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VLA DETECTION OF THE EXCITING SOURCES OF HH 83, HH 117, HH 124, HH 192, HH 300, HH 366, AND HH 375

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RESUMEN

Presentamos observaciones sensitivas hechas con el VLA a 3.6 cm hacia nueve campos conteniendo objetos Herbig-Haro. En 7 de los 9 campos observados hemos detectado fuentes de radio dentro de los elipsoides de error de la fuente *IRAS* que se cree excita el flujo: HH 366 en B5, HH 300 en B18w, HH 192 en L1527, HH 83 en L1641, HH 117 en L1598, HH 124 cerca de NGC 2264 y HH 375 en L1157. Estas fuentes de radio son muy probablemente chorros térmicos producidos por las estrellas excitadoras de la región. En el caso de IRAS 04368+2557 obtuvimos un mapa de mayor resolución angular a 2 cm que revela que la fuente de radio está alargada en la dirección del flujo molecular observado en la región y por lo tanto confirmamos su naturaleza como un chorro térmico. Para dos flujos, HH 376 en L1152 y HH 363 en L1221, no detectamos fuentes de radio que pudiesen estar asociadas con la fuente excitadora. Cuando combinamos estos resultados con otros estudios de similar sensitividad, concluimos que la mayoría de las fuentes de energía de los objetos HH pueden detectarse en observaciones que alcancen un ruido rms de alrededor de 20 μJy.

ABSTRACT

We present sensitive VLA observations at 3.6 cm of nine fields containing Herbig-Haro objects. In 7 out of the 9 observed fields we detect radio sources inside the error ellipsoid of the *IRAS* source that is believed to be exciting the outflow: HH 366 in B5, HH 300 in B18w, HH 192 in L1527, HH 83 in L1641, HH 117 in L1598, HH 124 near NGC 2264 and HH 375 in L1157. These radio sources are quite likely thermal jets produced by the stars that excite the region. In the case of IRAS 04368+2557 we made a map of higher angular resolution at 2 cm that shows that the source is elongated in the direction of the molecular outflow in the region, confirming its nature as a thermal jet. For two flows, HH 376 in L1152 and HH 363 in L1221, we did not detect any radio source coinciding with the infrared driving source. When these results are combined with previous sensitive observations, we conclude that most HH energy sources can be detected at 3.6 cm in surveys reaching rms noise levels of about 20 μJy.

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

1. INTRODUCTION

Perhaps the most remarkable discovery made in the field of star formation in the last two decades is that newborn stars possess powerful collimated outflows. When these supersonic outflows interact with surrounding gas they give rise to regions of shocked gas that in the optical regime are detected as Herbig-Haro objects. Other manifestations of this phenomenon are the molecular outflows in the mm regime and the vibrational-rotational emission of molecular hydrogen in the near-infrared.

In most cases the star responsible for the outflow is still deeply embedded in gas and dust and is undetectable in the optical and near-infrared and some-

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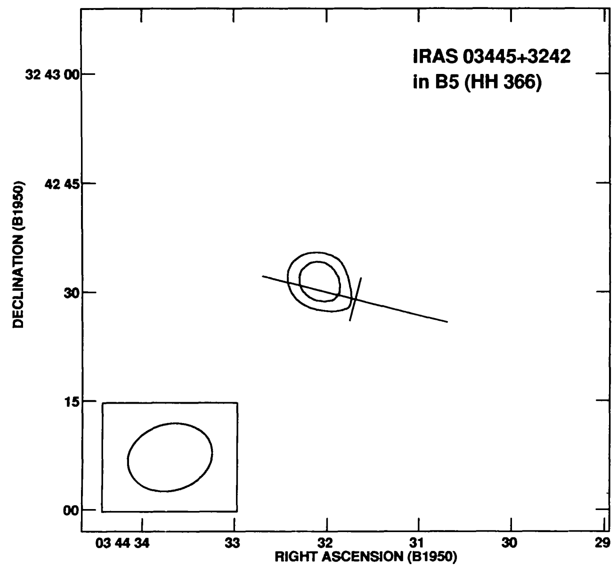

Fig. 1. Natural-weight VLA map at 3.6 cm wavelength of the central region of the HH 366 outflow in B5, a dark cloud in Perseus. The cross marks the position of the IRAS 03445+3242 source. The radio source inside the *IRAS* error ellipsoid is proposed to be associated with the exciting star of the flow. The half power contour of the beam is shown in the bottom left corner. Contour levels are −4, 4, and 5 times the rms noise of 15 μJy beam^{-1}.

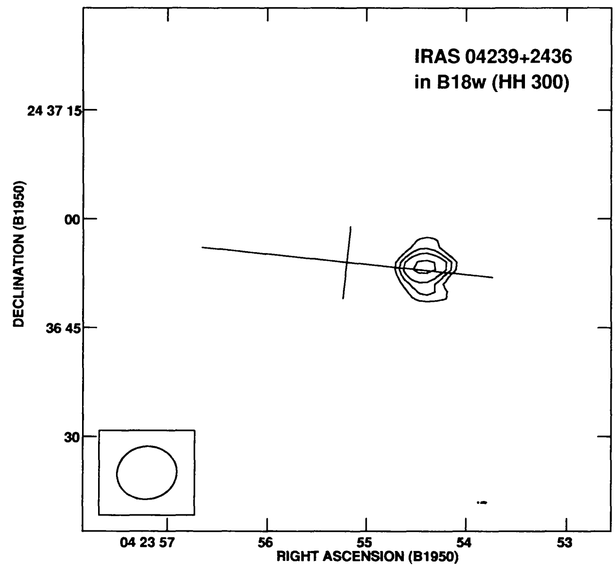

Fig. 2. Same as in Figure 1 for the HH 300 flow region around IRAS 04239+2436 in Taurus. Contour levels are −4, 4, 5, 6, and 8 times the rms noise of 23 μJy beam^{-1}.

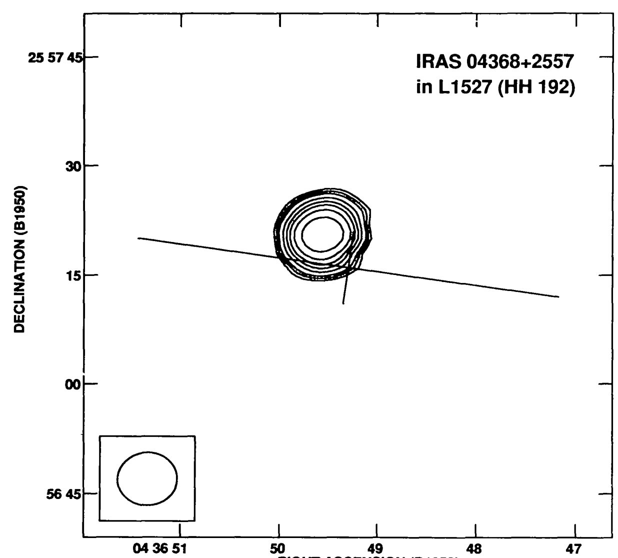

Fig. 3. Same as in Figure 1 for the HH 192 flow around IRAS 04368+2557 in L1527. Contour levels are −4, 4, 5, 6, 8, 10, 12, 15, and 20 times the rms noise of 28 μJy beam^{-1}.

times even at longer wavelengths. Fortunately, it has also become evident that these heavily obscured pre-main sequence objects are frequently sources of free-free centimeter continuum emission at the mJy level. In the best studied case, VLA 1 in the Herbig-Haro 1/2 system, it has been possible to establish that the radio continuum emission which originates in a collimated, partially ionized bipolar jet that is detectable within about one arcsec from the star (Rodríguez et al. 1990). The precise mechanism that ionizes the gas is still being debated, but it is clear that photoionization is not sufficient for the mostly low-luminosity outflow sources. Shock ionization, on the other hand, appears to be a viable process, and it is supported by the existence of a relation between distance-corrected radio continuum fluxes of the driving sources and the momentum rates of their associated outflows (Cabrit & Bertout 1992; Anglada et al. 1992; Anglada 1995).

Using the VLA in the continuum mode it has been possible to detect the exciting source of several outflow systems where other search techniques had failed. With this approach, the exciting sources of HH 1/2 (Pravdo et al. 1985), HH 80/81 (Rodríguez & Reipurth 1989), ρ Oph (André et al. 1990), and L1448 (Curiel et al. 1990), among others, have been detected, providing important information on the parameters of these young stars. Since these radio sources are highly collimated and emit free-free radiation, they are usually called thermal jets. For recent reviews, see Anglada (1995) and Rodríguez (1997).

In a continuing effort to detect and study Herbig-

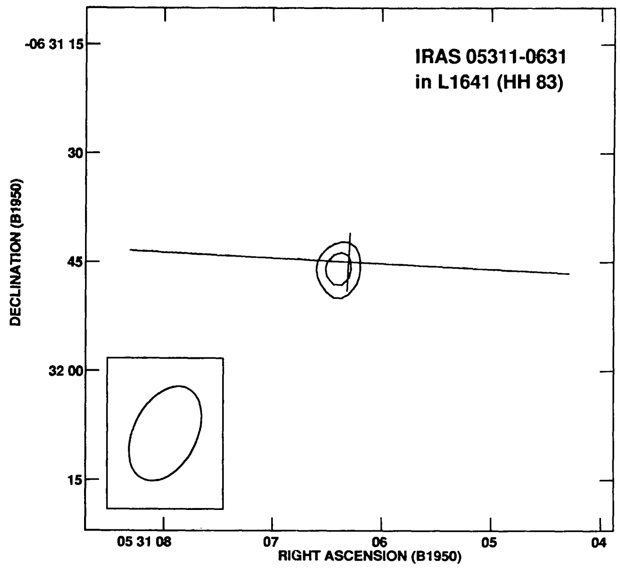

Fig. 4. Same as in Figure 1 for the HH 83 flow region in L1641. The cross marks the position of IRAS 05311-0631. Contour levels are −4, 4, and 5 times the rms noise of 17 μJy beam^{-1}.

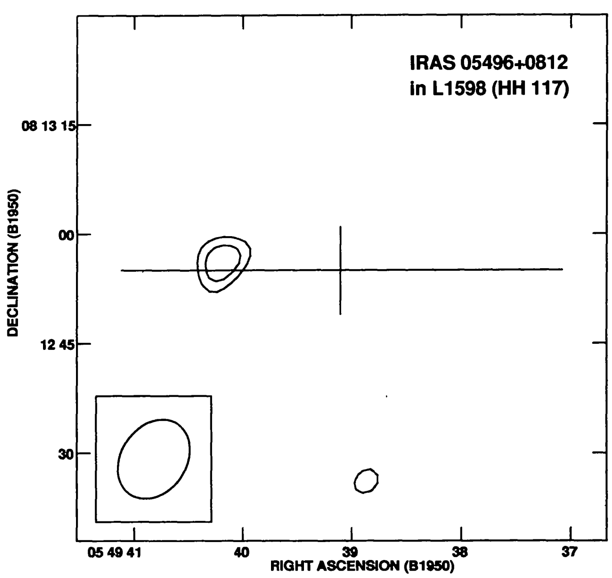

Fig. 5. Same as in Figure 1 for the HH 117 flow in the λ Ori region. The cross marks the position of IRAS 05496+0812. Contour levels are −4, 4, and 5 times the rms noise of 24 μJy beam^{-1}.

Haro energy sources in the radio continuum at centimeter wavelengths, we here report on a study made toward nine regions with Herbig-Haro objects. Previous results of this program were reported in Rodríguez & Reipurth (1989, 1994, 1996).

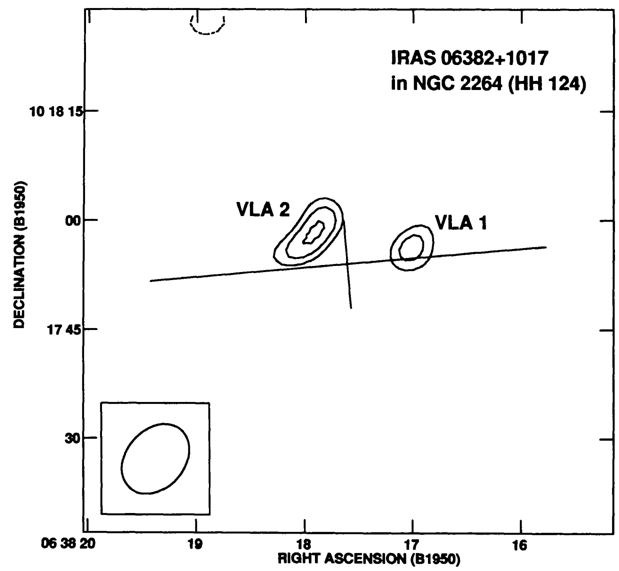

Fig. 6. Same as in Figure 1 for the HH 124 flow in the NGC 2264 region. The cross marks the position of IRAS 06382+1017. Contour levels are −4, 4, 5, and 6 times the rms noise of 24 μJy beam^{-1}. Note that in this object there are two radio sources inside the *IRAS* ellipsoid, VLA 1 is the western and VLA 2 the eastern object.

2. OBSERVATIONS

Sensitive continuum observations of the nine fields containing Herbig-Haro objects were made during 1996 May 12, June 27, and July 30 using the VLA of the NRAO[3] in the C/D and D configurations. On-source integration times of one to two hours were obtained for the observed fields. The absolute amplitude calibrator was 0134+329, and the phase calibrators were 0059+581, 0333+321, 0400+258, 0539-057, 0550+032, 2005+642, and 2229+695. 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 maps of the regions, these maps have typical angular resolution of $\sim 9''$ and rms noise of about 20 μJy and are shown in Figures 1–7. The positions and flux densities of the sources detected are given in Table 1. We considered as detections only those signals above 5-σ. In this Table we also give the name and position of the proposed *IRAS* counterpart. The radio sources without counterparts are most probably background objects.

[3]The National Radio Astronomy Observatory is operated by Associated Universities Inc. under cooperative agreement with the National Science Foundation

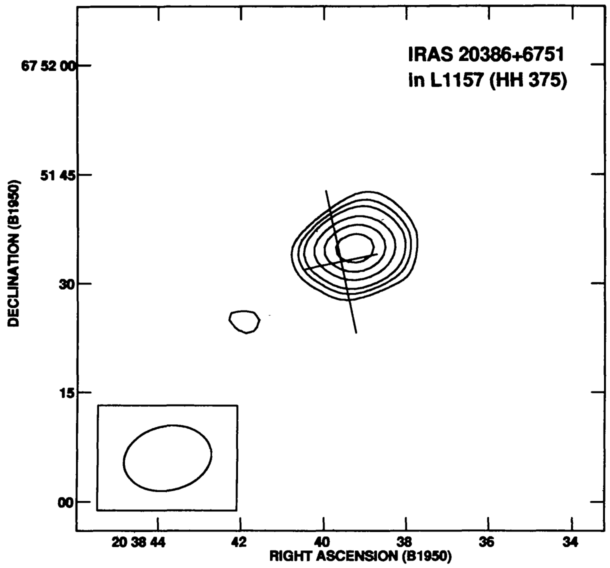

Fig. 7. Same as in Figure 1 for the HH 375 flow in L1157. The cross marks the position of IRAS 20386+6751. Contour levels are −4, 4, 5, 6, 8, 10, and 12 times the rms noise of 20 μJy beam^{-1}.

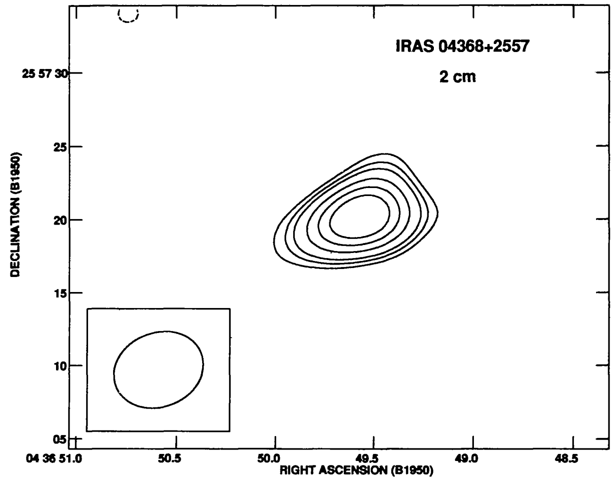

Fig. 8. Natural-weight VLA map at 2 cm wavelength of the exciting source of the HH 192 flow at IRAS 04368+2557 in L1527. This source is elongated along the axis of the molecular outflow studied by Tamura et al. (1996). The half power contour of the beam is shown in the bottom left corner. Contour levels are −4, 4, 5, 6, 8, 10, and 12 times the rms noise of 60 μJy beam^{-1}.

3. THE HH 366 FLOW IN B5

Barnard 5 is a dense cloud core in the direction of Perseus (Langer et al. 1989). It contains a CO outflow studied by Goldsmith, Langer, & Wilson (1986), Fuller et al. (1991) and Langer, Velusamy, & Xie (1996). Recently, Bally, Devine, & Alten (1996) discovered a giant bipolar HH flow co-axial with the CO flow and stretching across 22 arcmin on the sky, corresponding to a projected length of 2.2 pc at the assumed distance of 350 pc. The brighter southwestern lobe is redshifted and the fainter eastern lobe is blueshifted. The source is B5 IRS1 (= IRAS 03445+3242), a 10 $L_\odot$ embedded class I source, associated with a small reflection nebula (e.g., Moore & Emerson 1992). The source has been gradually fading at near-infrared wavelengths (Moore & Emerson 1994). We have detected a faint source with a total flux of 0.11 mJy at 3.6 cm located inside the error ellipse of the *IRAS* source, at a distance of 5 arcsec from the nominal *IRAS* position, and we consider it virtually certain that they are one and the same object.

4. THE HH 300 FLOW IN B18W

Barnard 18 is part of the dense filamentary clouds which are abundant in Taurus. The westernmost cloud core, called B18w, harbors a giant HH flow, HH 300, with a projected extent of 1.2 pc at the assumed distance of 140 pc (Reipurth, Bally, & Devine 1997). It is driven by IRAS 04239+2436, an embedded class I source with the very low luminosity of 1.3 $L_\odot$. Inside the *IRAS* uncertainty ellipse, Myers et al. (1987) detected a near-infrared source, and based on their photometry between 1.2 and 20 μm they suggested that it is obscured by more than 30 magnitudes of visual extinction. Greene & Lada (1996) found that the source has a very rich infrared emission line spectrum. We have detected a radio source of 0.22 mJy at 3.6 cm inside the *IRAS* error ellipse, at a distance of 11 arcseconds from the nominal *IRAS* position and less than 2 arcseconds from the near-infrared source of Myers et al. (1987). With such close positional coincidence, we believe the radio and near- and far-infrared sources are identical.

5. THE HH 192 FLOW IN L1527

The *IRAS* source 04368+2557 is located in L1527, a cloud core in Taurus. The source has a luminosity of about 1.8 $L_\odot$ and is very deeply embedded; in the near-infrared no stellar counterpart is visible, only a faint reflection nebula (e.g., Tamura et al. 1991). It drives a chain of HH objects, HH 192, discovered by Eiroa et al. (1994), and also a molecular outflow (e.g., Tamura et al. 1996). High resolution mm observations provide evidence for an infalling envelope around the source (e.g., Myers et al. 1995, Ohashi et al. 1997). The source appears to be extremely young, by modelling the energy distribution Kenyon, Calvet, & Hartmann (1993) estimate an age of about 4.6×10^3 yr. Sub-mm maps at 800 μm have revealed

TABLE 1

SOURCES DETECTED AT 3.6-CM

HH	Region		α(1950)[a]	δ(1950)[a]	Flux[b] (mJy)	Counterpart	α(1950)[c]	δ(1950)[c]
HH 366	B5	(1)	03 44 32.08	+32 42 31.3	0.11	IRAS 03445+3242	03 44 31.7	+32 42 29
		(2)	03 44 17.97	+32 43 16.0	0.24			
		(3)	03 44 21.11	+32 42 41.0	0.28			
		(4)	03 44 42.94	+32 42 49.1	2.42			
HH 300	B18w	(1)	04 23 54.42	+24 36 53.3	0.22	IRAS 04239+2436	04 23 55.2	+24 36 54
		(2)	04 24 10.82	+24 39 31.9	4.02			
HH 192	L1527	(1)	04 36 49.57	+25 57 20.5	0.81	IRAS 04368+2557	04 36 49.3	+25 57 16
		(2)	04 36 45.14	+25 59 37.7	2.09			
		(3)	04 36 55.59	+25 56 17.9	1.07			
HH 83	L1641	(1)	05 31 06.38	−06 31 46.1	0.12	IRAS 05311−0631	05 31 06.3	−06 31 45
		(2)	05 30 53.82	−06 28 14.5	1.95			
		(3)	05 30 57.62	−06 32 27.7	0.27			
HH 117	L1598	(1)	05 49 40.19	+08 12 56.2	0.14	IRAS 05496+0812	05 49 39.1	+08 12 55
		(2)[d]	05 49 42.70	+08 16 22.2	26.79			
HH 124	N2264	(1)	06 38 17.01	+10 17 56.2	0.18	IRAS 06382+1017	06 38 17.6	+10 17 54
		(2)	06 38 17.91	+10 17 58.3	0.20	IRAS 06382+1017	06 38 17.6	+10 17 54
		(3)	06 38 23.50	+10 17 24.5	0.60			
		(4)	06 38 24.98	+10 18 30.5	0.37			
		(5)	06 38 26.58	+10 17 10.1	0.66			
		(6)	06 38 28.64	+10 14 49.8	15.25			
HH 376	L1152	(1)	20 36 29.10	+67 48 55.6	2.63			
HH 375	L1157	(1)	20 38 39.26	+67 51 34.9	0.26	IRAS 20386+6751	20 38 39.6	+67 51 33
		(2)	20 38 14.14	+67 50 26.8	0.57			
		(3)	20 38 24.32	+67 54 37.1	0.48			
		(4)	20 38 47.68	+67 49 05.2	3.56			
		(5)	20 38 52.21	+67 55 44.5	4.91			
		(6)	20 38 58.92	+67 48 48.3	1.81			
HH 363	L1221	(1)[e]	22 26 21.23	+68 45 17.3	0.51			
		(2)	22 26 25.63	+68 48 05.5	0.63			
		(3)	22 26 25.54	+68 46 17.7	0.28			
		(4)	22 26 41.58	+68 45 18.7	0.21			

[a] VLA position with accuracy of $\sim 1''$.
[b] Total flux density corrected for primary beam response. Typical rms error is ~20 μJy.
[c] Position of *IRAS* counterpart. For reference and positional accuracy see text and figures.
[d] Bright, extended source.
[e] Core of a triple-component source with total flux density of ~ 10 mJy and angular extent of $\sim 1'$.

a fainter companion, about 20 arcseconds or 2800 AU from the source, suggesting that it is a protobinary system (Fuller, Ladd, & Hodapp 1996). We have detected a bright radio source within the *IRAS* uncertainty ellipse, with a separation of 6 arcseconds from the nominal *IRAS* position; with a total flux of 0.81 mJy this is the brightest of the young sources detected in the present paper. We note that we failed to detect at 3.6 cm, at a 4-σ level of 0.11 mJy, the 800 μm source L1527B detected by Fuller et al. (1996).

We did additional 2 cm observations with the VLA in the D configuration during 1996 July 30. A natural weight map of the source is shown in Figure 8. The source appears elongated, and a least-squares fit to a gaussian ellipsoid with the task IMFIT of AIPS gives deconvolved angular dimensions at half maximum of $7\farcs1 \times 2\farcs3 \pm 0\farcs6$ and a position angle for the major axis of $110^\circ \pm 5^\circ$. The major axis of the radio source is then well aligned with the axis of the molecular outflow (Tamura et al. 1996) and is also near perpendicular to the elongated $C^{18}O$ structure studied by Ohashi et al. (1997). The flux density of the radio source at 2 cm is 1.30±0.12 mJy, which combined with the 3.6 cm flux density, give a spectral index of 0.8±0.2, a value typical of thermal jets. We then conclude that the VLA source is a thermal jet that excites the outflow associated with IRAS 04368+2557.

6. THE HH 83 FLOW IN L1641

HH 83 is a fine HH jet emerging from a cavity illuminated by the embedded *IRAS* source 05311−0631 (Reipurth 1989). The source was detected at 1300 μm by Reipurth et al. (1993) and in the near-infrared by Moneti & Reipurth (1995). A poorly collimated molecular outflow has been studied by Bally, Castets, & Duvert (1994) and Nakano et al. (1994). We have detected a faint 3.6 cm source with a total flux of 0.12 mJy, located within a fraction of an arcsecond from the precise infrared position of Moneti & Reipurth (1995).

7. THE HH 117 FLOW IN L1598

HH 117 and HH 118 together form a bipolar HH complex centered on the *IRAS* source 05496+0812, which is located in L1598, a wind-blown cloud that forms part of the λ Ori molecular ring (Reipurth 1994; Reipurth, Bally, & Devine 1998). The HH flow is co-axial with a molecular outflow found by Schwartz, Gee, & Huang (1988). The source was detected at 1300 μm by Reipurth et al. (1993). We have detected a radio source with a total flux of 0.14 mJy at 3.6 cm, located inside the *IRAS* uncertainty ellipse, and with a separation of 16 arcseconds from the nominal *IRAS* position.

8. HH 124 IN THE NGC 2264 REGION

The HH 124 object is an HH jet centered on the *IRAS* source 06382+1017 located in a cometary shaped cloud north of the young cluster NGC 2264 (Walsh, Ogura, & Reipurth 1992). Large field imaging of the region has shown that HH 124 has two distant bow shocks on either side of the *IRAS* source, thus forming a giant HH flow (Ogura 1995). The source was detected at 1300 μm by Reipurth et al. (1993). Near-infrared imaging of the source region was done by Piché, Howard, & Pipher (1995) and by Moneti & Reipurth (1995), who both detected a near-infrared nebula, which in K shows a point-like condensation, assumed to be the same source detected by *IRAS* and at 1300 μm. The positions derived for this K-band source, however, differ by 17 arcseconds in the two studies. Both sets of infrared images show an additional point source about 19 arcsecond to the WSW of the nebulous source (called Star 1 by Moneti & Reipurth), and Piché et al. derived their coordinates assuming that this is identical to KHα 136, a nearby optically visible Hα emission star. This is, however, not certain.

Our 3.6 cm map in Fig. 6 reveals two sources, both within the *IRAS* uncertainty ellipse. They are separated by 13.5 arcseconds, and are about of equal brightness: VLA 1, which is the westernmost object has a total flux of 0.18 mJy, and VLA 2 to the east has 0.20 mJy. Given the present state of uncertainty in the near-infrared coordinates, we are unable to correlate these two VLA sources with near-infrared objects. We do, however, note that the infrared reflection nebula has two nebular condensations, which conceivably could be illuminated by two embedded sources.

The separation of 13.5 arcseconds for the two VLA sources corresponds to a projected separation of 10 800 AU or 0.05 pc at the assumed distance of 800 pc.

9. THE HH 376 FLOW IN L1152

The L1152 cloud contains two embedded *IRAS* sources, of which IRAS 20359+6746 illuminates the bright reflection nebula RNO 124 (Cohen 1980) and drives the giant HH flow HH 376 (Reipurth et al. 1997). Our 3.6 cm map does not reveal any radio source in the region of the *IRAS* source.

10. THE HH 375 FLOW IN L1157

The *IRAS* source 20386+6751 is embedded in the small compact cloud L1157 in Cepheus, and drives a bipolar molecular outflow, which has strong shock induced enhancements of SiO and other species (Umemoto et al. 1992; Mikami et al. 1992) and has been extensively studied (for references, see Gueth, Guilloteau, & Bachiller 1996). Strong infrared H_2 emission was detected by Hodapp (1994) and Davis & Eislöffel (1995), and the southernmost of their H_2 knots was found to coincide with a Herbig-Haro object, HH 375 (Devine, Reipurth, & Bally 1997).

Our 3.6 cm map shows the presence of a relatively bright radio source with a total flux of 0.26 mJy and located inside the (rather small) *IRAS* uncertainty ellipse, only 3 arcseconds from the nominal *IRAS* position.

11. THE HH 363 FLOW IN L1221

The L1221 cloud contains the embedded *IRAS* source 22266+6845, which drives a U-shaped molecular outflow (Umemoto et al. 1991) and the HH object HH 363 (Alten et al. 1997). Our 3.6 cm map does not reveal any radio source in association with the *IRAS* source.

12. CONCLUSIONS

We have presented sensitive VLA observations at 3.6 cm of nine fields with Herbig-Haro objects, and in seven of these we detected a radio source within the error ellipse of the *IRAS* sources suspected of driving the HH flows. This is a detection rate of about 75%, much higher than in our first VLA survey of HH energy sources at 3.6 cm (Rodríguez & Reipurth 1994), which was a much less deep survey. A similarly high detection rate was achieved in our recent survey (Rodríguez & Reipurth 1996), which was as sensitive as the present survey, albeit with fewer objects. With the larger combined sample we can now confidently conclude that *almost all HH energy sources can be detected at 3.6 cm in surveys reaching rms noise levels of about 20 μJy.* We interpret the radio emission as evidence for small thermal jets closely associated with the driving sources. Our VLA positions are typically an order of magnitude more accurate than previous *IRAS* positions, and the presence of free-free emission strongly suggests that the radio objects mark the position of the exciting star of the flow. These studies will be followed, in the case of the brighter sources, by high angular resolution radio observations that will provide information on the accurate position of the source, its morphology, and the physical scale at which collimation is already present.

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