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# RECENT ADVANCES IN THE STUDY OF THERMAL RADIO JETS

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RESUMEN

El entendimiento del fenómeno de eyección colimada de gas por estrellas jóvenes ha avanzado mucho en años recientes, sobre todo en lo que se refiere a las manifestaciones a gran escala (décimas de pc o más) del mismo. Sin embargo, nuestro conocimiento del "motor" que energiza a estos flujos es aún limitado. Existe bastante concenso en el sentido de que la aceleración y colimación de estos vientos involucra procesos magnetohidrodinámicos en un disco de acreción, pero se requieren observaciones de muy alta resolución espacial para poner a prueba los modelos. En la actualidad, una de las mejores técnicas disponibles para ésto es el estudio de los chorros térmicos mediante interferómetros de radio. En esta reseña, discuto ejemplos recientes de resultados obtenidos con esta técnica.

ABSTRACT

Great advance has been made recently in the understanding of the collimated outflow phenomenon frequently found in association with young stars, in particular in what refers to its large scale (tenths of pc or more) manifestations. These manifestations include the Herbig-Haro objects and the molecular bipolar outflows. Our understanding of the "engine" that powers these outflows is, however, still limited. There is some consensus in the sense that the acceleration and collimation of these winds involves magnetohydrodynamic processes in an accretion disk, but observations with very high angular resolution are needed to test the models. At present, one of the best available techniques to study outflows with the required high angular resolution is the observation of thermal jets using radio interferometers. In this review, I discuss recent examples of results obtained with this technique.

*Key words:* **ISM: JETS AND OUTFLOWS — STARS: PRE-MAIN-SEQUENCE**

## 1. INTRODUCTION

The collimated, bipolar flows that emanate from young stars interact with the surrounding gaseous medium producing the Herbig-Haro objects and the molecular bipolar outflows. Observations with the highest angular resolution possible are required to understand the mechanism that accelerates and collimates these flows close to the star. At centimeter wavelengths the continuum emission originating very close to a young stellar object is dominated by free-free (thermal) emission from ionized, collimated outflows (these radio sources are thus called thermal jets). This emission can be detected and imaged using radio interferometers with angular resolutions in the range of $0\overset{''}{.}1$, comparable to that achieved by the *Hubble Space Telescope.*

In this review, I discuss recent results in the field of thermal jets, giving emphasis to the so-called quadrupolar outflows and to a new very high angular resolution image of the thermal radio jet in HL Tau.

## 2. THERMAL JETS

The high angular resolution and accurate positional accuracy provided by the radio observations, together with the fact that they are practically unaffected by dust obscuration have allowed this type of observations to discriminate, identify, and provide accurate positions for the exciting sources of outflows, and to study the collimation very close to the star. A recent example (see Figure 1) of this application is the detection of an alternative candidate for the exciting source of the classic HH 7–11 flow (Rodríguez, Anglada, & Curiel 1997).

It is also possible to estimate the mass loss rate in the jet following Reynolds (1986). For this, we assume a pure hydrogen jet with constant opening angle, terminal velocity, and ionization fraction, as well as constant electron temperature, taken to be equal to $10^4$ K. We further assume that the jet axis is perpendicular to the

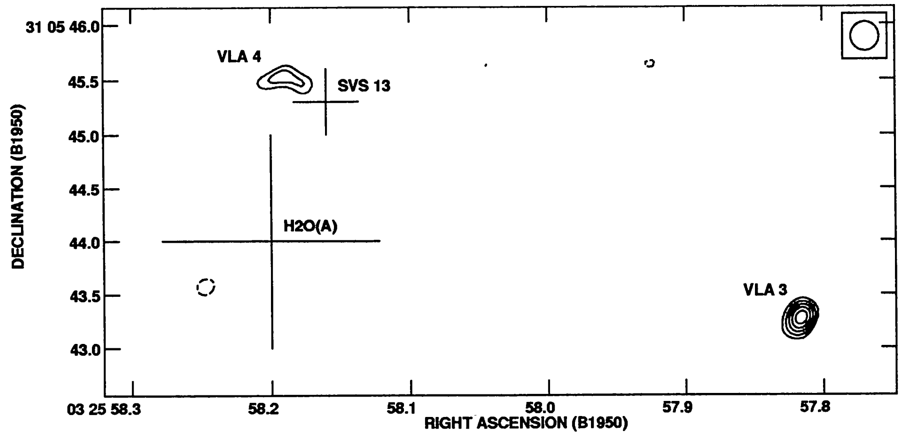


Fig. 1. Natural-weight VLA map at 3.6 cm wavelength made in the A configuration of the sources VLA 3 and VLA 4 at the central region of the HH 7–11 outflow. The positions of the near-infrared/optical source SVS 13 and of the water maser $H_2O$(A) are indicated with crosses. The source VLA 4 is associated with the infrared/optical source SVS 13. The source VLA 3 is a newly detected object that has been proposed by Rodríguez et al. (1997) as a candidate to excite the HH 7–11 outflow. The half power contour of the beam is shown in the top right corner. Contour levels are −3, 3, 4, 5, 6, and 7 times the rms noise of 20 $\mu$Jy beam$^{-1}$.

line-of sight (that is, with an inclination angle of $i = 90°$) since variations in $i$ from 45° to 90° change the mass loss estimate by less than 10%. Given the elongated appearance of the jet, it is unlikely that $i$ has values values that are much smaller than 45°.

Under these assumptions, the mass loss rate in the jet is given by

$$\dot{M}_{-6} = 1.9\ v_8\ x_0^{-1}\ S_{mJy}^{0.75}\ \nu_9^{-0.45}\ d_{kpc}^{1.5}\ \theta_0^{0.75},$$

where $\dot{M}_{-6}$ is the mass loss rate in $10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$, $v_8$ is the terminal velocity of the jet in $10^3$ km s$^{-1}$, $x_0$ is the ionization fraction, $S_{mJy}$ is the observed flux density in mJy, $\nu_9$ is the observed frequency in GHz, $d$ is the distance in kpc, and $\theta_0$ is the opening angle in radians.

The opening angle is estimated to be

$$\theta_0 = 2\ tan^{-1}(\theta_{min}/\theta_{maj}),$$

where $\theta_{min}$ and $\theta_{maj}$ are the deconvolved minor and major axes of the jet. The terminal velocity can be obtained from proper motions and radial velocity information obtained from studies of the jets at larger scales. If this information is not available, an educated guess has to be made. If the star is of low (that is, solar) mass, a value of $v_8 = 0.3$ is adopted. If the star is more massive, values of $v_8 = 0.5 - 1$ are usually adopted.

It is usually found that the momentum rate in the ionized jet is an order of magnitude smaller than that found in the larger scale molecular outflow. This result has been taken to indicate that jets are only partially ionized and that the total momentum rate is much larger than the ionized momentum rate.

## 3. QUADRUPOLAR OUTFLOWS

It has become increasingly evident that in some regions of star formation quadrupolar outflows, that is, flows that appear to be the close superposition in the sky of two distinct bipolar outflows, are observed. There are, however, several explanations proposed to explain this peculiar four-lobed morphology: (1) Each pair of red and blue lobes could be the limb-brightened walls of the evacuated cavities of a single bipolar outflow (Avery, Hayashi, & White 1990). (2) A single outflow lobe could be split into two lobes as a result of the interaction with a high density molecular clump (Mizuno et al. 1990; Torrelles et al. 1993). (3) Multiple episodes of outflow activity, with precession of the outflow axis, could produce a complex lobe morphology (e.g., Fukue & Yokoo

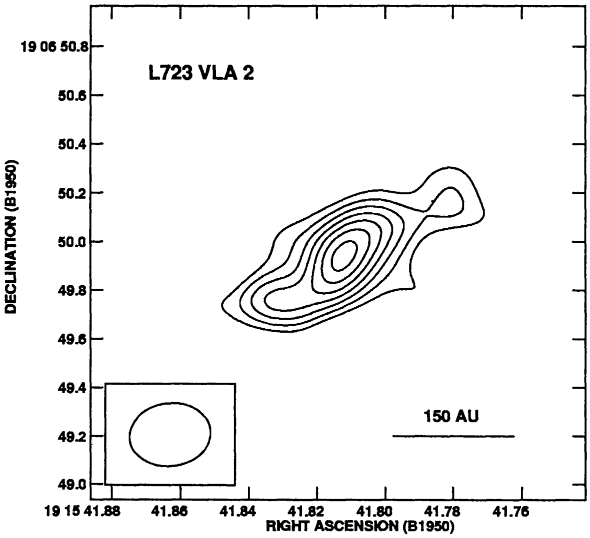


Fig. 2. VLA map at 3.6 cm wavelength of the source VLA 2 at the core of the quadrupolar outflow in L723. Contours are −3, 3, 4, 5, 6, 7, 8, and 9 times the rms noise of 11 $\mu$Jy beam$^{-1}$. The half power contour of the synthesized beam is also shown. The major axis of VLA 2 aligns with the axis of the large CO lobe pair that has a position angle PA $\simeq$ 110°.

1986; Narayanan & Walker 1996). (4) The four-lobed structure could be produced by two independent bipolar outflows driven by two stars or even by a binary system (e.g., Anglada et al. 1991; Garay et al. 1996).

The currently known cases of outflows with a quadrupolar structure are L723 (Goldsmith et al. 1984), IRAS 16293−2422 (Walker et al. 1988; Mizuno et al. 1990), Cepheus A (Bally & Lane 1991), IRAS 21334+5039 (Smith & Fischer 1992), IRAS 20050+2720 (Bachiller, Fuente, & Tafalla 1995), and HH 111 (Cernicharo & Reipurth 1996).

The study of the thermal jets associated with these quadrupolar outflows has provided important information on their nature and on which of the proposed models is more viable. The sources L723 and HH 111 have been investigated in greater detail and we summarize these studies in what follows.

### *3.1. L723*

L723 is an isolated molecular cloud located at a distance of 300±150 pc (Goldsmith et al. 1984). A peculiar quadrupolar molecular outflow has been observed in this region (Goldsmith et al. 1984; Moriarty-Schieven & Snell 1989; Avery et al. 1990; Hayashi, Hasegawa, & Kaifu 1991). The morphology of this outflow, that is particularly evident in the CO maps of Avery et al. (1990), consists of two pairs of lobes with a common center. The larger pair of lobes extends along a direction with a position angle PA $\simeq$ 110°, while the smaller pair extends along a direction with PA $\simeq$ 30°.

Two radio continuum sources, VLA 1 and VLA 2, were found at the center of this outflow through Very Large Array (VLA) observations at 3.6 cm (Anglada et al. 1991). The two radio continuum sources are separated by 15″ (4500 AU in projection), and both lie within the error ellipsoid of IRAS 19156+1906. The recent high angular resolution study of Anglada, Rodríguez, & Torrelles (1996) reveals that while the source VLA 1 appears unresolved at their angular resolution of $\sim 0\rlap{.}''3$, the source VLA 2 appears as clearly elongated approximately along the direction of the larger pair of lobes of the molecular outflow (see Figure 2).

This alignment and the flux density and deconvolved angular size dependences with frequency observed between 3.6 and 6 cm are consistent with VLA 2 being a thermal radio jet, and suggest that this source is related to the excitation of the larger pair of outflow lobes. Additional evidence in support of this interpretation comes from the VLA ammonia study of Girart et al. (1997), who find heating and line broadening toward VLA 2, while no emission is detected at the position of the source VLA 1. The exciting source of the second, more compact lobe pair is still to be determined.

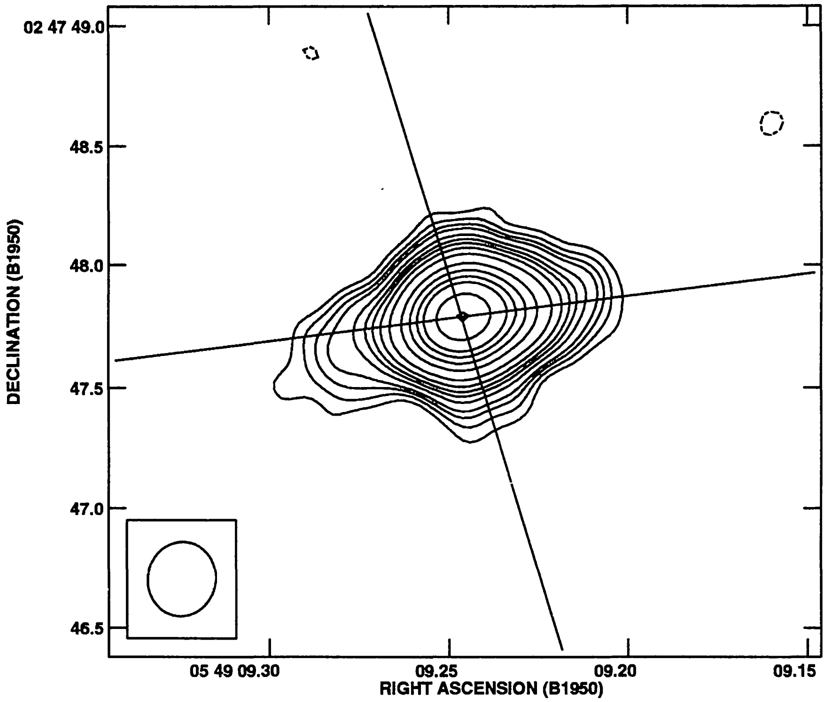


Fig. 3. VLA map at 3.6 cm wavelength of the exciting source at the core of the quadrupolar outflow in HH 111. Contours are −3, 3, 4, 5, 6, 8, 10, 12, 15, 20, 30, 40, 50, 60, 80, and 100 times the rms noise of 5.4 $\mu$Jy beam$^{-1}$. The half power contour of the synthesized beam is also shown. The straight lines give the position angles of the two flows in the region.

### *3.2. HH 111*

HH 111 is a spectacular HH jet located in L1617 in the Orion B cloud complex (Reipurth 1989). The whole jet complex stretches over 6′, which at the distance of 460 pc corresponds to 0.8 pc. It consists of a bright highly collimated jet, a small faint counterjet, and at least four bow shocks, two on each side of the source. The exciting source was detected in the radio continuum at 2 and 3.6-cm by Rodríguez & Reipurth (1994). This thermal jet appeared to align very well with the optical flow (at a position angle of about 277°). Recently, Gredel & Reipurth (1993; 1994) and Reipurth & Cernicharo (1996) found a second outflow in the infrared and in high-velocity CO. Then, HH 111 is a quadrupolar outflow.

Motivated by this result, Rodríguez & Reipurth (1998) undertook a deeper integration with the VLA toward the core of HH 111. The resulting map (see Figure 3) reveals that, in addition to the previously known elongation along the optical HH flow, the radio source shows weaker elongations approximately in the north-south direction, *closely aligned with the axis of the second outflow* . Then, the HH 111 thermal jet is also quadrupolar. Is this the first detection of a close binary radio jet? The centroids of the two jets appear to coincide in projection within 0.″1, that is, 50 AU at the distance of the source. This superposition could be just a chance alignment, with the two sources actually being much more separated physically. However, if the system is indeed a binary jet, it could be used to test models of the formation of collimated outflows (in the same spirit that twins are used to test hypothesis in genetics). Most models for collimation of jets require of organized magnetic fields over scales larger than the apparent separation of the components of this binary jet. Again, if the association is real, the period of the binary would be in the range of $10^2$ years, while the age of the optical jet is more in the range of $10^3$–$10^4$ years. How is it possible that the binary has completed many orbits without wrapping significantly the magnetic fields? Is the collimation produced very close to the star, so that at 50 AU we have mostly ballistic motions of the gas? The study of close binary jets should help us set constraints in the modeling of jets from young stars.

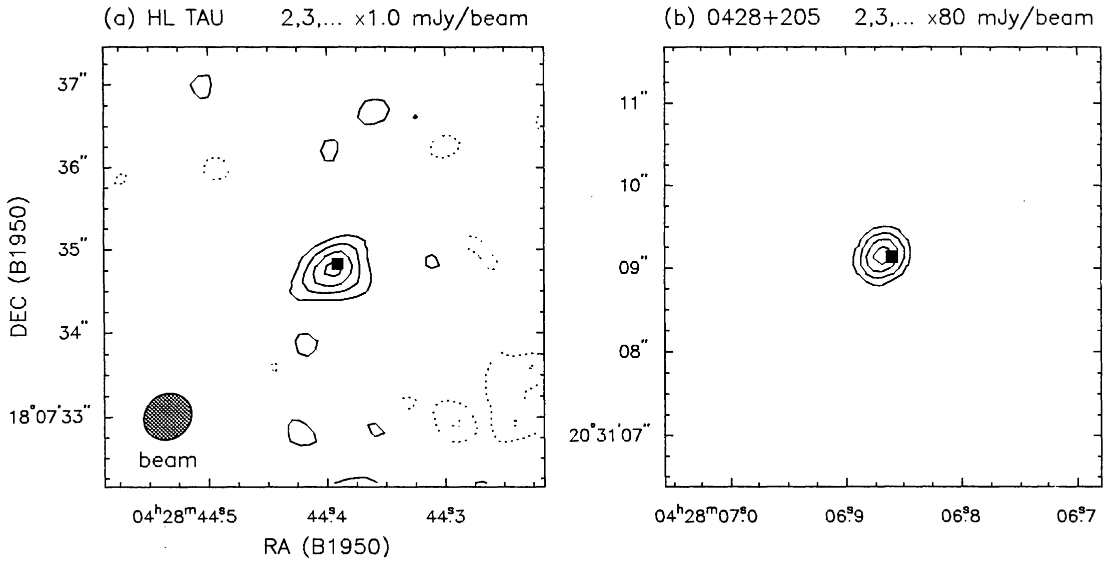


Fig. 4. (*a*) VLA map at 7-mm of HL Tau. At this relatively low angular resolution (0.″5) the emission from the dust disk is detected. (*b*) VLA map at 7-mm of the point source 0428+205. The half power contour of the synthesized beam for the HL Tau map is shown.

## 4. HL TAU AT 7-MM

### *4.1. The HL Tau Disk*

HL Tau is among the brightest millimeter continuum sources in the nearby Taurus complex (distance of 140 pc) and has been the subject of many studies that attempted to image its suspected protoplanetary disk.

TABLE 1

THE HL TAU DISK

| Wavelength (mm) | Flux Density (mJy) | Angular Size (arc sec) | Position Angle (Degrees) | Instrument | Reference |
|---|---|---|---|---|---|
| 0.9 | 2500 | $0.9\times \leq 0.7$ | 126 | CSO-JCMT | Lay et al. (1994) |
| 2.7 | 100 | $1.0\times 0.5$ | 125 | BIMA | Mundy et al. (1996) |
| 7.0 | 10 | $0.75\times 0.35$ | 125 | VLA | Wilner et al. (1996) |

It has been only in the last few years that this disk has been resolved spatially and Table 1 presents a summary of these results from three different groups. As can be seen from Table 1, the deconvolved angular dimensions and position angle derived at three wavelengths with three different instruments are consistent.

In Figure 4 we show the 7-mm map of the HL Tau disk from Wilner, Ho, & Rodríguez (1996). This map was made with an angular resolution of $\sim$ 0.″5 and clearly demonstrates that the emission is extended.

### *4.2. The HL Tau Jet*

While the dust emission from the disk dominates the radio continuum from HL Tau at mm wavelengths, the free-free emission from the ionized jet dominates the radio continuum at longer wavelenghts (Wilner et al. 1996). The wavelength at which both emission processes are comparable is around 1 cm (for HL Tau, for other young stars this transition wavelength could be very different).

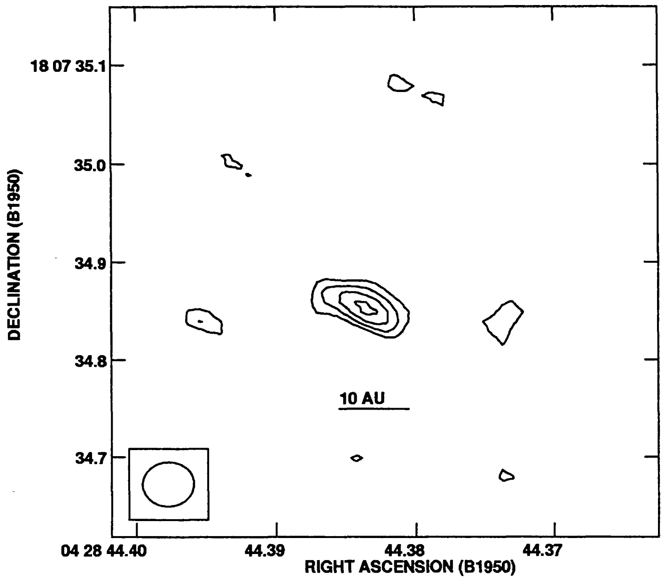


Fig. 5. VLA map at 7 mm wavelength of HL Tau. At the high angular resolution (0."04) of this map only the compact thermal jet is detected. Contours are −4, −3, 3, 4, 5, and 6 times 0.17 mJy beam$^{-1}$. The half power contour of the beam is shown, as well as a scale of 10 AU (assuming a distance of 140 pc).

TABLE 2

THE HL TAU THERMAL JET

| Wavelength (mm) | Flux Density (mJy) | Angular Size (arc sec) | Position Angle (Degrees) | Instrument | Reference |
|---|---|---|---|---|---|
| 36.0 | 0.52 | 0.30×0.18 | 81 | VLA | Rodríguez et al. (1994) |
| 7.0 | 2.7 | 0.10×0.04 | 82 | VLA | Wilner et al. (1998) |

At 3.6-cm the study of Rodríguez et al. (1994) shows a source whose parameters are summarized in Table 2. If interpreted as a thermal jet, the 3.6-cm source is not perpendicular to the disk (see Table 1). This discrepancy has difficulted the interpretation of the true nature of the 3.6-cm source. Of course, the jet and the disk are expected to be perpendicular on theoretical considerations, but it is unclear what is happening in this particular source. The situation is further complicated by the fact that the large scale optical jet (Mundt et al. 1990) is perpendicular to the disk. It is relevant to note that Anglada (1996) finds that the thermal jets and the larger scale outflow phenomena have axes aligned typically within 10°, but much less is known of the relative orientation between jets and disks.

New, very high angular resolution (0."04) observations made by Wilner, Rodríguez, & Ho (1998) at 7-mm with the Very Large Array in its longest configuration have added information that may lead to the solution of this problem.

We already noted that at an angular resolution of 0."5, the 7-mm emission map of HL Tau shown in Figure 4 traces the emission from dust in the disk. However, when the same source is observed at the same frequency but with an angular resolution an order of magnitude higher (0."04) something remarkable happens: the extended but relatively faint disk emission is resolved out by the interferometer and all that is left is the emission from the compact, relatively bright thermal jet (see Figure 5). The position angle of the 3.6-cm and high angular resolution 7-mm images are consistent. Furthermore, the flux densities and deconvolved angular sizes of the source scale with frequency as expected for a thermal jet.

For a collimated wind of constant temperature, velocity, and ionization fraction, the flux density and angular dimension of the source depend on frequency as $S_\nu \propto \nu^{1.3-0.7/\epsilon}$ and $\theta_{maj} \propto \nu^{-0.7/\epsilon}$, respectively, where $\epsilon$ is the power law index that describes the dependence of the jet half-width, $w$, (perpendicular to the jet axis) with the distance to the jet origin ($w \propto r^{\epsilon}$). For the simplest case of a biconical jet (that is, a jet with constant opening angle) one has $\epsilon = 1$ and an expected behavior of $S_\nu \propto \nu^{0.6}$ and $\theta_{maj} \propto \nu^{-0.7}$. For HL Tau we obtain $S_\nu \propto \nu^{1.0}$ and $\theta_{maj} \propto \nu^{-0.7}$, in reasonable agreement with the expected values. This result supports the interpretation of the centimeter emission from HL Tau as arising from a thermal jet.

A possible explanation for the discrepancy in alignment between the large scale optical jet and the compact radio jet is that, in the radio, we are seeing gas that left the star in the last few months, while in the optical the observed gas left the star decades ago and the jet axis may have precessed in between.

The map shown in Figure 5 suggests that collimation is already present at a few AU from the star. Most models for collimation of jets produce the collimation over much larger scales. The combination of these high angular resolution studies with theoretical modeling of the disk should greatly improve our understanding of the collimated outflow phenomenon.

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