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THERMAL JETS IN STAR-FORMING REGIONS: HIGH-MASS CASES

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RESUMEN

Usando interferómetros sensitivos a longitudes de onda centimétricas es posible detectar y cartografiar la emisión libre-libre de los flujos ionizados y colimados (chorros térmicos) que caracterizan a los objetos estelares muy jóvenes. La mayoría de los chorros térmicos detectados están siendo producidos por estrellas de baja masa. Sin embargo, recientemente ha quedado claro que el fenómeno de los flujos altamente colimados no está restringido a las estrellas de baja masa, sino que aparece también en asociación con objetos de alta masa. En este artículo revisamos las observaciones de dos de los casos mejor estudiados de chorros térmicos emanando de estrellas jóvenes de alta masa: HH 80-81 y Cep A HW2.

ABSTRACT

Using sensitive interferometers at centimeter wavelengths it is possible to detect and map the free-free emission from the ionized, collimated outflows (thermal jets) that characterize very young stellar objects. Most of the thermal jets detected are powered by low-mass, solar-type stars. However, it has recently become evident that the phenomenon of highly collimated outflows is not restricted to low-mass young stars, but that appears also in high-mass objects. In this paper we review two of the best studied cases of thermal jets emanating from high-mass young stars: HH 80-81 and Cep A HW2.

Key words: **STARS–MASS LOSS — STARS–PRE-MAIN-SEQUENCE**

1. INTRODUCTION

One of the major results in the field of star formation in the last 15 years has been the discovery that collimated, bipolar outflows are characteristically present in very young stars (Snell, Loren, & Plambeck 1980; Rodríguez, Moran, & Ho 1980b). This phenomenon has been the key element in our present efforts to unify our picture of star formation and include Herbig-Haro objects and jets, bipolar molecular outflows, and protoplanetary disks in the same scenario.

Radio continuum observations of thermal jets have provided important information on the collimation phenomenon at the smallest scales (tenths of arc sec or tens of AUs at the distance of the closest star-forming regions) that is possible to image now. We can define a thermal jet as a small ($\leq 1''$) continuum source with elongated morphology and thermal (that is, flat or rising with frequency) spectrum. The thermal jet is expected to be two-sided (bipolar), located at the center of an outflow, and with its major axis well-aligned with the outflow axis, as defined on much larger physical scales by the presence of Herbig-Haro objects and jets and by bipolar molecular outflows.

In general thermal jets are found in association with low luminosity ($\leq 100\ L_{\odot}$) sources. Perhaps the best studied example of the prototypical thermal jet is VLA 1 in the HH1-2 region (Rodríguez et al. 1990). The study of thermal jets have provided important new advances in our understanding of the collimated outflow phenomenon:

1. Since the exciting sources of the outflows are usually deeply embedded objects, in several cases sensitive centimeter observations have been the first to discover the weak outflow sources (e.g., HH1-2: Pravdo et al. 1985) with posterior observations at other wavelengths confirming these detections.

2. In many cases, the centimeter observations have provided a significant improvement in the positional accuracy (by more than two orders of magnitude in some cases) of the outflow sources. In general, *IRAS* and other FIR positions have been notably improved (e.g., RNO 43, B 335: Anglada et al. 1992).

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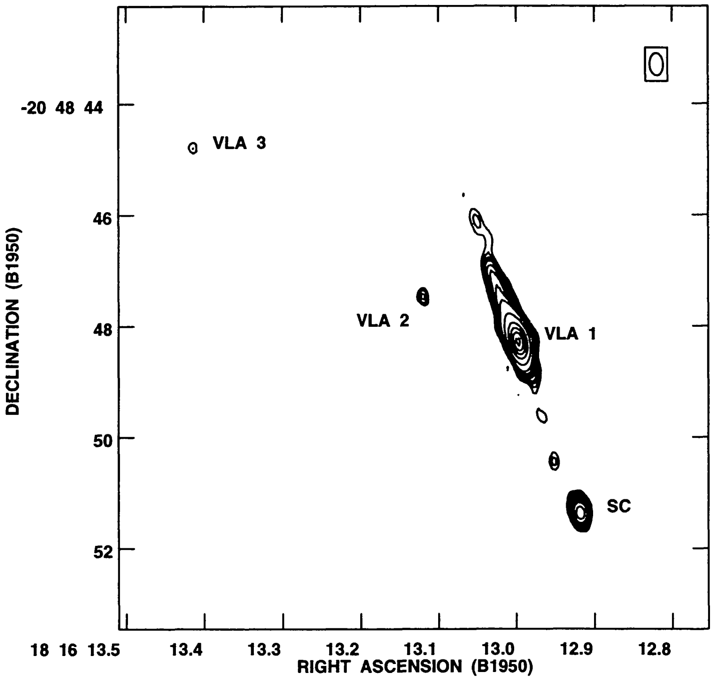

Fig. 1. Deep radio continuum map toward the HH80-81 central region at 3.5-cm. This map was made by Gómez, Rodríguez, & Martí (1995) concatenating data at different epochs from Martí, Rodríguez, & Reipurth 1993; 1995). Contour levels are -6, -5, 5, 6, 7, 8, 10, 12, 15, 20, 40, 80, 120, 160, and 200 times 9.1 μJy beam^{-1}, the rms noise of the map. The angular resolution is $0\farcs40 \times 0\farcs24$ with position angle of 3°. The thermal jet (VLA 1) is known to exhibit proper motions in its condensations (Martí, Rodríguez, & Reipurth 1995), and since this map averages the time variations over several years, it does not represent accurately the jet. The names of other radio continuum sources in the field are also indicated in the figure.

3. These radio continuum observations have permitted, in a number of cases, to distinguish and to discriminate among several candidates for the outflow excitation. Useful additional criteria adopted to favor a candidate in front of other candidates are proximity of the source to a high density and/or a temperature peak and jet-like morphology of the radio source.

4. Given the high angular resolution of the interferometers (tenths of arc sec), the mapping of thermal jets provides direct evidence that collimation is already present very close to the star (tens of AUs).

5. In the case of low luminosity objects ($L_\star \leq 300\ L_\odot$) it has been possible to establish (Anglada 1995) that a correlation exists between the centimeter radio continuum luminosity and the momentum rate in the outflow (as measured by the high-velocity CO emission). This correlation strongly supports the notion that the large scale phenomena (molecular outflows) are being produced by the small scale jets.

For recent reviews on the thermal jets see Anglada (1995) and Rodríguez (1995). As we mentioned, most of the research in this topic has been made toward low-mass stars. It has become evident in the last years that thermal jets are also present in more luminous objects. In what follows we will discuss two of the best studied cases of thermal jets powered by young massive stars.

2. HH 80-81

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. 1980a; Martí, Rodríguez & Reipurth, 1993), the luminosity of

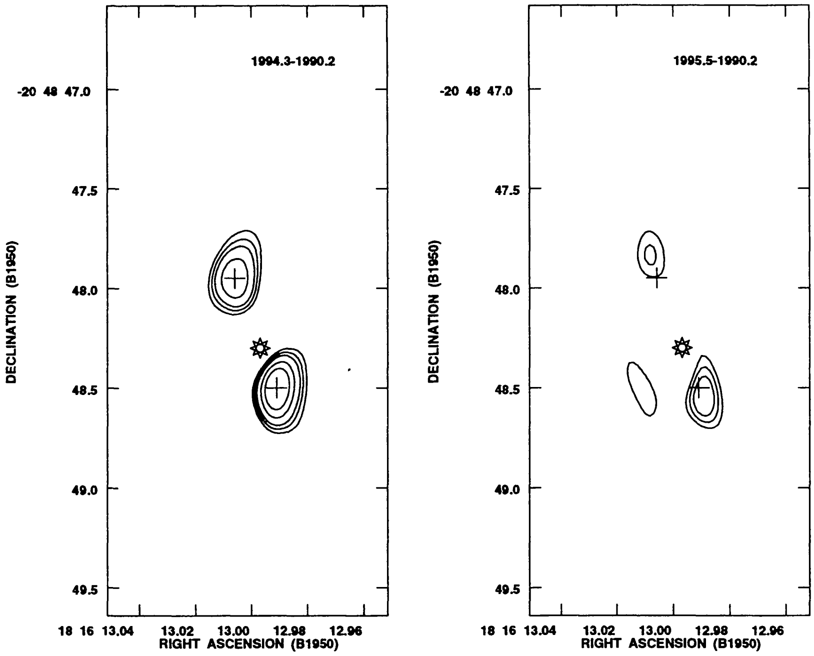

Fig. 2. Difference radio continuum maps (1994.3-1990.2 and 1995.5-1990.2) made at 3.5-cm toward the thermal jet HH80-81 VLA 1. Data from Martí, Rodríguez, & Reipurth 1996). Contour levels are -4, 4, 5, 6, 8, and 10 times 30 μJy beam^{-1}, the average rms noise of the maps. The angular resolution is $\sim$ 0.″3. The star marks the position of the peak emission of the 1990.2 individual map, believed to coincide with the invisible exciting star. The crosses mark the positions of the new twin condensations (N4 and S4) discovered by Martí et al. (1995) in the 1994.3-1990.2 difference map (left hand side map). Note that in the most recent difference map (1995.5-1990.2; right hand side map) the condensations have become fainter and continue to displace away from the central star.

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.

Martí et al. (1993) found in the radio continuum an extraordinarily well collimated outflow, at all the angular scales observed, with a total projected linear size of about 5.3 pc. At the core of this outflow, they mapped a thermal jet coincident with IRAS 18162−2048. A map of this source, VLA 1, is shown in Figure 1.

Even when the appearance of this thermal jet does not change dramatically with time, Martí et al. (1995) have been able to detect proper motions in several of the condensations in the jet. The corresponding velocities of the condensations are in the range 600-1400 km s^{-1}, confirming that we are dealing with a high-mass object. It is known observationally (although not explained theoretically) that the final velocity of ejecta tends to be of the order of the escape velocity of the source from which they emanate. Then, from solar-mass stars we expect velocities in the range of 300 km s^{-1}, while from massive stars we expect larger velocities, in the range of ~1000 km s^{-1}.

Martí et al. (1995) also noted, by subtracting maps made in 1990 and 1994 the appearance of new twin condensations (named N4 and S4) near the core that must have been ejected between the two epochs of observation. We have continued (Martí, Rodríguez, & Reipurth 1996) to follow the proper motions of these two new condensations and subtraction maps (1994-1990 and 1995-1990) do show that these new condensations partake in the large proper motions observed by Martí et al. (1995) for the more external, older condensations (see Figure 2). From the regular separation of the external condensations, Martí et al. (1995) propose a periodicity of 6 or 7 years for the ejections and speculate that a new ejection event should take place around year 2000-2001. This prediction provides a unique opportunity to monitor the source at infrared and radio wavelengths and to follow its behaviour 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).

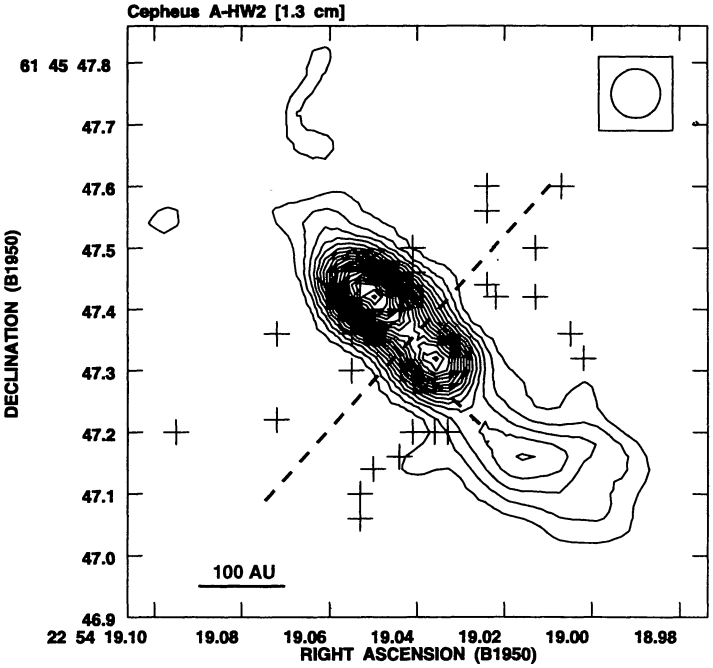

Fig. 3. VLA-A continuum map of the Cepheus A HW2 thermal radio jet made at 1.3 cm by Torrelles et al. (1996). Contours are −3, 3, 6, 9, 12, 15, ... times 0.12 mJy beam^{-1}, the rms noise of the map. The half power contour of the beam is shown in the top right-hand corner. Crosses indicate the position of the H_2O maser spots detected in a region of about 0.8 arc sec around HW2. Dashed lines indicate the major and minor axes of the disk traced by the maser spots.

An accurate position for the powerful H_2O maser (Rodríguez et al. 1980a) in the region has been determined recently by Gómez et al. (1995). The maser is found to coincide with the weak source VLA 3 (see Figure 1) and not with the thermal jet (VLA 1). The relationship between H_2O masers and thermal jets is discussed by Gómez et al. (1995).

3. CEP A HW2

Cepheus A is one of the best examples of molecular outflows associated with high-mass star formation (see Garay et al. 1996, and references therein). This energetic molecular outflow of complex morphology is probably powered by the radio-continuum source HW2 (Hughes & Wouterloot 1984; Torrelles et al. 1986). Recent multi-frequency VLA radio continuum observations of HW2 carried out by Rodríguez et al. (1994) indicate that this source is a thermal radio jet, with a deconvolved size of ~ 0.8 ×0.1 arc sec (P.A. = 48°) at 3.5 cm. Rodríguez et al. found that the deconvolved FWHM major axis of this source decreases with frequency as $[\frac{\theta_{maj}}{''}] \simeq 2.7\,[\frac{\nu}{GHz}]^{-0.57}$, while the total flux density conforms to a power law of the form $[\frac{S_\nu}{mJy}] \simeq 2.5\,[\frac{\nu}{GHz}]^{0.69}$, suggesting that the radio emission from HW2 arises in a biconical ionized thermal jet according to the calculations by Reynolds (1986). Rodríguez et al. (1994), assuming that the wind velocity is 700 km s^{-1}, estimate a mass loss rate $\dot{M}_\star \simeq 8\times10^{-7}$ $M_\odot$ yr^{-1} for HW2, which is about 100 times larger than that expected for a B0.5 ZAMS star, the type of star suspected to be exciting HW2 (Torrelles et al. 1985, 1986). Consequently, the HW2 jet could represent one of the most powerful thermal radio jet known associated with a pre-main-sequence star, and one of the best sources for studying the phenomenon of outflow collimation in young stars.

To investigate the structure of Cep A HW2 with unprecedented angular resolution and fidelity, Torrelles et al. (1996) carried on simultaneous 1.3-cm continuum and water maser observations of the region. This type of observations allows to use the strong maser features to cross-calibrate the continuum data, correcting for phase noise due to atmospheric turbulence. This powerful technique, that was developed and applied successfully by Reid & Menten (1990) to study the radio continuum emission from the photosphere of red giant stars, was used for the first time by Torrelles et al. (1996) to investigate a star-forming region. The resulting continuum map (see Figure 3) has remarkable signal-to-noise ratio and indicates that most of the continuum emission is coming from two bright condensations (although a fainter "tail" is also present to the SW). This double morphology gives support to the proposition that the radio continuum emission from thermal jets arises in a biconical geometry that can only be resolved spatially with very high angular resolution observations.

With the technique used by Torrelles et al. (1996) it is possible also to locate the water masers very accurately with respect to the continuum source. These authors study their spatial distribution and kinematics and conclude that the 28 maser spots mapped by them in association with Cep A HW2 probably trace a rotating circumstellar molecular disk of radius ~ 300 AU, nearly perpendicular to the radio jet.

4. CONCLUSIONS

The detection and study of thermal jets associated with massive young stars suggests that the phenomenon of collimated mass loss extends over all the range of spectral masses. However, these sources are relatively rare with respect to the low-mass cases. As discussed by Martí et al. (1983), the expected number of collimated outflows in the Galaxy scales as the mass of the central star inversely to the sixth power. However, given their larger luminosity, once detected it is possible to study collimated outflows emanating from massive stars in great detail. Furthermore, these more massive cases are frequently associated with powerful water masers that can be used to cross-calibrate the continuum observations, as it has already been done in the case of Cep A HW2.

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