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RADIO CONTINUUM OBSERVATIONS OF HERBIG-HARO OBJECTS

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RESUMEN

Los objetos Herbig-Haro (HH) son nebulosidades ópticas excitadas por el viento de una estrella jóven en su interacción con el medio ambiente. Estos objetos HH se han estudiado fundamentalmente con espectroscopía óptica y ultravioleta y, más recientemente, en el cercano infrarrojo. Sin embargo, la componente ionizada de esos objetos puede ser estudiada también a través de su emisión libre-libre. Esta emisión continua ha sido detectada en longitudes de onda centimétricas en varios objetos HH. Así, el número de detecciones ha ido creciendo lentamente desde que se encontró por primera vez continuo de radio en los objetos prototipo HH 1 y 2, hace ya diez años. Tanto la observaciones de continuo de radio de los objetos HH, así como de sus fuentes de energía, se han convertido en una poderosa técnica para estudiar el fenómeno de los flujos en las regiones de formación estelar. En este artículo, se presenta una revisión de observaciones recientes de continuo de radio de objetos HH clásicos, haciendo una comparación con observaciones ópticas. Se discuten individualmente unos cuantos objetos HH detectados en el radio.

ABSTRACT

Herbig-Haro (HH) objects are optical nebulosities excited by the wind of a young star, during its interaction with the ambient medium. HH objects have been mainly studied spectroscopically at optical and UV wavelengths, and more recently in the near infrared. However, the ionized gas component of these shocked regions can also been studied via its free-free emission. This continuum emission has been recently detected at centimeter wavelengths in a number of HH objects. The number of detections has been slowly increasing since the first detection of radio continuum in the prototype HH 1 and 2 objects, 10 years ago. Radio observations of this continuum emission from HH objects and their powering sources is becoming a powerful technique to study the outflow phenomenon in star-forming regions. A review of recent radio continuum observations of classical HH objects is presented, including a comparison with optical observations. Some examples of radio detected HH objects are also discussed.

Key words: **ISM: JETS AND OUTFLOWS — ISM: DUST, EXTINCTION — RADIO CONTINUUM: GENERAL — STARS: FORMATION — STARS: MASS LOSS — STARS: PRE-MAIN-SEQUENCE**

1. INTRODUCTION

It is now generally accepted that energetic mass outflow is an essential part of the star formation process. Optical observations carried out during the past few years have shown that young stellar objects (YSOs) often generate highly collimated jets, with velocities of several hundred km s^{-1} (Mundt 1988). These "Herbig-Haro

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1995RMxAC...1...59C

(HH) jets" tend to have a chain of low-excitation knots, that in some cases points towards a much brighter, higher excitation HH object with a bow-shaped morphology (e.g., HH 1 and HH 34), which apparently corresponds to the "head" of the jet. These optical outflows are generally bipolar in the sense that there are objects moving away from their energy source on both sides of the outflow. The shocks at the end of the jets are reasonably well understood in terms of simple bow-shock models (e.g., Hartigan et al. 1987), but the excitation in the jets themselves and the collimation mechanism remain controversial (e.g., Raga et al. 1993; Biro 1994; Raga 1995 for a review). On the other hand, the inner part of these jets and their energy sources are usually deeply embedded in dense gas, rendering them undetectable at optical wavelengths and in several cases even in the near infrared.

Recent studies have shown that some of these optical HH-jets have radio continuum emission associated with either the energy source (e.g., HH 7-11 and HH 94-95) or the HH object (e.g., HH 32), or with both (e.g., HH 1-2 and HH80/81). Reviews of this topic have been presented by Rodríguez (1989), Torrelles (1990), Rodríguez (1994, 1995) and Anglada (1995). Since the discovery of radio continuum emission in the HH 1 and 2 objects (Pravdo et al. 1985) about 10 years ago, several other optical HH objects have been searched for this type of emission and only upper limits have been obtained for most of them (e.g., Curiel et al. 1989; Rodríguez & Reipurth 1993; Curiel, Wilner, & Rodríguez 1995; Curiel & Rodríguez 1995). So far, only a few optical HH objects have radio continuum emission associated with them: HH 1 and 2 (Pravdo et al. 1985; Rodríguez et al. 1990), HH 80 and 81 (Rodríguez et al. 1989; Martí et al. 1993), Cepheus A-GGD37 (e.g., Hughes 1989, 1990; Garay et al. 1995), HH 32 (Anglada et al. 1992), and HH 12 (Snell & Bally 1986; Curiel et al. 1995b). Some other HH objects have unconfirmed faint radio continuum emission associated with them: HH 101 (Brown 1987), RNO43c (Anglada et al. 1992), and HH 68 and 69 (Girart et al. 1995). In addition, a few continuum sources have been proposed as radio-HH objects: the Serpens radio jet (Curiel et al. 1993), Cepheus A (Hughes 1993; Garay et al. 1995), HH 80N (Martí et al. 1993; Girart et al. 1994), and L1551 radio jet (Curiel et al. 1995d). In this paper some of the general characteristics of the radio continuum emission associated with optical and radio HH objects are reviewed, including a brief discussion of the origin of this emission.

2. GENERAL CHARACTERISTICS OF THE RADIO CONTINUUM EMISSION

The radio continuum emission in optical and radio HH objects has the following properties: 1) it appears extended (typically between 0".5 and 6") with typical fluxes between 0.2 and 2 mJy; 2) the spectral indices are either consistent with optically thin thermal free-free emission ($\alpha \sim -0.1$, with $S_\nu \propto \nu^\alpha$), or optically thin non-thermal synchrotron emission ($\alpha \sim -0.4$), or a combination of both; 3) proper motions have been measured in a few cases (e.g., HH 1 and 2, Serpens radio jet and HH 80/81); 4) the observed radio continuum fluxes seem to be about a factor of two smaller than predicted from Hα observations, assuming an optically thin H II region.

The detection of radio continuum emission in HH 1 and 2 (Pravdo et al. 1985) and the subsequent detailed VLA study of these objects opened a new way of studying the HH phenomenon. Radio continuum observations of HH objects have two main advantages. First, since radio continuum emission arises from the same shock waves that produce the emission lines observed in optical HH objects and jets (see, e.g., Curiel et al. 1987, 1993), it offers a way to detect and study the ionized gas component of classical HH objects and jets, as well as optically obscured ones that otherwise would be completely hidden from view by their high density surroundings. Second, the angular resolution provided by interferometers such as the VLA, MERLIN and AT (between 10" and 0".05) is similar or even better than those obtained at optical wavelengths (including the HST telescope) which allow the study of individual condensations in a given HH object. Furthermore, it is possible to measure proper motions in these condensations within a few years (e.g, Rodríguez et al. 1989, 1990; Curiel et al. 1993; Martí et al. 1995). On the other hand, radio continuum observations have some disadvantages. As it has been already mentioned, the flux density is small and large integration times are required to detect and study the radio continuum emission in detail. In addition, continuum observations do not provide information about the radial velocity of the ionized gas, although in some cases this information is obtained from optical observations. Even in the case of optically obscured radio-HH objects and jets, the radial velocity might be obtained from near infrared observations (e.g., [Fe II] or Brγ line emission) (Curiel et al. 1993).

Shock wave models show that the radio continuum emission scales linearly with the density of the ambient medium and with a power law of the shock velocity (e.g., Curiel et al. 1987; McKee & Hollenbach 1987). This dependence indicates that HH objects excited by high velocity shock waves (typically $\geq$ 100 km s^{-1}) and/or traveling through a high density medium (typically $\geq$ 1000 cm^{-3}) are probably the best candidates to be detected at radio continuum wavelengths. For instance, following the formulation given by Curiel et al. (1987) it can be shown that an HH object with an angular size of 1" would produce a flux density higher than 0.2

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1995RMxAC...1...59C

mJy at 6 cm when the factor $n_4 \times v_7^{1.68} > 1.0$, where n_4 is the ambient density in units of 10^4 cm^{-3} and v_7 is the shock velocity in units of 100 km s^{-1}. This result makes the high-excitation HH objects (where V_{sh} is typically $\geq$ 100 km s^{-1}) the best candidates to search for radio continuum emission associated with them. In fact, after the detection of HH 1 and 2, this type of emission has been searched and detected in a few more high-excitation HH objects such as HH 32 (Anglada et al. 1992), GGD37(S) (Hughes 1989, 1990; Garay et al. 1995), and HH 80 and 81 (Rodríguez et al. 1989). The fact that these sources are typically weak, about 0.3–2 mJy at 3.6 cm, and that they are between the brightest HH objects known make the detection of this type of emission in other HH objects very difficult, unless they are moving through an unusually dense gas. For instance, in regions where a highly collimated jet is still traveling through a high density molecular core, the interaction of the jet with the dense ambient gas will produce a substantial amount of radio continuum as well as optical and near infrared lines. However, these jets (or at least part of them) would be heavily obscured by the dense molecular core, rendering them undetectable at optical (and even near infrared) wavelengths, being detected only as radio HH objects or jets. As discussed below, this kind of scenario seems to occur in a number of regions such as L1551-IRS5, the Serpens radio jet, HH 80/81 and Cep A. On the other hand, low-excitation objects (where V_{sh} is typically $\sim$ 20-40 km s^{-1}) are expected to produce much less radio continuum emission than high-excitation ones, making their detection very unlikely. However, recent VLA observations of HH 12 have shown that this classical low-excitation object has relatively strong radio continuum emission associated with it, probably suggesting a very high density ambient gas. Below, 4 examples are used to briefly describe the general characteristics observed in the tentative four kinds of regions: high-excitation radio-optical HH objects, low-excitation radio-optical HH objects, radio-optical HH-jets and radio HH-jets.

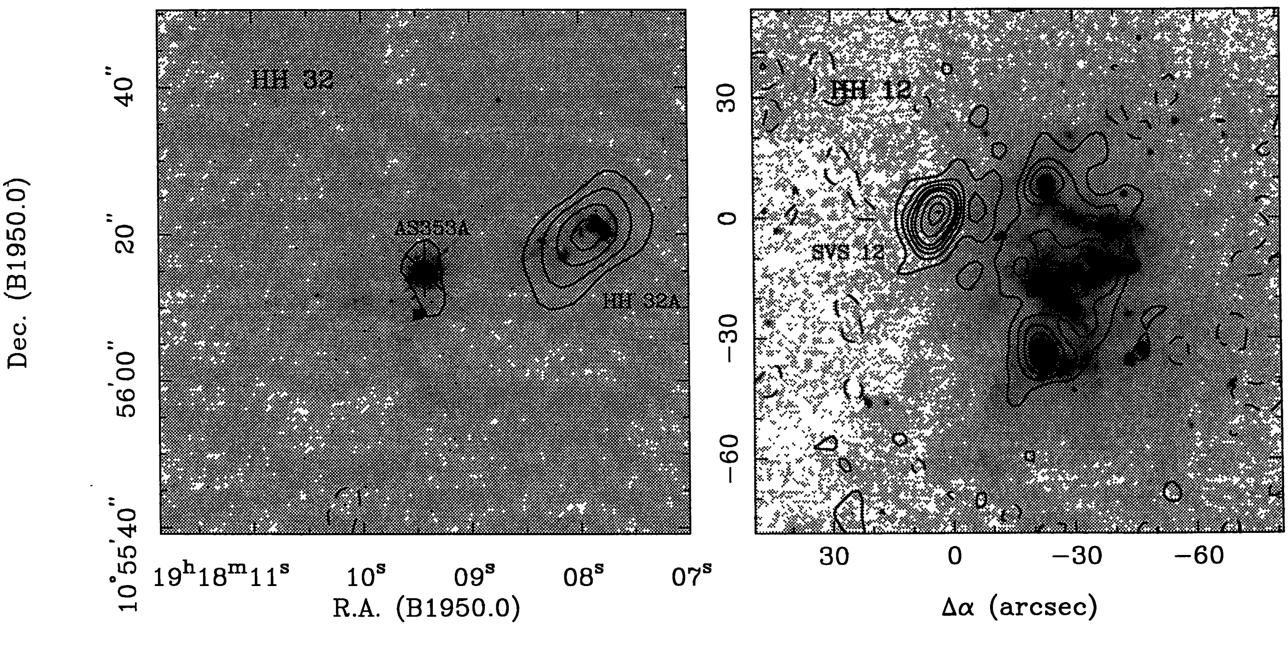

Fig. 1.— An example of two radio-optical HH objects. Left: Overlay of a 3.6-cm VLA map (taken from Anglada et al. 1992) and an HST Hα line image of the high-excitation HH 32 optical jet (from Curiel et al. 1995a; in preparation). The radio continuum emission clearly coincides with the optical HH 32A knots. Right: Overlay of a 3.6-cm VLA-D configuration map and an Hα line image of the low-excitation HH 12 optical object. The brightest radio source is associated with SVS 12, the most likely energy source of this system. The extended radio emission seems to follow the optical morphology, having two relatively bright and "compact" knots and fainter extended emission connecting the multiple optical knots.

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1995RMxAC...1...59C

3. RADIO CONTINUUM EMISSION IN INDIVIDUAL HH OBJECTS

3.1. High-Excitation Radio-Optical HH Objects: HH 32

HH 32 is a classical high-excitation HH-jet with a red-shifted lobe with three condensations (HH 32A, B and D) and a blue-shifted lobe with one condensation (HH 32C), aligned with its energy source AS353A. All of these condensations show emission line profiles that agree very well with predictions of bow shock models (Solf, Böhm, & Raga 1986; Raga, Böhm, & Solf 1986; Hartigan, Raymond, & Hartmann 1987), from which one speculates that they might correspond to individual "interstellar bullets" or "shocked cloudlets". Recent VLA observations of this jet (Anglada et al. 1992, see Fig. 1) show a single radio continuum source spatially coinciding with HH 32A, the brightest knot in this jet. The spectral index of the radio emission is still unknown and therefore, its origin has not been established. A comparison between the radio continuum flux and the Hα flux obtained for HH 32A indicate that the radio continuum expected from the observed Hα flux is about a factor of two higher than the value observed (Anglada et al. 1992). A similar discrepancy was previously found for the HH 1 and 2 objects by Pravdo et al. (1985). At present, this anomaly is a mystery without a satisfactory explanation. One can speculate that this discrepancy may be due to an overestimated of the reddening and/or to a relatively high collisionally excited Hα contribution to the total Hα emission due to the bow-shock geometry of the object. [The relationship between Hα and radio continuum applies only to the recombination component of the Hα emission.] It would be interesting to see if such a difference is constant in all the optical HH objects detected at radio wavelengths, or if it changes with the characteristics of the objects, for instance, for low and high-excitation objects.

3.2. Low-Excitation Radio-Optical HH Objects: HH 12

HH 12 is one of the most extended complexes of Herbig-Haro objects known to date, measuring $\sim 30'' \times 50''$ in size. The optical emission knots of HH 12 are blue-shifted with respect to the ambient cloud and coincide with the blue lobe of a CO outflow (Edwards & Snell 1983). Unlike many other HH objects, the outflow source has not been positively identified. Among the proposed candidates, the infrared source SVS 12, located 20" to the east of HH 12, seems very likely to be the exciting source of this complex (e.g., Stapelfeldt et al. 1991). However, proper motions of HH 12B and HH 12F are directed toward the north (Herbig & Jones 1983), roughly perpendicular to the direction of SVS 12. It is difficult to reconcile this result with an outflow from SVS 12.

Recent VLA observations of this region show that this HH object has extended radio continuum emission associated with it. Figure 1 shows an overlay of the 3.6 cm radio continuum emission (shown in contours) and the optical Hα emission (grey scale) observed in this object. This figure shows a clear relationship between the radio continuum emission and the Hα line emission; the stronger and more compact radio continuum knots are associated with the brighter knots in Hα, and the extended radio emission follows the stronger, extended Hα emission.

3.3. Radio-Optical HH-Jets: L1551-IRS5

The L1551 molecular outflow is one of the best studied low-mass star forming regions. The outflow lobes have an angular extend of several tens of arcminutes on the sky. Its energy source, IRS5, is a YSO, located at the base of a small ($\sim 10''$ long) optical and near IR jet (Mundt & Fried 1983; Neckel & Staude 1987; Campbell et al. 1988). The proximity of this region (140–160 pc) makes it possible to study small spatial elements. Multiple optical observations have revealed that several knots in the jet have proper motions of $\sim 0''.3$ yr^{-1} or ~ 190 km s^{-1} (Neckel & Staude 1987; Fridlund & Liseau 1994).

Recent VLA and MERLIN observations of this region have shown a radio jet nearly aligned with the optical jet (see Fig. 2). This radio jet contains at least one knot on each side of the outflow with extended emission connecting these knots with the central source (see Fig. 2). These observations show that the radio jet traces the inner part of the highly collimated outflow, and that the knotty structure observed in the optical jet continues even closer to the powering source. If the radio knots are associated with recent ejection of material they most likely have transverse velocities similar to those measured in the optical knots ($\sim$190 km s^{-1}). Given its closeness, these proper motions can be measured with the VLA and MERLIN even comparing observations conducted one year apart. Measuring the proper motions of the radio knots and comparing the spatial distribution of the radio jet emission with that of the optical jet, we expect to find a physical and kinematical connection between them (Curiel et al. in progress). In fact, following the evolution of both the

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1995RMxAC...1...59C

radio and the optical jets, we would probably be able to witness the transition of a radio HH-knot into an optical HH-knot. Preliminary results suggest that the outermost SW radio knot coincides spatially with a new knot that has recently started to appear in the optical (Fridlund & Liseau 1994; Curiel et al. 1995d, in preparation).

3.4. Radio HH-Jets: Serpens Radio Jet

The Serpens radio jet is located in the core of the Serpens molecular cloud (e.g., Torrelles et al. 1992), and is associated with the very YSO FIRS 1 (Curiel et al. 1993; Casali et al. 1993). VLA observations have shown that this source exhibits extraordinary characteristics. The central source coincides with H_2O and OH masers as well as an IRAS source which clearly marks it as a site of recent star formation. In addition, while this source is associated with a star forming region, its outer components exhibit nonthermal spectra (characteristic of optically thin synchrotron emission) and large proper motions of about $0''.12$ yr^{-1} (Rodríguez et al. 1989; Curiel et al. 1993). The positive and negative spectral indices observed along the jet seem to be the result of a combination of thermal and non-thermal emission produced within the same shock waves (Curiel et al. 1993).

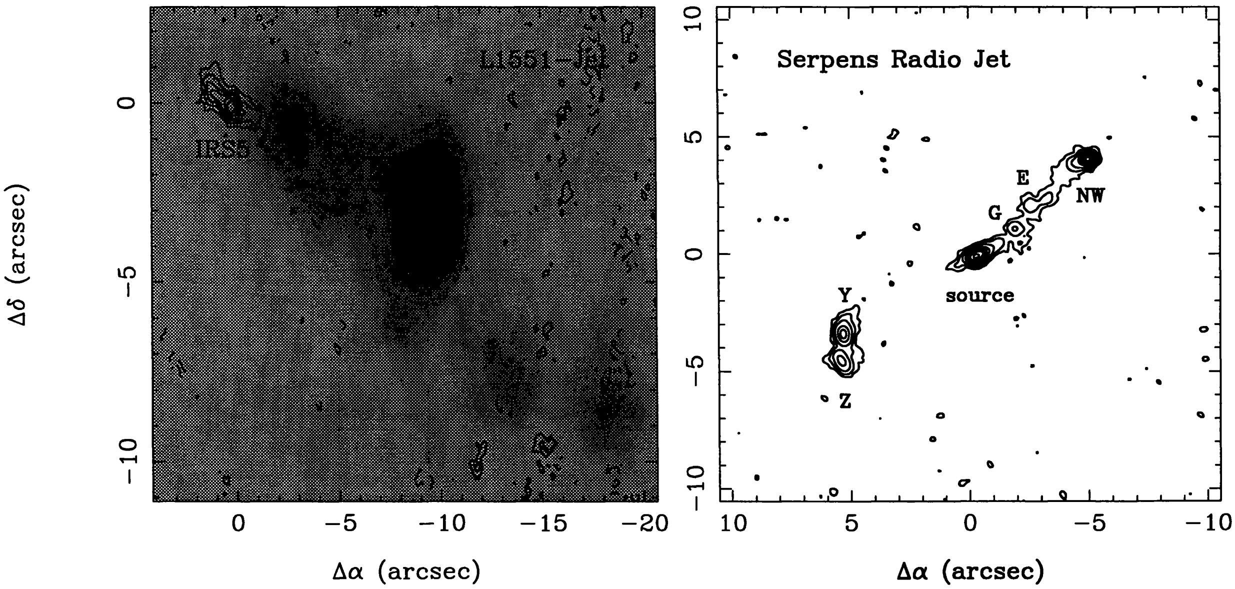

Fig. 2.— An example of two radio HH objects. Left: Overlay of the 18-cm MERLIN map and a [SII] line image (taken from Whitney & Gómez 1995) of the L1551-jet. The radio jet is nearly aligned with the optical jet, and traces the inner part of the outflow. Note that at the distance of this object, $1''$ corresponds to ~140 AU. The contour level increments are –5, –3, 3, 5, 7, 9, 12 and 15 times the 1-σ noise level of 36 μJy beam^{-1}. Right: 3.6 cm wavelength VLA-A configuration map of the Serpens radio jet. The three main components as well as two of the brightest knots in the jet are identified. At a distance of 300 pc, $1''$ corresponds to 300 AU. The contour levels are –6, –3, 3, 6, 12, 24, 48, 60, 80 and 100 times the 1-σ rms value of 16 μJy beam^{-1}.

Recent high angular resolution observations, at 3.6 cm wavelength with the A-array, have shown that this source exhibits a *one-sided radio jet morphology*, being in many respects very similar to Herbig-Haro optical jets, but having smaller dimensions (Curiel et al. 1993). The Serpens radio jet exhibits a knotty and extended emission connecting the central source with the outer NW component (Fig. 2). It also shows some wiggles, similar to those found in several Herbig-Haro jets (e.g., Strom et al. 1986; Reipurth 1989). In addition, the tangential velocities $\sim$ 200 km s^{-1} derived for these radio-HH knots are similar to those measured in some knots in a number of optical HH objects such as HH 1-2, HH 111 and HH 46/47 (e.g., Reipurth et al. 1992; Heathcote & Reipurth 1992; Eislöffel & Mundt 1992,1994). The predicted optical fluxes in the radio-HH knots would be in principle easily detectable if they were not so heavily obscured (Curiel et al. 1993).

There is some evidence indicating that both, precession and periodic ejection of material, are present in this radio jet (Curiel et al. 1993, 1994). Multiepoch observations of this region (Curiel et al. 1994; Curiel et al.

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1995RMxAC...1...59C

1995c) have shown that: (a) the major axis of the central source seems to be rotating clockwise, with an angular speed of about 1°5 per year; (b) the knots in this jet are moving away from the central source with a similar tangential velocity of ~ 0″12 per year, and with an angular dispersion of ~18° (see Fig. 3); and (c) the powering source is still ejecting material as shown by the very recent detection of a new knot at the base of the jet. These characteristics, along with the ~ 60 yr dynamical age of this radio jet, indicate that FIRS 1 is currently a very active YSO.

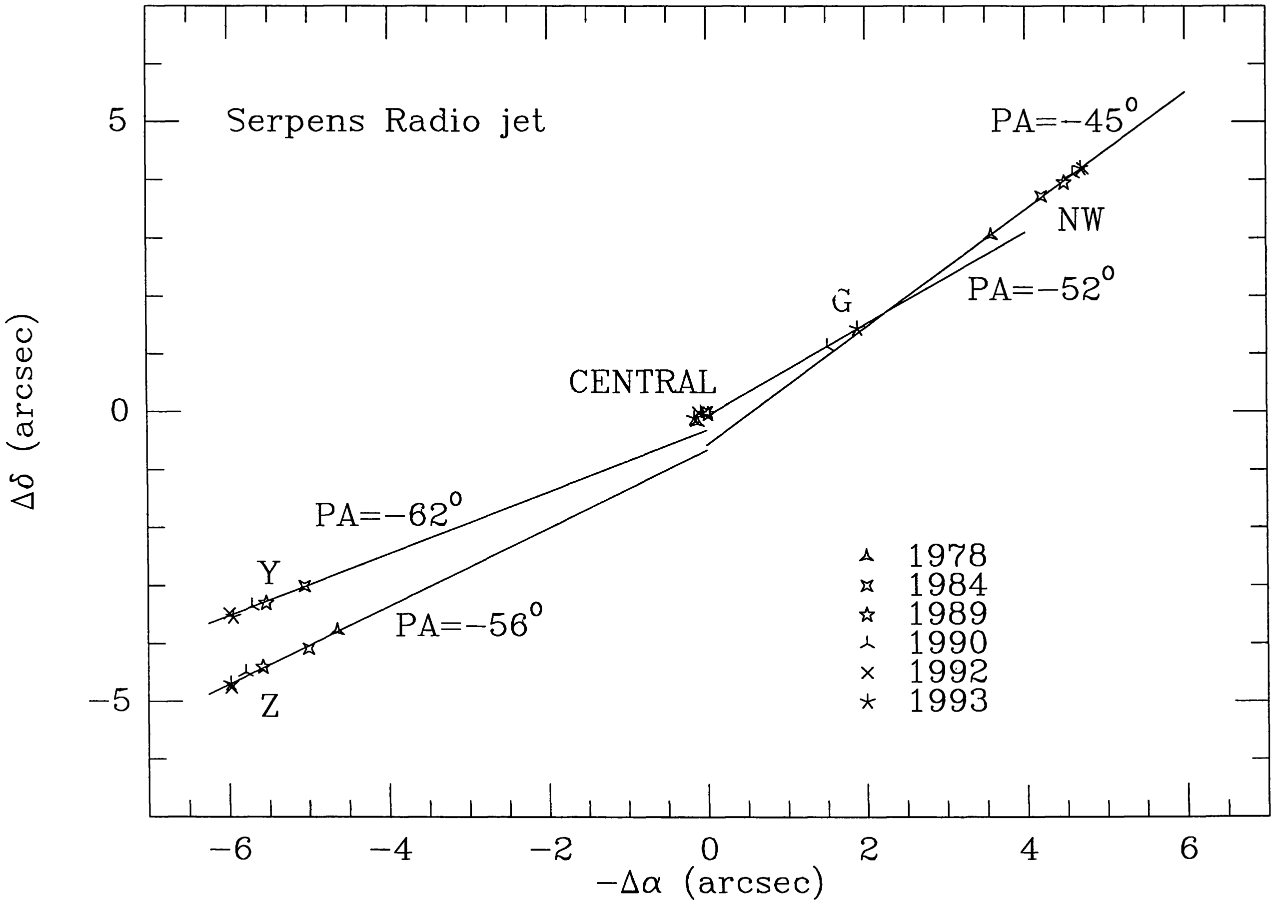

Fig. 3.— Graphical representation of the proper motions of the four brightest knots (NW, Y, Z, and G) in the Serpens radio jet. All the positions obtained for these knots between 1978 and 1993 were included. The angular displacement of the knots is given with respect to the position of the central source in the 1984 epoch. The position angles of these proper motions were obtained by making a least-squared fit to the position of a given knot at all the observed epochs, and are shown in the figure as solid lines. This figure clearly shows that the knots are moving away from the central source but with different directions within an opening angle of ~ 18°.

Finally, the intriguing properties of this radio jet have been recently observed in at least two massive YSO. The radio emission in HH 80/81 and Cep A also seem to be the result of a combination of thermal free-free and non-thermal optically thin synchrotron processes (Martí et al. 1993; Garay et al. 1995). In addition, at least one radio knot in Cep A (Hughes 1993) and some of the knots in HH 80/81 (Martí et al. 1995) also have proper motions. Also, the wiggles observed in HH 80/81 seem to be consistent with the powering source being precessing.

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1995RMxAC...1...59C

4. SUMMARY

Radio continuum observations of Herbig-Haro Objects have provided a new way to study this phenomenon. This type of emission arises from the shock waves that produce the line emission observed in optical HH objects. At present, only 11 optical HH objects have been detected at radio centimeter wavelengths, and 4 radio objects have been proposed to be radio-HH objects heavily obscured by the dense molecular core, rendering them undetectable at optical wavelengths. Radio observations provide information about the ionized component of the shocked gas. The results show that the radio emission is typically thermal, optically thin free-free emission. However, in some cases, the extended emission seems to be the result of a combination of both thermal (free-free) and non-thermal (optically thin synchrotron) emission components. It is possible to measure proper motions of radio-optical HH objects, as well as radio-HH objects, within a few years. In a few cases, there is evidence indicating that both, precession and periodic ejection of material are taking place.

Finally, recent radio continuum observations indicate that observations at radio wavelengths can be very useful for detecting and studying Herbig-Haro objects and jets associated with very young stellar objects deeply buried in molecular clouds and undetectable at optical wavelengths. This type of objects could also be detected in the near infrared, providing further information about the shocked gas. Thus, the combination of radio and near infrared observations could prove very useful for the study of the physical properties of optically obscured HH objects and jets.

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