plus the precession of the flow axis could produce the observed morphology (e.g., Ladd & Hodapp 1997; Narayanan & Walker 1996); and (4) the quadrupolar outflow is really a pair of independent flows that are driven by two protostars in the same region (e.g., Anglada et al. 1991; Walker et al. 1993; Garay et al. 1996). Observations with high angular resolution and sensitivity toward the regions are required to determine the more suitable model.

In this paper we present a sensitive study made at 3.5 cm toward IRAS 00342+6347, the exciting source of the HH 288 quadrupolar outflow, with the purpose of advancing our understanding of the nature of this type of outflow. In § 2 we describe the observations; in § 3 we discuss them, and finally in § 4 our main conclusions are given.

2. OBSERVATIONS

The continuum observations of the HH 288 region were made during 2002 March 3, 9, and 11 using the VLA of the NRAO[2] in the A configuration. A total on-source integration time of about 3 hours was obtained for the observed field. The absolute amplitude calibrator was 1331+305 (J2000 coordinates), with an adopted flux density of 5.13 Jy. The phase calibrator was 0102+584 (J2000 coordinates), with a bootstrapped flux density of 2.41±0.10 Jy (average for the three days observed).

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

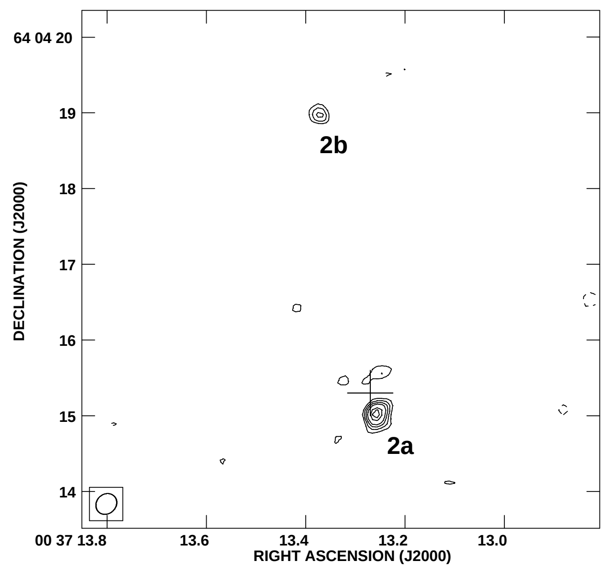

Fig. 1. VLA map of the 3.5 cm continuum emission from the central region of the molecular outflow in HH 288. Contour levels are −3, 3, 4, 5, 6, 8, and 9 times 11 μJy beam^{-1}, the rms noise of the image. The position of the mm source of Gueth et al. (2001) is marked with a cross. The half-power contour of the synthesized beam ($0\farcs29 \times 0\farcs26$; PA = −45°) is shown in the bottom left corner of the map .

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 region. The positions and flux densities of the five sources detected are given in Table 1. We considered as detections only those signals above 5 σ. In this table we also give proposed counterparts to some of the centimeter sources.

3. DISCUSSION

The region observed contains the spectacular HH 288 bipolar outflow that has been imaged in H_2 (see Gueth et al. 2001) and in CO (Gueth et al. 2001). The study of Gueth et al. (2001) clearly indicates that the outflow is quadrupolar with a large north-south outflow and a more compact east-west outflow.

Rodríguez et al. (2002) observed the region with the VLA at 3.5 cm and an angular resolution of $9\farcs2 \times 4\farcs9$; PA = +53°, detecting two sources, VLA 2 and VLA 3, near the central part of their image. The source VLA 2 falls at the center of the outflow and was associated with the powering source or sources of the outflow. Our higher angular resolution ($\sim 0\farcs3$)

TABLE 1

SOURCES DETECTED AT 3.5 CM IN HH 288

VLA Source	Position[a] α(J2000)	Position[a] δ(J2000)	Flux Density (μJy)	Counterpart	References
4	00 37 07.339	+64 04 56.42	126 ± 16		
2a	00 37 13.258	+64 04 15.02	161 ± 13	IRAS 00342+6347-mm	(1)
2b	00 37 13.372	+64 04 18.97	79 ± 13		
3a	00 37 14.627	+64 03 50.95	153 ± 16	H_2 knot	(1)
3b	00 37 14.838	+64 03 57.05	138 ± 16		

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

(1) Gueth et al. 2001

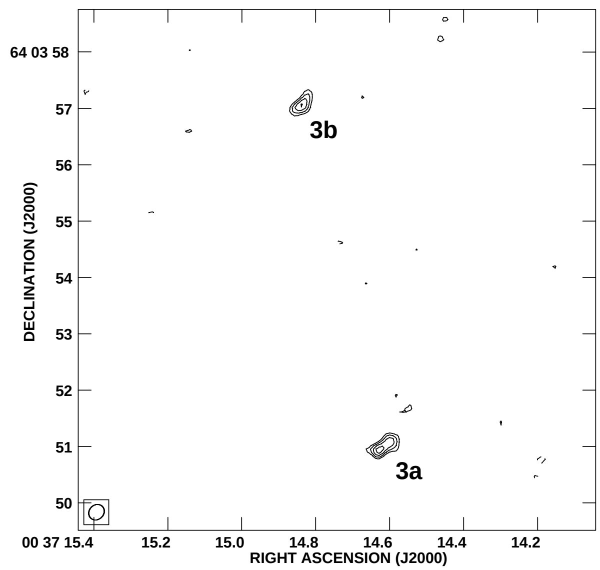

Fig. 2. Map of the 3.5 cm continuum emission of sources VLA 3a and 3b. Contour levels are −3, 3, 4, 5, and 6 times 11 μJy beam^{-1}, the rms noise of the image.

image, shown in Figure 1, indicates that the source is double with an angular separation of $\sim 4''$. Following the nomenclature of Rodríguez et al. (2002) we call these sources VLA 2a and VLA 2b. Both sources are inside the error ellipsoid of IRAS 00342+6347 (see Fig. 3). Source 2a (see Table 1) is the brightest of the two and coincides within $0\farcs5$ with the position of the 2.6 mm continuum source observed by Gueth et al. (2001). Following these authors we propose that 2a is associated with the powering source of the large north-south outflow. Further evidence favoring this hypothesis comes from the fact that VLA 2a has deconvolved dimensions of $0\farcs26 \pm 0\farcs06 \times 0\farcs15 \pm 0\farcs10$; PA $= +171^\circ \pm 32^\circ$. Despite the modest signal-to-noise ratio of the position angle of the major axis of VLA 2a, it is consistent with that of the large north-south outflow. About $0\farcs6$ north of VLA 2a there is a faint region of 3.5 cm emission that may be part of the outflow (see Fig. 1).

Can VLA 2b, the other radio source in the region, be powering the compact east-west outflow? Given the proximity between VLA 2a and VLA 2b this is a feasible suggestion. The CO and H_2 images of the outflow (Gueth et al. 2001) are consistent with independent origins for the outflows as long as these origins are not separated by more than a few arcseconds, about the separation of VLA 2a and 2b. Future studies of this quadrupolar outflow made with higher angular resolution and sensitivity are required to test our suggestion that the east-west outflow may be emanating from, VLA 2b. Also, a deeper VLA image may show that VLA 2b is elongated along the east-west outflow.

About $1'$ to the SE of VLA 2, Rodríguez et al. (2002) detected an additional source, VLA 3. Our observations (Figure 2) show that this is also a double source, with angular separation of $\sim 7''$. What is the nature of this double source? In Figure 3 we show the 2MASS K_s-band image of the region, where it can be seen that the position of VLA 3a coincides within $1''$ with the position of an H_2 knot of the outflow. This spatial coincidence makes us think that this source is probably associated with the outflow. Deeper images of the H_2 emission that show the complete outflow can be seen in Gueth et al. 2001. The source VLA 3b has deconvolved dimensions of $0\farcs43 \pm 0\farcs09 \times 0\farcs18 \pm 0\farcs08$; PA $= +139^\circ \pm 14^\circ$. This orientation and its position along the flow axis are reasons to also associate VLA 3b with the outflow; however, the possibility of an extragalactic source cannot be discarded. A determination of the radio

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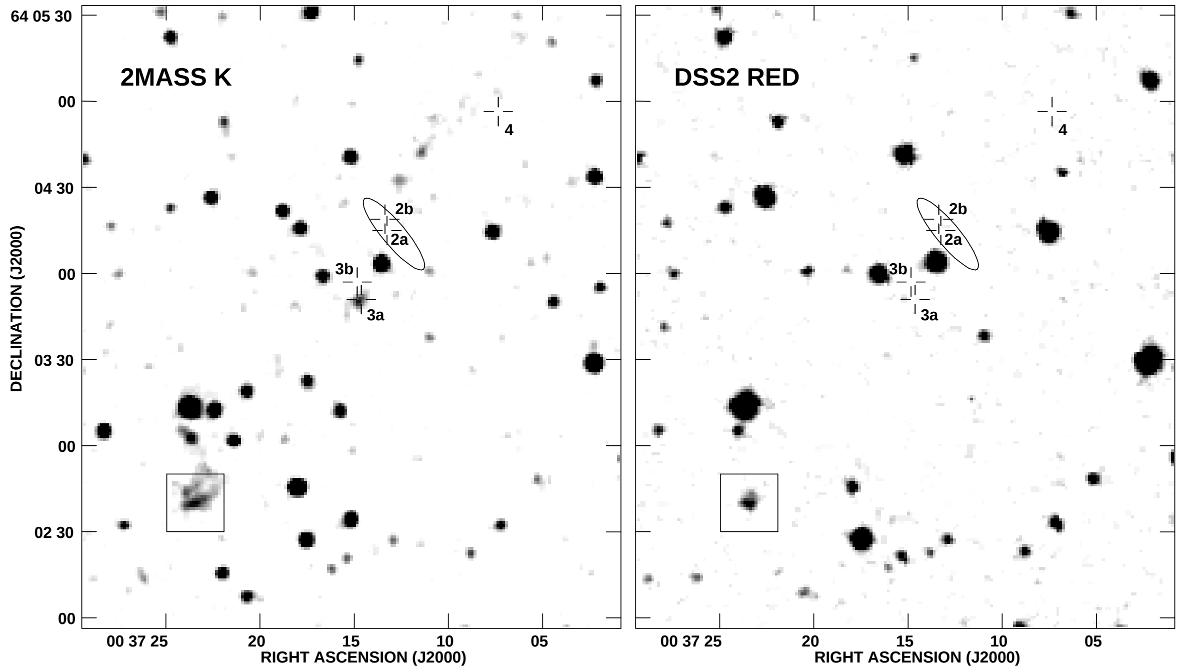

Fig. 3. Greyscale representation of the 2MASS K_s-band image (left) and the red image from the second generation Digital Sky Survey (right) for the HH 288 region. The positions of the sources given in Table 1 are marked with crosses. The error ellipsoid of IRAS 00342+6347 is also shown. The position of the brightest H_2 knot in the outflow is marked with a box.

spectral index is needed for a more definitive classification of these sources. In Fig. 3 we also show the red image from the DSS2, where it can be seen that the brightest H_2 knot in the outflow is detected in the red band.

The source VLA 4 (Fig. 3) has no counterpart in the literature and we tentatively propose it is an extragalactic background source. This is statistically consistent with our results. In the field mapped, we have detected a total of 5 sources above a 5-σ level, which was 55 μJy at the center of the field. Using eq. (A11) of Anglada et al. (1998), the expected number of background sources in the field is 1 ± 1. Thus, most of the sources detected are expected to be related to the star-forming regions studied. However, as noted above, a determination of the radio spectral indices would be very helpful toward the identification of the nature of these sources.

4. CONCLUSIONS

Our high angular resolution imaging of the core of the quadrupolar HH 288 outflow reveals that the source VLA 2 is actually double, formed by components 2a and 2b. Given its elongation in the direction of the north-south outflow, we propose that VLA 2a drives this outflow. Unfortunately, the other component (VLA 2b) is unresolved and we cannot determine its orientation in order to search for a possible association with the small east-west outflow.

Future observations with higher sensitivity are required to test the suggestion that VLA 2a and VLA 2b could be powering, respectively, the north-south and east-west outflows that form the quadrupolar outflow in the region.

Source VLA 3a coincides spatially and could be associated with an H_2 knot in the outflow. The brightest knot in the H_2 outflow is also visible in the red image from the DSS2.

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