Part 5. Young stellar objects

Jets at all Scales
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Radio observations of jets from massive young stars

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Abstract. The formation of low mass stars takes place with the assistance of an accretion disk that transports gas and dust from the envelope of the system to the star, and a jet that removes angular momentum and allows accretion to proceed. In the radio, these ionized jets can be studied very close to the star via the thermal (free-free) emission they produce and at larger scales by the molecular outflows that result from their interaction with the surrounding medium. Is the same disk-jet process responsible for the formation of massive stars? I will review recent evidence for the presence of collimated jets and accretion disks in association with forming massive stars. The jets in massive protostars have large velocities that could produce a synchrotron component and I discuss the evidence for the presence of this non-thermal process in the jet associated with the HH 80-81 system.

Keywords. radiation mechanisms: nonthermal, stars: formation, ISM: jets and outflows

1. Introduction

A successful model, based on accretion via a circumstellar disk and a collimated outflow in the form of jets (Shu, Adams, & Lizano 1987), has been developed and found to be consistent with the observations for the case of low-mass star formation. An important question related to star formation is whether or not this model can simply be scaled up for the case of high-mass protostars or if other physical processes (i.e., merging; Bonnell, Bate, & Zinnecker 1998; Stahler, Palla, & Ho 2000; Bally & Zinnecker 2005) are present.

Since processes such as merging are expected to destroy or severely alter a disk-jet system, an observational approach to this issue has been to search, has has been found in low-mass stars (e. g. Rodríguez *et al.* 1998), for disk-jet systems also in massive protostars. In this contribution, I will concentrate on recent radio (centimeter, millimeter, and sub-millimeter) results obtained with interferometers. The forming massive stars are usually very heavily obscured and only radio and far-infrared observations can penetrate the surrounding dust and allow studies to be made. The interferometry is requiered because we are interested in the smallest possible scales of the phenomenon. Of course, star formation is now a field with observational and theoretical results coming from many angles and I recommend reading the recent reviews by McKee & Ostriker (2007), and Zinnecker & Yorke (2007).

2. Searching for Jets Associated with Massive Protostars

The study of massive forming stars is difficult because, in comparison to low mass stars, few massive stars form per unit time. This implies that one has to go to larger distances to find massive protostars. In addition, they form in clusters and stellar multiplicity is a problem in that it difficults identifying which of the stars is, for example, responsible for a large scale molecular outflow.

One can search for jets in the radio continuum. However, this in not easy because the compact, thermal (i.e., free-free) radio sources found at centimeter wavelengths in regions of star formation can have different natures. Some of them are ultracompact or hypercompact H ii regions, photoionized by an embedded hot luminous star. Other sources are clumps of gas or even circumstellar disks that are being externally ionized by a nearby star, such as the Orion proplyds (e.g., O'Dell & Wong 1996; Zapata *et al.* 2004) and the bright-rimmed clouds (e.g., Carrasco-González *et al.* 2006). An additional class of sources is formed by the thermal jets, collimated outflows that emanate from young stars and whose ionization is most probably maintained by the interaction of the moving gas with the surrounding medium (Eisloffel *et al.* 2000). Finally, there are also some examples of "radio Herbig-Haro" objects, obscured knots of gas that are being collisionally ionized by the shock produced by a collimated outflow (e.g., Curiel *et al.* 1993). There are also compact non-thermal sources, of which the most common are the young low-mass stars with active magnetospheres that produce gyrosynchrotron emission (e.g., Feigelson & Montmerle 1999). There are also emission regions where fast shocks may produce synchrotron emission (e.g., Henriksen *et al.* 1991; Garay *et al.* 1996).

To advance in the understanding of the nature of these compact radio sources it is necessary to have good quality data that allows the observer to establish the angular size, the morphology, the spectral index, the time variability, the polarization, and the presence of proper motions in them. Only a handful of the known star-forming regions have been studied carefully enough to clearly establish the nature of their compact radio sources. An example of a recent detection of a jet associated with a massive protostar is the case of the W75N region (Carrasco-González *et al.* 2010). These authors found that the radio continuum source Bc, previously believed to be tracing an independent star in the region, exhibits important changes in total flux density, morphology, and position. These results suggest that source Bc is actually a radio Herbig-Haro object, one of the brightest known, powered by the VLA 3 jet source (see Fig. 1). This result consolidates VLA 3 as a jet source, that given its morphology and spectral index was long suspected to be such a source.

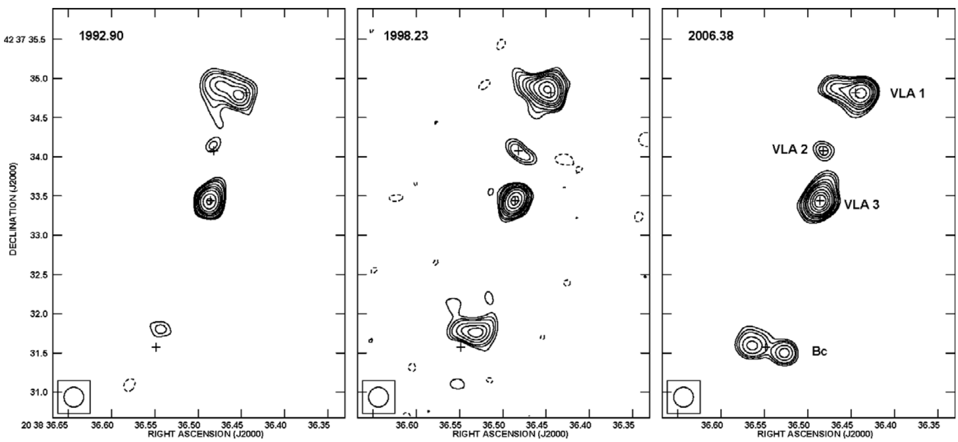

Figure 1. VLA contour images of the 3.6 cm emission from W75N for the three epochs (1992.90, 1998.23, and 2006.38) analyzed by Carrasco-González *et al.* (2010). Contours are –4, 4, 5, 6, 8, 10, 12, 15, 20, 25, and 30 times 80 μJy beam–1. The images have been restored with a circular beam of $0.''25$, shown in the bottom left corner of the images. The crosses mark the centroids of the radio sources for epoch 2006.38. Note the morphology changes and proper motions of VLA Bc, that suggest it is a radio HH object produced by the jet source VLA 3.

3. IRAS 16547-4247: The Most Massive Protostar with a Jet and a Disk

The source IRAS 16547-4247 is the best example of a highly-collimated outflow associated with an O-type protostar studied so far, and its study may reveal important information about the way high-mass stars form. The systemic LSR velocity of the ambient molecular cloud where IRAS 16547-4247 is embedded is –30.6 km s^{-1} (Garay *et al.* 2007). Adopting the galactic rotation model of Brand & Blitz (1993) and assuming that the one-dimensional root-mean square (rms) velocity dispersion among molecular clouds is 7.8 km s^{-1} (Stark & Brand 1989), Rodríguez *et al.* (2008) estimate a distance of 2.9±0.6 kpc for the source. IRAS 16547-4247 has a bolometric luminosity of 6.2×10^4 $L_\odot$, equivalent to that of a single O8 zero-age main-sequence star, although it is probably a cluster for which the most massive star would have a somewhat lower luminosity. Garay *et al.*

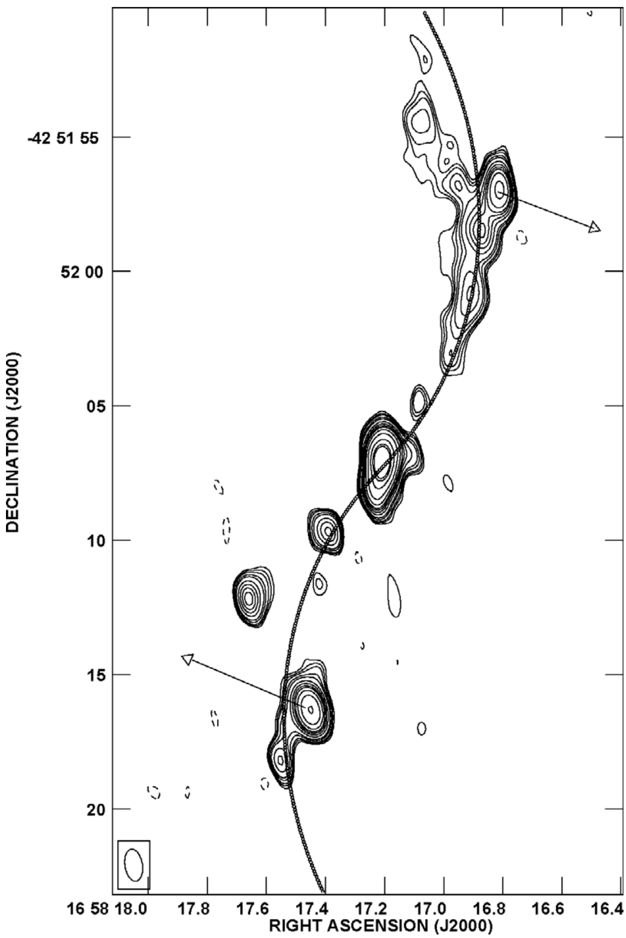

Figure 2. VLA contour image at 8.46 GHz toward IRAS 16547-4247 for epoch 2003.74. Contours are –25, –20, –15, –10, –8, –6, –5, –4, 4, 5, 6, 8, 10, 15, 20, 25, 30, 40, 60, 100, 140, 160, and 200 times 27 μJy beam^{-1}. The half power contour of the synthesized beam ($1''.20 \times 0''.65$; P.A. = 9°) is shown in the bottom-left corner. The solid line indicates the position of the spiral model discussed by Rodríguez *et al.* (2008). The arrows indicate the proper motions of components N-1 and S-1 for a period of 300 years.

(2003) detected an embedded triple radio continuum source associated with the IRAS 16547-4247. The three radio components are aligned in a northwest-southeast direction, with the outer lobes symmetrically separated from the central source by an angular distance of $\sim 10''$, equivalent to a physical separation in the plane of the sky of about 0.14 pc. The positive spectral index of the central source is consistent with that expected for a radio thermal (free-free) jet (e.g., Anglada 1996; Rodríguez 1997), while the spectral index of the lobes suggests a mix of thermal and nonthermal emission.

Rodríguez *et al.* (2008) do not detect proper motions along the axis of the outflow in the outer lobes of this source at a 4-σ upper limit of $\sim$160 km s^{-1}. This suggests that these lobes are probably working surfaces where the jet is interacting with a denser medium. However, the brightest components of the lobes show evidence of precession, at a rate of $0\overset{\circ}{.}08$ yr^{-1} clockwise in the plane of the sky (see Figure 2). It may be possible to understand the distribution of almost all the identified sources in this region as the result of ejecta from a precessing jet.

This source also has good evidence favoring the existence of an associated disk. Franco-Hernández *et al.* (2009) found a rotating structure associated with IRAS 16547-4247, traced at small scales ($\sim$50 AU) by water masers. At large scales ($\sim$1000 AU), they find a velocity gradient in the SO_2 molecular emission with a barely resolved structure that can be modeled as a rotating ring or two separate objects. The velocity gradients of the masers and of the molecular emission have the same sense and may trace the same structure at different size scales. The position angles of the structures associated with the velocity gradients are roughly perpendicular to the outflow axis observed in radio continuum (see Fig. 2) and several molecular tracers. Franco-Hernández *et al.* (2009) estimate the mass of the most massive central source to be around 30 solar masses from the velocity gradient in the water maser and SO_2 emissions. They conclude that their results suggest that the formation of this source, one of the most luminous protostars known, is taking place with the presence of ionized jets and disk-like structures.

Evidence for disks in association with other massive forming stars has been provided recently by Beuther & Walsh (2008; IRAS 18089–1732), Zapata *et al.* (2009; W51 North), and Galván-Madrid *et al.* (2010).

4. A Magnetized Jet in IRAS 18162−2048

The highly collimated HH 80-81 radio jet is driven by the massive protostar IRAS 18162−2048, with a luminosity of $\sim$17000 $L_\odot$ (Aspin & Geballe 1992). The jet consists of a chain of radio sources aligned in a SW-NE direction and terminates at both ends in optical/radio Herbig-Haro objects. With a total extension of 5.3 pc (for an assumed distance of 1.7 kpc; Rodríguez *et al.* 1980), this is the largest and most collimated protostellar radio jet known so far. Early radio observations showed that the spectrum of the emission from the central source is characterized by a positive spectral index, suggesting that it is dominated by thermal free-free emission (Martí *et al.* 1993). In contrast, the spectral indices of the emission from HH 80-81, HH 80 N, as well as from some of the knots in the jet lobes, suggest that an additional non-thermal component could be present in these sources (Martí *et al.* 1993).

Theoretical models for the formation of jets from young stellar objects require magnetic fields, on one hand close to the star to accelerate centrifugally gas off a rotating accretion disk and on the other at larger distances to collimate the outflow. Evidence of synchrotron emission has been found in a handful of objects, as suggested by negative (non-thermal) spectral indices. In contrast with free-free emission that is unpolarized, synchrotron emission brings information on the strength and direcion of the magnetic field. Carrasco-González *et al.* (2010, in preparation) have found polarized synchrotron emission arising from the lobes of the jet associated with the massive protostar IRAS 18162−2048 (see Fig. 3). The direction of the apparent magnetic field and the increase of the polarization at the projected edges of the jet are consistent with what is predicted for a confining helical magnetic field configuration. This result could open a new way of investigating the nature and relevance of magnetic fields in star formation.

Furthermore, recent theoretical works (e.g. Bosch-Ramón *et al.* 2010), suggest that protostellar jets could be a source of gamma rays. These models postulate, as a working hypothesis, the presence of relativistic electrons in such jets. Our detection of synchrotron emission in the HH 80-81 jet demonstrates the presence of relativistic electrons in the jets from massive protostars, providing an observational ground to the theoretical conjecture, making these objects a potential target for future high-energy studies.

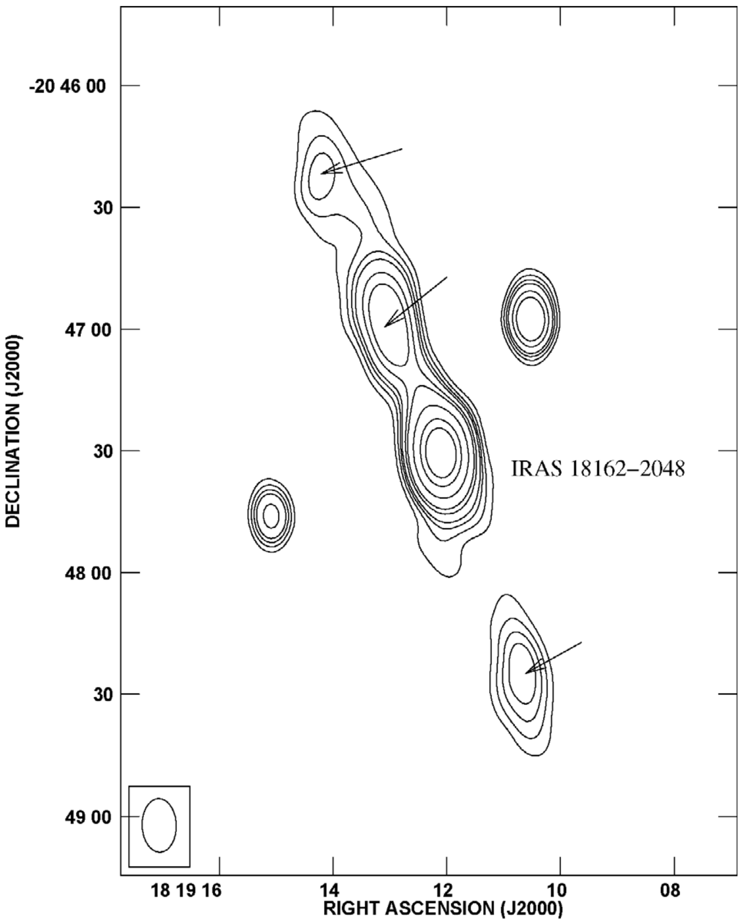

Figure 3. VLA contour image at 4.9 GHz toward IRAS 18162–2048. Contours are –4, 4, 6, 8, 10, 15, 20, 40, 80, and 120 times 26 μJy beam^{-1}, the rms noise of the image. The half power contour of the synthesized beam ($13''.2 \times 8''.4$; P.A. = 2°) is shown in the bottom-left corner. The components where Carrasco-González *et al.* (2010, in preparation) detected linear polarization are indicated with arrows. The central source is indicated as IRAS 18162–2048 and has a thermal spectrum and no detectable polarization. The other two sources in the field probably trace stars in the cluster associated with IRAS 18162–2048.

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Discussion

de Gouveia Dal Pino: What is the typical extinction of the jets coming out of massive stars and at what distance have you observed the non-thermal components?

Rodriguez: They can extend over several parsecs. However, the two lobes where polarization was detected are relatively close to the central source, at about 0.5 pc.

BENAGLIA: Which is the degree of polarization of the Carrasco-Gonzalez + 2010 source? And the threshold for detection?

RODRIGUEZ: The degree of polarization in this source goes from 10% to 40%. This type of sources are weak and we can detect polarization above 10%. Ammonia is very useful to study dense ($\gtrsim 300\,\mathrm{cm}^{-3}$) molecular gas, so it will usually be detecxtable in massive star-forming regions.

BENAGLIA: Which is the ratio of number of sources with detected polarization to total number studied?

RODRIGUEZ: We studied in detail for polarization six jets rom massive young stars. Only HH 80-81 showed detectable polarization.

BENAGLIA: Which will be a time scale to look for source variability (when nothing but emission with a negative spectral index is what you see)?

RODRIGUEZ: There is clear evidence of variability in time scales of years. Faster variability may be present, but the very high signal-to-noise ratios and with the required short time separations.