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VLA DETECTION OF THE EXCITING SOURCES OF HH 34, HH 114, AND HH 199

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RESUMEN

Presentamos observaciones sensitivas hechas con el VLA hacia cuatro campos conteniendo objetos Herbig-Haro: HH 34, HH 114, HH 199 y HH 212. En todos los campos, excepto el último, hemos detectado fuentes de radio que probablemente están asociadas con las fuentes excitadoras de, la región. En el caso de HH 34, la detección de una contraparte de radio apoya la idea de que las estrellas jóvenes que están produciendo flujos HH generalmente emiten en el radiocontinuo a niveles detectables con integraciones moderadamente largas (unas horas) hechas con el VLA. En el campo de HH 114, detectamos fuentes independientes asociadas tanto con la fuente *IRAS* como con una fuente milimétrica en la región. Nuestras observaciones no pueden favorecer de manera conclusiva a una de estas fuentes como el objeto excitador dominante del campo. Finalmente, en HH 199 detectamos una fuente, asociada con la fuente *IRAS* de la región, que podría ser un chorro térmico o bien una binaria de radio sin resolver.

ABSTRACT

We present sensitive VLA observations at 3.6-cm of four Herbig-Haro fields: HH 34, HH 114, HH 199, and HH 212. In all fields but the last we detect radio sources that are probably associated with the exciting source of the region. In the case of HH 34, our detection of a radio counterpart supports the notion that newborn stars which are actively producing HH flows generally emit in the cm radio continuum at levels that are detectable with a moderately long (a few hours) integration made with the VLA. In the HH 114 field, we detect independent sources associated with both an *IRAS* source and a millimeter object in the region. Our present observations cannot favor either of the sources as the dominant exciting object in the region. Finally, in HH 199 we detect a source that could be a thermal jet or an unresolved radio binary and that is associated with the *IRAS* source in the field.

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

1. INTRODUCTION

Newborn stars are known to 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 sometimes even at longer wavelengths. Fortunately, it has also become evident that these heavily obscured pre-main sequence objects are frequently sources of 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 originates in a collimated, partially ionized bipolar outflow that is detectable within about one arcsec from the star (Rodríguez et al. 1990). The precise mechanism producing this emission 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).

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. For a recent review, see Anglada (1995).

In a continuing effort to detect and study Herbig-Haro energy sources in the radio continuum at centimeter wavelengths, we here report on the radio detection for the first time of the driving sources of the HH 34, HH 114 and HH 199 flows. Previous results were reported in Rodríguez & Reipurth (1989, 1994).

2. OBSERVATIONS

Sensitive continuum observations of the four fields containing the Herbig-Haro objects were made during 1994 November 17 using the VLA of the NRAO[1] in the C configuration. On-source integration times of one to two hours were obtained for the HH fields. The absolute amplitude calibrator was 1328+307, and the phase calibrators were 0529+075, 0539–057, and 2007+777. 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 $\sim 3''$. The positions and flux densities of the sources detected are given in Table 1. In this table we also give the name and position of proposed counterparts at other wavelengths. The radio sources without counterparts are most probably background objects.

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

3. THE HH 34 ENERGY SOURCE

The Herbig-Haro object HH 34 was discovered by Guillermo Haro, according to the notes in the HH catalogue by Herbig (1974). In a later CCD imaging study of the region, a perfectly collimated HH jet was discovered, pointing directly towards HH 34, and it was realized that HH 34 is a working surface for this jet (Reipurth 1985; Reipurth et al. 1986). Subsequently, Bührke, Mundt, & Ray (1988) found a fainter counter-bow shock, HH 34-North, thus showing that the complex is a bipolar HH flow. A proper motion analysis of the complex shows the two bow shocks to move away from each other, both with velocities around 300 km s^{-1} (Heathcote & Reipurth 1992). Further studies revealed that HH 34 is only one of several bow shocks in the blue lobe (Reipurth & Heathcote 1992) and recently Bally & Devine (1994) found that the whole complex encompasses several other nearby HH objects (HH 33/40, HH 85, HH 86/87/88), thus stretching over an amazing almost 3 pc.

The driving source of this giant jet complex is a faint optically visible star, which is unusual, since most HH sources, specially those driving highly collimated jets, are normally deeply embedded objects. The source is a rich emission-line star (Reipurth et al. 1986), and based on its *IRAS* emission Cohen & Schwartz (1987) estimate a luminosity of 45 $L_\odot$. Employing 1.3-mm continuum observations, Reipurth et al. (1993a) found the star to be surrounded by a large amount of cold dust. Recently, Stapelfeldt & Scoville (1993) have mapped a ^{13}CO structure of $\sim$ 3000 AU in size elongated perpendicularly to the jet axis. This posible circumstellar disk appears to be inside a cavity of 0.1 pc in size (Anglada et al. 1995), which in turn is located inside a cold high density ammonia core of 0.4 pc in size (Anglada et al. 1989; 1995). In addition, Rudolph & Welch (1992) and Davis & Dent (1993) have found a peak of HCO^+ emission towards the position of this star. A weak CO outflow has been detected in HH 34 by Chernin & Masson (1995).

TABLE 1

SOURCES DETECTED AT 3.6-cm

Region		$\alpha(1950)^a$	$\delta(1950)^a$	Flux[b] (mJy)	Counterpart	$\alpha(1950)^c$	$\delta(1950)^c$
HH 114	(1)	05 15 33.22	+07 08 55.6	0.13	HH 114 MMS	05 15 33.45	+07 08 52.9
	(2)	05 15 35.24	+07 07 52.6	0.25	IRAS 05155+0707	05 15 35.1	+07 07 54
	(3)	05 15 35.68	+07 05 33.4	2.68	...	...	...
HH 34	(1)	05 33 03.63	−06 28 50.0	0.16	HH 34 Source	05 33 03.59	−06 28 50.5
HH 212	(1)	05 41 11.67	−00 59 17.3	24.00	...	...	...
HH 199	(1)	20 58 13.61	+77 24 02.2	0.15	IRAS 20582+7724	20 58 14.5	+77 24 05
	(2)	20 58 25.22	+77 21 46.4	1.55	...	...	...

[a] VLA position with accuracy of ∼ 0.″5.
[b] Total flux density corrected for primary beam response.
[c] Position of counterpart. For reference and positional accuracy see text and figures.

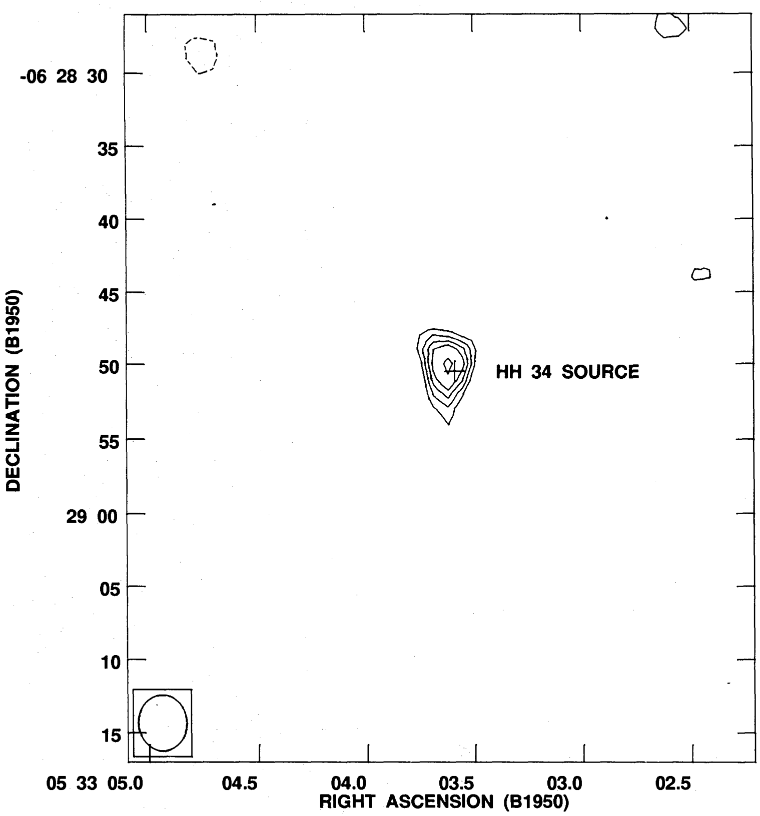

Fig. 1. Natural-weight VLA map at 3.6-cm wavelength of the exciting source of the HH 34 outflow. The cross marks the optical position of the source (Heathcote & Reipurth 1992). The half power contour of the beam is shown in the bottom left corner. Contour levels are −4, −3, 3, 4, 5, 6, and 8 times the rms noise of 15 μJy beam^{-1}.

Many of the sources of the finest jets have been detected in the radio continuum at centimeter wavelengths, such as HH 111 (Rodríguez & Reipurth 1994), a twin jet that as HH 34 is located in the Orion region, HH 47 (Curiel & Wilner 1996), HH 150 from HL Tau and HH 152 from XZ Tau (Brown, Mundt, & Drake 1985; Rodríguez et al. 1992; 1994), HH 1/2 (Pravdo et al. 1985; Rodríguez et al. 1990), and HH 243 (= RNO 43) (Anglada et al. 1992), among others. It was therefore a surprise when Rodríguez & Reipurth (1994) failed to detect the energy source of HH 34 in their 3.6-cm and 2-cm survey of HH energy sources. Spurred by the belief that also this source should emit in the radio continuum, we have now made an additional deeper map at 3.6-cm of the region (Figure 1) and this time we detected the source. The 3.6-cm position is given in Table 1, where it is compared to the accurate optical position (with error of 0.″7) derived by Heathcote & Reipurth (1992). The objects are seen to coincide to within one arcsec, giving confidence in the identification. The source is weak at 3.6-cm with an integrated flux density of only 0.16±0.02 mJy.

The anomality of the non-detection of the HH 34 source is thus removed, and we believe it is now correct to state that *it is a general property of newborn stars which are actively producing HH flows to emit in the cm radio continuum at detectable levels.*

4. THE HH 114/115 REGION

The Herbig-Haro objects HH 114 and HH 115 are located in molecular clouds in the λ Ori region (Reipurth 1994). They are two bow shocks, with a projected separation of 2.4 pc, thus forming a giant HH complex. CO observations show that a large bipolar molecular outflow co-exists with the HH flow (Reipurth, Bally, & Devine 1996).

A possible driving source of the HH complex is the *IRAS* source 05155+0707, located approximately on the HH flow axis. However, Chini et al. (1996) have discovered a very cold class 0 source, HH 114 MMS, only 1.5 arcmin to the north-west of the *IRAS* source, and also on the axis of the HH flow. They suggest that this new source may be a better candidate for the driving source of the outflow activity.

Our 3.6-cm map in Figure 2 shows radio continuum sources associated with *both* IRAS 05155+0707 and with HH 114 MMS. In both cases the radio source coincides with the counterpart, within the positional errors. The probability of detecting a 3.6-cm source with flux density above 0.1 mJy in a region of 6″×6″ is only $\sim 5 \times 10^{-4}$ and we thus consider

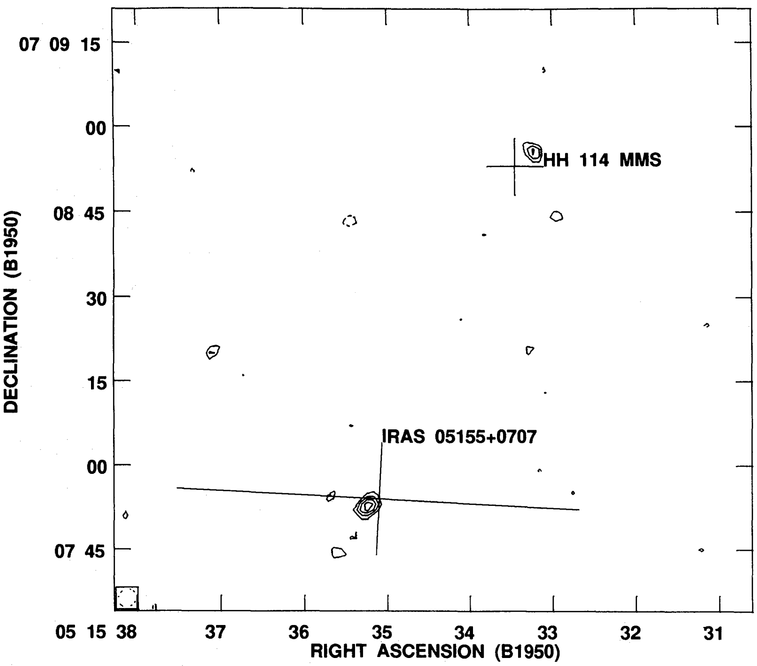

Fig. 2. Natural-weight VLA map at 3.6-cm wavelength of the central region of the HH 114/115 system. The crosses mark the positions of HH 114 MMS and of IRAS 05155+0707. Radio continuum sources were detected in association with both sources. The half power contour of the beam is shown in the bottom left corner. Contour levels are −4, −3, 3, 4, 5, 6, and 8 times the rms noise of 14 μJy beam^{-1}.

the associations to be very significant. The radio source associated with IRAS 05155+0707 (see Figure 2) shows evidence of elongation along the axis of the HH 114/115 flow, thus providing evidence in favor of its identification as the exciting source of the system. However, further research is needed to discriminate which of the two sources is actually driving the outflow.

HH 114 MMS is one of only a small number of known class 0 sources, of which an increasing number have been detected in the radio continuum (e.g., Anglada 1995), and it appears that centimeter continuum emission may well be an observational signature of class 0 sources, just as it is for HH energy sources.

5. THE HH 199 SOURCE REGION

Bally et al. (1995) have discovered two large Herbig-Haro flows, HH 199 and HH 200, both associated with molecular outflows and emanating from the core of the L1228 cloud. HH 200 flows from an optically visible T Tauri star, while 1.5 arcminutes to the south-east the *IRAS* source 20582+7724 drives the HH 199 flow, a nearly 2 pc long bipolar chain of HH knots. The position angle of the HH 199 jet system is about 60°. IRAS 20582+7724 is a rather bright *IRAS* source with fluxes at 12, 25, 60 and 100 μm of 1.2, 3.2, 11.8 and 18.2 Jy, respectively, and with rising fluxes towards longer wavelengths it is clearly a Class I source.

In addition to HH 199, IRAS 20582+7724 drives another flow, detected in the infrared by Hodapp (1994) and Bally et al. (1995). These latter authors show that this infrared flow is pure H_2 line emission. It consists of knots both east and west of the *IRAS* source, along a position angle of about 100°. Bally et al. (1995) discuss the relation between HH 199 and the IR flow, both emanating from the *IRAS* source, and discuss as possible explanations that the *IRAS* source is an unresolved binary with each star having its own outflow, that a single flow undergoes complex deflections at dense walls of gas, or that a single flow is precessing or wobbling.

Tafalla, Myers, & Wilner (1994) have observed the dense gas around the *IRAS* source as traced by C_3H_2 and HCN. These authors found sudden shifts in the line velocity of these molecules, with a systematic velocity pattern that agrees in direction and velocity sense with the CO outflow. Tafalla et al. identified three distinct velocity components in the core, and interpreted these results as evidence for the disruption of the dense core by the bipolar outflow from

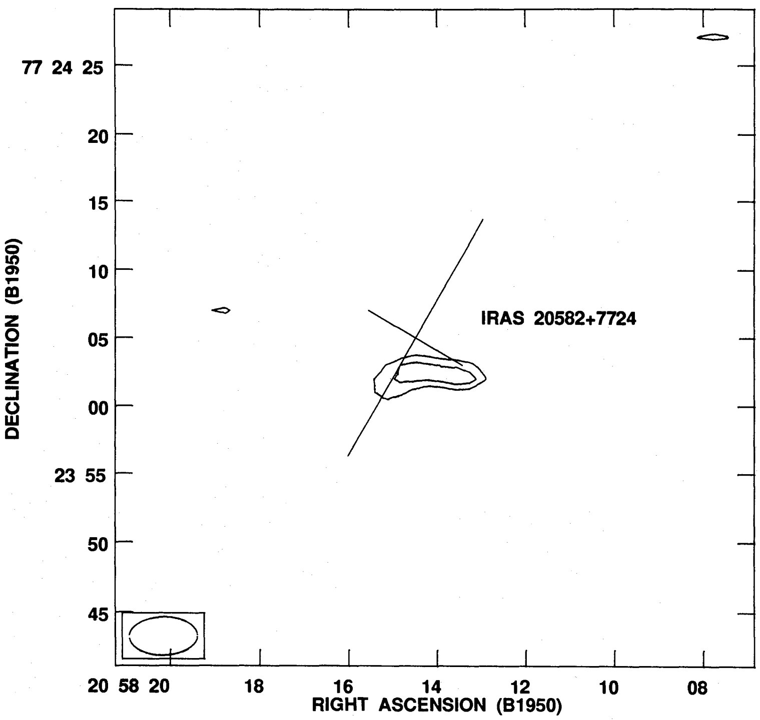

Fig. 3. Natural-weight VLA map at 3.6-cm wavelength of the central region of the HH 199 system. The cross marks the position of IRAS 20582+7724. The half power contour of the beam is shown in the bottom left corner. Contour levels are −4, −3, 3, and 4 times the rms noise of 17 μJy beam^{-1}.

the *IRAS* source. Recently, Anglada, Sepúlveda, & Gómez (1996) have detected this core in ammonia.

Our 3.6-cm map in Figure 3 shows that the *IRAS* source coincides with an elongated radio continuum source. Given the weakness of the source (0.15 mJy) it is difficult to establish if the source is indeed elongated or if we are observing an unresolved double. Both interpretations are feasible. In the case of a single, elongated source, we find that the position angle of the deconvolved major axis is consistent with that of the H_2 flow. This interpretation would classify the radio source as a thermal jet (Rodríguez 1995; Curiel 1995), however, it does not rule out the possibility that the star producing the thermal jet has a companion with no radio emission that may play a role in the hypothesized wobbling of the jet. On the other hand, given the presence of two outflows from the *IRAS* source, it is also possible that the VLA source is an unresolved young radio binary, with each component driving a separate flow, similar to the case of HH 1/2 and HH 144 (Reipurth et al. 1993b).

Unfortunately, the source is detected at only the 4-σ level and we cannot reach more definitive conclusions. Anglada (1996) has independently detected this source at the same flux density.

6. THE HH 212 SOURCE REGION

This is a highly collimated bipolar infrared H_2 jet emerging from the *IRAS* source 05413−0104 embedded in the Orion B clouds (Zinnecker et al. 1996). The source is a class I object, with fluxes measured at 25, 60 and 100 μm of .3, 17.3, and 59.4 Jy. The position of the *IRAS* source is very uncertain, but Claussen, Wilking, & Wootten (1996) have detected an H_2O maser with the VLA with position $\alpha(1950) = 05^h\ 41^m\ 18\overset{s}{.}92$; $\delta(1950) = -01^\circ\ 04'\ 09\overset{''}{.}2$, and they note that masers from low-luminosity sources are usually located very close to the driving source, typically within 150 AU ($0\overset{''}{.}3$ at the distance of Orion). Curiel (1996) has detected ammonia in association with the central regions of this outflow. However, we fail to detect sources associated with the *IRAS* source or the H_2O maser at a 4-σ upper limit of 0.06 mJy.

7. CONCLUSIONS

We have presented sensitive VLA observations at 3.6-cm of four Herbig-Haro fields: HH 34, HH 114, HH 199, and HH 212. In all fields but the last we detect radio sources that are very likely associated with the exciting source of the region. In the case of HH 34, our detection of a radio counterpart supports the notion that newborn stars which are actively producing HH flows emit in the cm radio continuum at detectable levels. In the HH 114 field, we detect independent sources associated with both an *IRAS* source and a millimeter object in the region, while in HH 199 we detect a source associated with the *IRAS* source in the field.

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