THERMAL RADIO JETS

LUIS F. RODRIGUEZ
Instituto de Astronomía, UNAM
Apdo. Postal 70-264
México, DF, 04510 México

Abstract. Since thermal radio jets can be observed with subarsecond angular resolution and are unaffected by dust absorption, they provide a useful tool to study collimated outflows very close to the young stars that produce them. Here, I review recent results on this area, giving emphasis to the study of thermal jets in the case of the quadrupolar outflows in L723 and HH 111.

1. Introduction

Young stars are known to possess powerful collimated winds that interact with their surrounding gaseous medium producing the Herbig-Haro objects and the molecular bipolar outflows. As demonstrated by these Proceedings, great advance has been made in our understanding of these large scale (tenths of pc or more) manifestations of the mass loss activity in young stars. Our understanding of the "engine" that powers these outflows is, however, still limited. There is a degree of consensus in the sense that the acceleration and collimation of these winds involves magnetohydrodynamic processes in an accretion disk, but many basic questions remain. What is the collimation scale? Why are the terminal velocities of these winds comparable with the escape velocity of the central object? What is the ratio between accreted and ejected material? Are these winds the mechanism by which the forming star gets rid of excess angular momentum and magnetic flux?

Certainly, observations with the highest angular resolution possible are required to address these important issues. In this paper, I review recent results in the field of thermal jets. At centimeter wavelengths the continuum emission from young stellar objects is dominated by free-free

B. Reipurth and C. Bertout (eds.), Herbig–Haro Flows and the Birth of Low Mass Stars, 83–92.

(bremsstrahlung) emission from ionized, collimated outflows (thermal jets), that can be observed using radio interferometers with angular resolutions in the range of 0.″1. This field was pioneered by the studies made toward T Tauri stars with the Very Large Array by Cohen *et al.* (1982), and this radio interferometer is still the instrument of choice given its great sensitivity. Recent reviews concerning thermal jets have been given by Anglada (1995; 1996), and Rodríguez (1995; 1996).

2. Thermal Jets

2.1. HOW ARE THERMAL RADIO JETS IDENTIFIED?

Since the thermal jets are detected via their centimeter continuum emission, it could be easy to erroneously identify another type of source as one of them. There are, however, a number of criteria that allow the reliable identification of a radio source as a thermal jet.

1. One expects them to be located at the centroid of the outflow region. A calculation of whether or not the source detected in the solid angle considered could be an unrelated background source is also valuable. This test can be made using background source counts. For example, extrapolating from the results of Condon (1984) to 3.6-cm (the most sensitive wavelength at the VLA) one expects $\sim 0.01\ S^{-0.8}$ background sources per square arc min above a flux density of S (in mJy). Then, if for example other observations of the region suggest that the exciting source should be located in a region of solid angle of 0.5 square arc min and a source of 0.5 mJy is detected at 3.6-cm in this solid angle, most likely this source is associated with the region considered since the *a priori* possibility of the source being a background object is only $\sim$0.01.

2. The thermal jets are expected to be elongated along the large-scale outflow axis, as traced by the Herbig-Haro objects and/or the bipolar outflow.

3. Thermal jets should show characteristic dependences with frequency for the total flux density, S_ν, and the deconvolved major axis, θ_{maj}. The theoretical radio continuum spectra of a confined thermal jet has been calculated by Reynolds (1986). 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 ϵ 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 $\theta_{maj} \propto \nu^{-0.7}$. Anglada (1996) presents a list of sources where these frequency dependences have been measured.

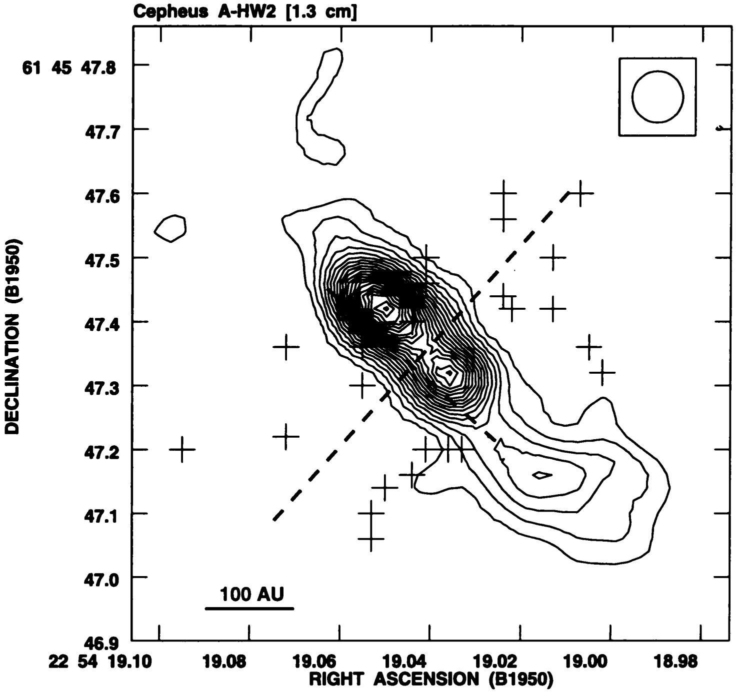

Figure 1. VLA-A continuum map of the Cepheus A HW2 thermal radio jet at 1.3 cm. Contours are −6, −3, 3, 6, 9, 12, 15, etc ... times 0.12 mJy $beam^{-1}$, the rms noise of the map. The beam is shown in the top right-hand corner. Crosses indicate the position of the H_2O maser spots detected in a region of about 0.8 arcsec around HW2. Dashed lines indicate the major and minor axes of the disk that is proposed to be traced by the maser spots.

4. The gas detected in the radio continuum has left the star in the last months or years. One then expects to be able to measure variations and/or proper motions of condensations in the jet on timescales of years or even less. The case of HH 80-81 is well studied by Marti *et al.* (1993; 1995), who 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 (since a correlation is expected between outflow velocity and the mass of the star).

5. Thermal jets are intimately associated with warm, dense molecular gas (as traced by ammonia: see Torrelles *et al.* 1992, 1993a; Gómez *et al.* 1994; or CS: see Yang *et al.* 1997). Finally, it has become evident recently

that at least in some cases the thermal jets can be associated with H_2O masers (Gómez *et al.*, 1995). The relation between the thermal jets and the H_2O masers is unclear: while in Cep A HW2 the masers seem to be tracing a circumstellar disk perpendicular to the jet (see Figure 1 and Torrelles *et al.* 1996), in L1448C the masers appear to be related morphologically and kinematically with the jet (Chernin, 1995).

2.2. ADVANTAGES AND DISADVANTAGES

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 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 these sources (e.g., HH 1-2: Pravdo *et al.* 1985; L1448C: Curiel *et al.* 1990; NGC 2264G: Gómez *et al.* 1994; HH 24: Bontemps *et al.* 1995, 1996) 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, positions from IRAS and other FIR observations have been notably improved (e.g., RNO 43, B 335: Anglada *et al.* 1992; HH 114, HH 199: Rodríguez and Reipurth 1996).

3. These radio continuum observations have permitted, in a number of cases, to distinguish and to discriminate among several candidates for the outflow excitation and even to propose alternative candidates. A recent example of this use of thermal jets is the finding by Rodríguez et al. (1997) of a radio source previously undetected at other wavelengths at the core of the HH 7-11 outflow (see Figure 2). These authors favor this new object as the most likely exciting source of this classic HH system, although noting that high-angular resolution molecular observations of the region are required to test more conclusively if the powering source of the outflow is this new radio object or the infrared/optical source SVS 13. Useful additional criteria that can be used to favor between candidates are the proximity of the source to a high density and/or a temperature molecular peak, the association with high velocity molecular gas, and the 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 or even less).

5. In the case of low luminosity objects ($L_\star \leq 300\ L_\odot$) it has been pos-

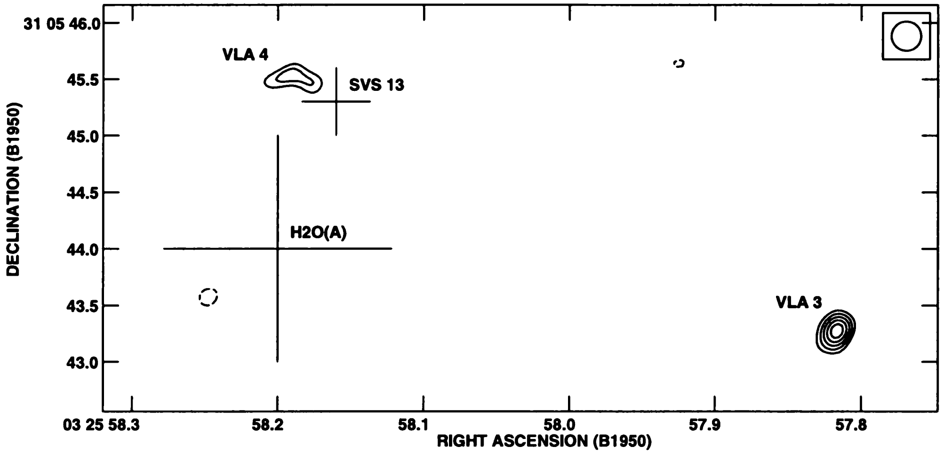

Figure 2. Natural-weight VLA map at 3.6 cm wavelength made in the A configuration of the sources VLA 3 and VLA 4 at the central region of the HH 7-11 outflow. The positions of the near-infrared/optical source SVS 13 and of the water maser H_2O(A) are indicated with crosses. The source VLA 4 is associated with the infrared/optical source SVS 13. The source VLA 3 is a newly detected object that has been proposed by Rodríguez *et al.* (1997a) 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 μJy beam^{-1}.

sible to establish (Anglada, 1996) 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.

A major disadvantage with the subarcsecond observations of thermal processes is the modest flux density contained in the very small synthesized beam. When observing a source with brightness temperature T_B, at a frequency ν, with a circular beam with angular diameter θ_B, the flux density inside the beam will be given by

$$\left[\frac{S_\nu}{mJy}\right] = 0.40 \left[\frac{\nu}{8.4\ GHz}\right]^2 \left[\frac{T_B}{10^3\ K}\right] \left[\frac{\theta_B}{0.1\ arc\ sec}\right]^2 . \quad (1)$$

This equation implies that very sensitive instruments are required for the study of thermal processes with high angular resolution. For free-free emission in typical astrophysical conditions, it is expected that $T_B \leq 10^4\ K$. The relatively low brightness temperature of thermal processes limits at present the use of very long baseline interferometry, that could provide milliarcsecond angular resolution. In addition to the relative weakness of

https://doi.org/10.1017/S0074180900061568 Published online by Cambridge University Press

the sources, since we are dealing with a continuum emission process we do not have direct radial velocity information. This limitation can be alleviated if proper motions can be measured in the future in the condensations of thermal jets (Marti *et al.*, 1995).

2.3. ARE THERMAL JETS ALWAYS PRESENT IN OUTFLOW REGIONS?

This is a difficult question to answer, since it seems to depend on how deep one is able to integrate on a given region. Rodríguez and Reipurth (1996; 1997a) have made relatively deep integrations (one to two hours) with the VLA at 3.6-cm, detecting the possible exciting source in 11 out of 14 regions studied. Many of these sources had been previously observed unsuccessfully with the VLA in the snapshot mode (integrations with 10 to 20 minutes of duration). The sources detected include HH 34, B5, HH 83, and IRAS 04368+2557 (= L1527). Most well-studied outflow sources have thermal jets at their centers. One notable exception is HH 212 (Zinnecker *et al.*, 1997).

3. Quadrupolar Outflows

One example of the possibilities provided by the study of thermal jets is given by the case of the 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 *et al.*, 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.* 1993b), (3) Multiple episodes of outflow activity, with precession of the outflow axis, could produce a complex lobe morphology (e.g., Fukue and Yokoo 1986; Narayanan and Walker 1996), and (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 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 and Lane, 1991), IRAS 21334+5039 (Smith and Fischer, 1992), IRAS 20050+2720 (Bachiller *et al.*, 1995), and HH 111 (Cernicharo and Reipurth, 1996). Here we will discuss recent results related to L723 and HH 111.

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 and Snell 1989; Avery *et al.* 1990; Hayashi *et al.* 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 *et al.* (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 3). 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.

3.2. HH 111

HH 111 is a spectacular HH jet located in L1617 in the Orion B cloud complex (Reipurth, 1989). The central 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 and Reipurth (1994). This thermal jet appeared to align very well with the optical flow (at a position angle of about 277°). Recently, Gredel and Reipurth (1993; 1994) and Cernicharo and Reipurth (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 and Reipurth (1997b) undertook a deeper integration with the VLA toward the core of HH 111. The resulting map (see Figure 4) reveals that, in addition to the previously known elonga-

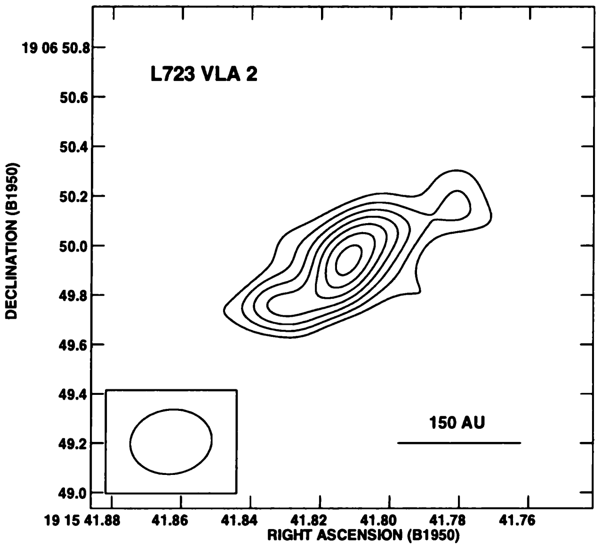

Figure 3. VLA map at 3.6 cm wavelength of the source VLA 2 at the core of the quadrupolar outflow in L723. Contours are −3, 3, 4, 5, 6, 7, 8, and 9 times the rms noise of 11 μJy beam^{-1}. The half power contour of the synthesized beam is also shown. The major axis of VLA 2 aligns with the axis of the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

tion 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 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

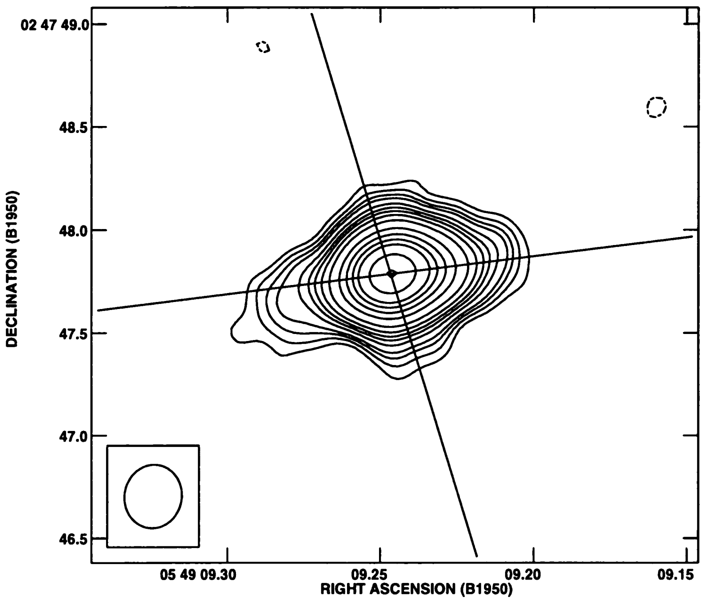

Figure 4. VLA map at 3.6 cm wavelength of the exciting source at the core of the quadrupolar outflow in HH 111. Contours are −3, 3, 4, 5, 6, 8, 10, 12, 15, 20, 30, 40, 50, 60, 80, and 100 times the rms noise of 5.4 μJy beam^{-1}. The half power contour of the synthesized beam is also shown. The straight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

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.

Acknowledgements: The author gratefully acknowledges comments from G. Anglada, J. Martí, and J. M. Torrelles and the continued support of DGAPA, UNAM and CONACyT, México.

References

Anglada, G. 1995, in Rev. Mexicana Astron. Astrofís. Ser. Conf. 1, Circumstellar Disks, Outflows and Star Formation, ed. S. Lizano & J. M. Torrelles (México, D.F.: Inst. Astron., UNAM), 67

Anglada, G. 1996, in ASP Conf. Ser. 93, Radio Emission from the Stars and the Sun, eds. A.R. Taylor & J.M. Paredes, (San Francisco: ASP), 3

Anglada, G., Estalella, R., Rodríguez, L.F., Torrelles, J.M., López, R, and Cantó, J. 1991, ApJ 376, 615

Anglada, G., Rodríguez, L.F., Cantó, J., Estalella, R., and Torrelles, J.M. 1992, ApJ 395, 494

Anglada, G., Rodríguez, L.F. and Torrelles, J.M. 1996, ApJ 473, L123

Avery, L.W., Hayashi, S.S., and White, G.J. 1990, ApJ 357, 524

Bachiller, R., Fuente, A. and Tafalla, M. 1995, ApJ 445, L51
Bally, J., & Lane, A.P. 1991, in Astrophysics with Infrared Arrays, ed. R. Elston, ASP. Conf. Ser. 14, 273
Bontemps, S., André, P., and Ward-Thompson, D. 1995, A&A 297, 98
Bontemps, S., Ward-Thompson, D., and André, P. 1996, A&A 314, 477
Cernicharo, J. and Reipurth, B. 1996, ApJ 460, L57
Chernin, L.M. 1995, ApJ 440, L97
Cohen, M., Bieging, J.H. and Schwartz, P.R. 1984, ApJ 253, 707
Condon, J.J. 1984, ApJ 287, 461
Curiel, S., Raymond, J., Rodriguez, L.F., Canto, J., and Moran, J.M. 1990, ApJ 365, L85
Fukue, J. and Yokoo, T. 1986, Nature 321, 841
Garay, G., Ramírez, S., Rodríguez, L.F., Curiel, S., and Torrelles, J.M. 1996, ApJ 459, 193
Girart, J.M., Estalella, R., Anglada, G., Torrelles, J.M., Ho, P.T.P., and Rodríguez, L.F. 1997, submitted to ApJ
Goldsmith, P.F., Snell, R.L., Hemeon-Heyer, M. and Langer W.D. 1984, ApJ 286, 599
Gómez, J.F., Curiel, S., Torrelles, J.M., Rodríguez, L.F., Anglada, G., and Girart, J.M. 1994, ApJ 436, 749
Gómez, Y., Rodríguez, L.F., and Marti, J. 1995, ApJ 453, 727
Gredel, R. and Reipurth, B. 1993, ApJ 407, L29
Gredel, R. and Reipurth, B. 1994, A&A 289, L19
Hayashi, S.S., Hasegawa, T. and Kaifu, N. 1991, ApJ 377, 492
Marti, J., Rodríguez, L.F., and Reipurth, B. 1993, ApJ 416, 208
Marti, J., Rodríguez, L.F., and Reipurth, B. 1995, ApJ 449, 268
Mizuno, A., Fukui, Y, Iwata, T., Nozawa, S., and Takano, T. 1990, ApJ 356, 184
Moriarty-Schieven, G.H. and Snell, R.L. 1989, ApJ 338, 952
Narayanan, N. and Walker, C.K. 1996, ApJ 466, 844
Pravdo, S.H., Rodríguez, L.F., Curiel, S., Cantó, J., Torrelles, J.M., Becker, R.H., and Sellgren, K. 1985, ApJ 293, L35
Reipurth, B. 1989, Nature 340, 42
Reynolds, S.P. 1986, ApJ 304, 713
Rodríguez, L.F. 1995, in Rev. Mexicana Astron. Astrofís. Ser. Conf. 1, Circumstellar Disks, Outflows and Star Formation, ed. S. Lizano & J. M. Torrelles (México, D.F.: Inst. Astron., UNAM), 1
Rodríguez, L.F. 1996, in Rev. Mexicana Astron. Astrofís. Ser. Conf. 4, VIII Reunión Regional Latinoamericana de Astronomía de la IAU, ed. E. Falco, J.A. Fernández, & R.F. Ferrero (México, D.F.: Inst. Astron., UNAM), 7
Rodríguez, L.F. and Reipurth, B. 1994, A&A 281, 882
Rodríguez, L.F. and Reipurth, B. 1996, Rev. Mexicana Astron. Astrofís. 32, 27
Rodríguez, L.F., Anglada, G., and Curiel, S. 1997, to appear in ApJL
Rodríguez, L.F. and Reipurth, B. 1997a, in preparation
Rodríguez, L.F. and Reipurth, B. 1997b, in preparation
Smith, H.A. and Fischer, J. 1992, ApJ 398, L99
Torrelles, J.M., Gómez, J.F., Curiel, S., Ho, P.T.P., Eiroa, C., and Rodríguez, L.F. 1992, ApJ 384, L59
Torrelles, J.M., Rodríguez, L.F., Cantó, J., and Ho, P.T.P. 1993a, ApJ 404, L75
Torrelles, J.M., Verdes-Montenegro, L., Ho, P.T.P., Rodíguez, L.F., and Cantó, J. 1993b, ApJ 410, 202
Torrelles, J.M., Gómez, J.F., Rodríguez, L.F., Curiel, S., Ho, P.T.P., and Garay, G. 1996, ApJ 457, L107
Walker, C.K., Lada, C.J., Young, E. T. and Margulis, M. 1988, ApJ 332, 335
Yang, J., Ohashi, N., Yan, J., Liu, C., Kaifu, N., and Kimura, H. 1997, ApJ 465, 683
Zinnecker, H., McCaughrean, M., and Rayner, J. 1997, in preparation