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LARGE PROPER MOTIONS AND EJECTION OF NEW CONDENSATIONS IN THE HH 80–81 THERMAL RADIO JET

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ABSTRACT

The HH 80–81 complex is the largest and most powerful stellar jet system of high collimation known. We have obtained second-epoch (1994.3) VLA observations of the HH 80–81 thermal radio jet and compared them with previous observations made 4.1 yr before (1990.2). Both sets of observations were made at 3.5 and 6 cm with an angular resolution of $\sim 0''.3$. Large proper motions have been detected in the condensations along the jet. These proper motions are in the range of 70–160 mas yr^{-1}, equivalent to 600–1400 km s^{-1} at the distance of 1.7 kpc of the source. Such large velocities have not been previously measured in the context of jets from young stellar objects, and they give support to the identification of the powering source of this Herbig-Haro complex as a very massive star. Between the two epochs of observation, an ejection event created two new knots in the jet flow that in 1994.3 appear symmetrically projected at only 500 AU from the central source. The existence of significant clumpiness and symmetry in the jet so close to the star gives support to the notion that disturbances in stellar jets are produced by the driving source, and not as a result of instabilities produced later in the flow.

Subject headings: ISM: individual (HH 80, HH 81) — ISM: jets and outflows — radio continuum: ISM — stars: formation — stars: pre–main-sequence

1. INTRODUCTION

HH 80–81 are two optically visible Herbig-Haro (HH) objects originally discovered by Reipurth & Graham (1988). These objects are located at the edge of the dark molecular cloud L291, a region of recent star formation. They were first detected in the radio by Rodríguez & Reipurth (1989), with centimetric flux densities of a few mJy. These authors also detected the possible driving source of the complex, an object deeply embedded inside the molecular cloud. Its location is coincident with the bright infrared source IRAS 18162−2048. At an estimated distance of 1.7 kpc (Rodríguez et al. 1980; Martí, Rodríguez, & Reipurth 1993), the luminosity of IRAS 18162−2048 must be as high as $\sim 2 \times 10^4\ L_\odot$, suggesting that we are dealing with a very massive young star.

During the period 1989–1990, we undertook a multifrequency program of matching beam and high-resolution radio observations of the HH 80–81 complex (Martí et al. 1993). As a result, our knowledge of the system improved with the discovery of HH 80-North, the heavily obscured northern counterpart of HH 80–81. HH 80-North is not optically visible because it is deeply embedded inside the molecular cloud, and it is the first HH object originally recognized as such in the radio wavelengths. More recently, Gredel (1994) has detected this object in the infrared in molecular hydrogen emission. Its HH nature has been further corroborated after the detection of downstream ammonia by Girart et al. (1994). Another remarkable result was the detection of an extraordinarily well collimated jet, at all the angular scales observed, with a total projected linear size of about 5.3 pc (Martí et al. 1993). This exceeds the dimensions of the previously known highly collimated jets from luminous massive stars (Poetzel, Mundt, & Ray 1989), as well as those of well-collimated jets from low-luminosity stars, which rarely exceed dimensions of half a parsec (e.g., Reipurth 1991). The high-resolution maps ($\sim 0''.3$) of the central exciting source, IRAS 18162−2048, exhibited the presence of several compact condensations along the jet suitable for measuring proper motions. According to the bow shock models of HH objects by Hartigan, Raymond, & Hartmann (1987), the full width of their optical emission lines is correlated with the shock velocity. Given the exceptionally large widths of the HH 80–81 optical lines ($\Delta v \sim 500$ km s^{-1}; Heathcote & Reipurth 1995), we expected an unusually fast jet. In addition, the fact that the system is powered by a massive object indicated (by analogy with what occurs in the stellar winds of main-sequence stars) that the HH 80–81 jet could be faster than those produced by young solar-mass stars. These various considerations suggested that large proper motions could be detectable in a few years. In view of this possibility, we carried out in 1994 second-epoch, high-resolution observations with the Very Large Array (VLA). The new results reported here have confirmed our expectations.

2. OBSERVATIONS

The observations were carried out using the VLA interferometer of NRAO[4] in its most extended A configuration. For all observations a bandwidth of 100 MHz was employed. The absolute amplitude and phase calibrators were always 1328+307 and 1730−130, respectively. The bootstrapped flux densities of 1730−130 are given in Table 1. The data were edited and calibrated using the Astronomical Image Processing System (AIPS) software package of NRAO. The log of the observations, indicating dates and wavelengths used, is also listed in Table 1. A detailed discussion of the 1990.2 first-epoch results can be found in Martí et al. (1993). The second-epoch data were obtained in four different days evenly spaced along a few weeks. In order to improve sensitivity, we concatenated

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TABLE 1

SUMMARY OF OBSERVATIONS

	$\lambda = 3.5$ cm		$\lambda = 6$ cm	
DATE	Flux Density of 1730−130 (Jy)	rms in Source Map (μJy)	Flux Density of 1730−130 (Jy)	rms in Source Map (μJy)
1990 Feb 24	7.59 ± 0.02	21	7.41 ± 0.02	20
1994 Mar 18	4.85 ± 0.08	19	4.64 ± 0.02	22
1994 Apr 17	5.00 ± 0.03	28	4.62 ± 0.02	37
1994 Apr 24	4.82 ± 0.02	30	4.53 ± 0.01	32
1994 Apr 25	4.60 ± 0.03	35	5.18 ± 0.07	34
All 1994 data	...	16	...	16

them into a single data set, and an averaged second-epoch date (1994.3) was assigned to the set.

In Figures 1 and 2, we show the 3.5 and 6 cm natural weight maps for the two epochs of observation, as well as a map made subtracting the 1990.2 from the 1994.3 maps. The maps have been rotated to facilitate comparison. For the same reason, all maps have been convolved with an identical restoring beam. The restoring beam used was of $0\farcs47 \times 0\farcs32$, with position angle of $1\fdg2$, corresponding to the synthesized beam of all the 3.5 cm data when natural weight and a tapering of 700 kλ are used.

Several condensations are identified in the maps of Figures 1 and 2. We numbered them following their distance from the core of the jet as N1, N2, ..., and S1, S2, ..., with N and S indicating north and south, respectively. A similar signal-to-noise ratio was achieved for both frequencies observed. However, given the modest signal-to-noise ratio of some of the condensations and the difficulty of resolving some of them from the core of the jet, not all condensations seen in the 3.5 cm map are also equally evident in the 6 cm map. As can be seen in the figures, as the condensations are more displaced from the center, they are more easy to distinguish from the core of the jet. However, they also become progressively weaker. The decrease in flux density is roughly consistent with an inverse square distance dependence. The condensations closer to the core are brighter but are difficult to distinguish from the core itself. To better estimate the positions of some of the condensations, we used maps made with natural weighting but reconstructed with the uniform-weight beam. These positions and their errors were determined with the task IMFIT of NRAO's AIPS data reduction package. This task uses a linearized least-squares solution to obtain the parameters and errors of the fit of a Gaussian ellipsoid function over selected regions of the map.

Remarkably, the subtraction of the maps from the two different epochs reveals (see lower part of both the 3.5 and 6 cm figures) the existence of new twin condensations (N4 and S4) near the core that must have been ejected between the two epochs of observation. In addition to these new twin condensations, the difference maps show negative contours at the positions of some of the condensations observed in 1990.2. If the condensations were moving remaining equally bright with time, one would expect to see a positive (solid-contoured) ahead of a negative (dash-contoured) clump. However, as the clumps displace, they also become progressively weaker (see above), and since the difference maps are noiser than the individual maps, the positive clumps become lost in the noise. Interestingly, the *total* flux density of the jet most probably remains approximately constant with the outer condensations becoming fainter, but with new condensation pairs appearing at the core.

3. DISCUSSION

For condensations identifiable in both observing epochs, a determination of the proper motion could be obtained. The results are listed in Table 2 for the different condensations, and they spread in the range of 70–160 mas yr^{-1}. For conden-

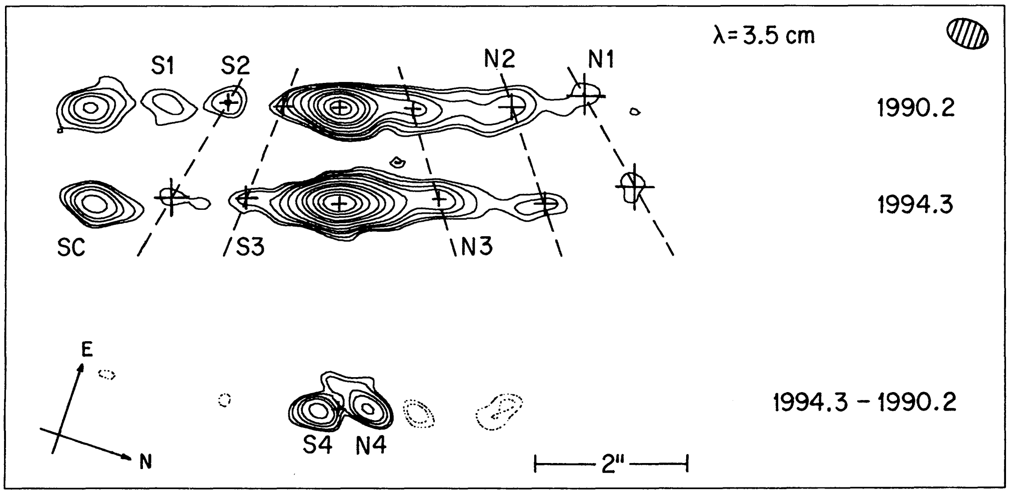

FIG. 1.—Radio maps at 3.5 cm wavelength of the exciting source of the HH 80–81 complex, for the epochs 1990.2 (*top*) and 1994.3 (*middle*). The lower panel (*bottom*) shows the subtraction of the 1990.2 image from that of 1994.3. Several condensations are identified in the two epoch maps and are connected by dashed lines. Displacement during the 4.1 yr interval is evident. The two newest condensations ejected can only be identified in the subtraction map. A cross marks the position of the centroid of the core, located at $\alpha(1950) = 18^{\mathrm{h}}16^{\mathrm{m}}12\fs997 \pm 0\fs005$ and $\delta(1950) = -20°48'48\farcs27 \pm 0\farcs05$. Crosses mark the 2 σ error bars for the position of the condensations with respect to the centroid of the core. Maps have been rotated 110° clockwise to facilitate comparison, and actual orientations of the north and east are shown in the bottom left corner. All maps have been made with the same restoring beam of $0\farcs47 \times 0\farcs32$, with position angle of $1\fdg2$. The beam is shown in the top right corner. Contour levels are −100, −80, −60, −40, −30, −20, −12, −8, −6, −4, −3, 3, 4, 6, 8, 12, 20, 30, 40, 60, 80, 100 times the rms noise of 21, 16, and 26 μJy beam^{-1} for the 1990.2 and 1994.3 maps and for the (1994.3 − 1990.2) subtraction map, respectively.

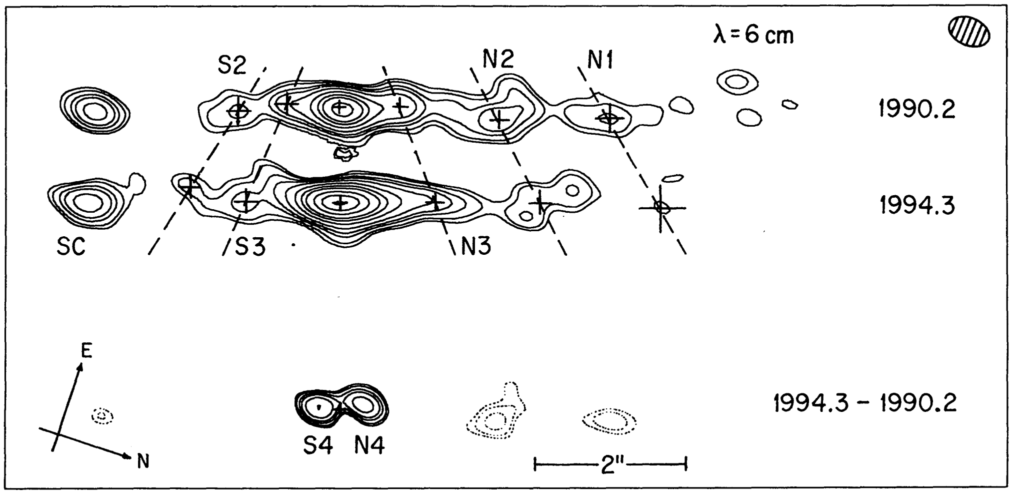

FIG. 2.—Same as Fig. 1, but for the 6 cm maps. Contour levels are −100, −80, −60, −40, −30, −20, −12, −8, −6, −4, −3, 3, 4, 6, 8, 12, 20, 30, 40, 60, 80, 100 times the rms noise of 20, 16, and 24 μJy beam^{-1} for the 1990.2 and 1994.3 maps and for the (1994.3 − 1990.2) subtraction map, respectively.

sations measured in both the 3.5 cm and 6 cm maps, the proper motion determination agrees well between both wavelengths. Adopting a distance of 1.7 kpc (Rodríguez et al. 1980; Martí et al. 1993), the corresponding velocities are in the range 600–1400 km s^{-1}. From the discussion of Martí et al. (1993), the distance to HH 80–81 could be as low as 1.2 kpc, a value that would lower the derived velocity range to 400–1000 km s^{-1}. Even in this case, the velocities are significantly larger than those found in low-mass stars (~200 km s^{-1}).

From the data of Table 2, it appears that these velocities seem to be higher with increasing distance from the central source. This is the first time that velocities of ~10^3 km s^{-1} have been measured in the context of radio jets from young stars. In fact, such high velocities have not been detected in any HH flow up to now. This supports the theory that the driving source must be a massive luminous star, as already indicated by the high infrared luminosity of IRAS 18162−2048. Previously, the proper motion observed in other HH jets associated with low-luminosity young stars gave typical values of ~200 km s^{-1} (e.g., Heathcote & Reipurth 1992; Eislöffel & Mundt 1994).

Concerning the condensations N4 and S4, ejected between the two observing epochs, only a lower limit to the velocity in the plane of the sky can be estimated, since we do not know the exact time when the ejection event took place. The velocity lower limits derived are of the order of ~600 km s^{-1}, i.e., consistent with the lower velocities measured for the other condensations. At the time of the second observation (1994.3), N4 and S4 appeared to be about 0.″3 away from the central core, equivalent to a projected distance of only 500 AU. This is the closest to a massive young star that HH knots have been observed. For the low-luminosity source DG Tau, even smaller distances have been measured (Kepner et al. 1993).

Knots have been seen to emerge from the low-luminosity source L1551 IRS 5 in the optical (Neckel & Staude 1987), and a knot is emerging from the HH 111 VLA source at 3.5 cm (Rodríguez & Reipurth 1994). In both these cases, however, the ejection is observed as one-sided; in the L1551 IRS 5 case, this is possibly due to extinction, but for HH 111 that cannot be the case.

What is really striking about the emergence of N4 and S4 is that they are very symmetric around the source. We interpret this to mean that the pair N4 and S4 were produced in a single ejection event less than 4 yr ago. Indeed, the idea of symmetric ejection can probably be extended to the rest of the knot pairs (N1 and S1, N2 and S2, etc.) because of their striking sym-

TABLE 2

PROPER MOTIONS AND VELOCITIES

	λ = 3.5 cm			λ = 6 cm		
CONDENSATION	Proper Motion (mas yr^{-1})	Velocity (km s^{-1})	Position Angle (degrees)	Proper Motion (mas yr^{-1})	Velocity (km s^{-1})	Position Angle (degrees)
N1	160 ± 20	1300 ± 200	36 ± 4	160 ± 20	1300 ± 200	26 ± 4
N2	120 ± 10	1000 ± 100	16 ± 6	90 ± 10	800 ± 100	15 ± 7
N3	70 ± 10	600 ± 100	32 ± 9	80 ± 10	600 ± 100	356 ± 9
N4	≥80	≥700	21 ± 8	≥70	≥600	28 ± 9
Core	≤30	≤300	…	≤30	≤300	…
S4	≥60	≥500	201 ± 12	≥60	≥500	196 ± 12
S3	170 ± 20	1300 ± 200	198 ± 4	160 ± 20	1300 ± 200	204 ± 4
S2	180 ± 20	1500 ± 200	195 ± 4	180 ± 20	1400 ± 200	179 ± 4
SC	≤30	≤300	…	≤30	≤300	…

metry. Only two HH jets are known to display similar symmetry, namely HH 111 (Gredel & Reipurth 1994) and HH 212 (Zinnecker 1994). The symmetry of the HH 80–81 radio jet is the only known for a massive young star and testifies to similar ejection processes in young stars of low and high mass. The fact that we now know of several cases of symmetric jets strongly suggests that the knots in jets are a direct result of energetic events in the driving sources, and not a result of Kelvin-Helmholtz instabilities in a flow, nor the result of interaction with an inhomogeneous ambient medium.

The knots are regularly spaced around the source. On the northern side, where separations are easiest to measure, we find separations between N1 and N2 of 1″.23, between N2 and N3 of 1″.34 and between N3 and N4 of 0″.97. If we assume an average tangential velocity of 1000 km s^{-1}, we find that the knots were ejected with intervals of 9.9, 10.9, and 7.8 yr, respectively, or on average one per every approximately 10 yr. If this is a recurrent phenomenon, we should expect another knot to be expulsed in 6–7 yr from now, that is, around the year 2000 or 2001. With this prediction, we have a unique opportunity to monitor the source at infrared and radio wavelengths to follow its behavior prior to, during, and after the event that would eject a new pair of knots. Disk accretion events are thought to be responsible for ejection of HH knots, and theory is becoming sufficiently detailed for meaningful comparisons with observations (Bell & Lin 1994).

In the maps of Figures 1 and 2 there is also a bright condensation south of the jet core. Surprisingly, it turned out that this knot did not present an appreciable proper motion, with a 3 σ upper limit of 300 km s^{-1}. In view of this fact, in Table 2 we refer to it as the *stationary condensation* (SC). It is not possible to rule out that it could be a background or foreground object, although this possibility is rather low given its clear alignment with the jet flow. On the other hand, the IRAS 18162−2048 region is known to contain a cluster of stars (Aspin & Geballe 1992), and the SC could be a radio source powered by a separate star, as in the case of VLA 1 and VLA 2 in the HH 1–2 region (Reipurth et a. 1993). The recent results of Aspin et al. (1995) suggest that their source 7 is the infrared counterpart of SC, favoring a separate star. In principle, the SC could also be a crossing shock in the flow (Cantó, Raga, & Binette 1989) or a bow shock in ambient dense gas, but further observations are required to settle this issue.

All condensations studied, including SC, have flat spectral indices, consistent with optically thin free-free emission. If we take condensation S2 as typical, from the 1990.2 data we obtain a 6 cm flux density of ~0.3 mJy and an angular diameter of ~0″.5 (~10^3 AU at 1.7 kpc). Assuming optically thin free-free emission from gas with an electron temperature of 10^4 K, we estimate an electron density of ~10^4 cm^{-3} and an ionized mass (protons plus electrons) of ~3×10^{-5} $M_\odot$ within a factor of 2. If a pair of these condensations is ejected every 10 yr at a velocity of 10^3 km s^{-1}, we obtain a mass-loss rate of ~6×10^{-6} $M_\odot$ yr^{-1}, a mechanical luminosity of ~500 $L_\odot$, and a momentum injection rate of ~6×10^{-3} $M_\odot$ km s^{-1} yr^{-1} for the jet. The momentum rate estimated for the ionized gas in the jet is about ~10 times smaller than the momentum rate estimated for the molecular outflow by Yamashita et al. (1989). This result suggests that the jet could be carrying a significant neutral component.

Proper motions only allow a determination of the tangential velocity component of the jet flow. The extremely high tangential velocities reported here suggest that it is unlikely that the jet has a substantial component along the line of sight. The large dimensions of the whole jet complex also supports this view. Furthermore, radial velocities have been determined for the visible working surfaces of the flow, HH 80 and 81, and they are clearly smaller than the jet tangential velocities (Heathcote & Reipurth 1995). We therefore feel justified in assuming that the HH 80–81 radio jet lies closer to the plane of the sky than to the line of sight.

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