Rev. Mexicana Astron. Astrof., **18**, 45-54 (1989)

RADIO OBSERVATIONS OF HERBIG–HARO OBJECTS

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RESUMEN. Los objetos Herbig–Haro son nebulosidades ópticas excitadas por una onda de choque producida por el viento estelar de una estrella joven. Se presenta una reseña de los resultados de observaciones de objetos Herbig–Haro y sus alrededores hechas recientemente en las radiofrecuencias. Estudios de gas neutro (tanto molecular como atómico) nos dan información sobre tres componentes claves para comprender estas regiones de formación estelar reciente con flujos gaseosos: 1) el gas denso de baja velocidad ($\Delta v \simeq 1$ km s^{-1}) que rodea a las fuentes excitadoras de los flujos, 2) el gas de alta velocidad ($\Delta v \simeq 10$ km $^{-1}$), que forma los llamados flujos bipolares y que parece ser gas de la nube ambiente acelerado por un viento estelar y, 3) el gas de velocidad extremadamente alta ($\Delta v \simeq 100$ km s^{-1}) que podría ser el viento mismo o al menos una componente gaseosa íntimamente asociada con él.

La componente de gas ionizado también puede estudiarse mediante su emision libre–libre. Las observaciones de esta emisión continua de los objetos HH y de sus fuentes excitadoras en las radiofrecuencias se están desarrollando como una técnica poderosa para estudiar el fenómeno de los flujos gaseosos en regiones de formación estelar. Se discuten observaciones recientes de radiocontinuo en algunos objetos HH.

ABSTRACT. The Herbig–Haro objects are optical nebulosities excited by a shock wave produced by the wind of a young star. A review of recent radio observations of Herbig–Haro objects and their environment is presented. Studies of neutral gas (both molecular and atomic) can give us information on three key components of these regions of recent star formation and outflows: 1) the dense, quiescent ($\Delta v \simeq 1$ km s^{-1}) gas surrounding the exciting source of the outflow, 2) the high–velocity ($\Delta v \simeq 10$ km s^{-1}) bipolar outflow gas, most probably ambient gas accelerated by a stellar wind and, 3) the extremely–high–velocity ($\Delta v \simeq 100$ km s^{-1}) gas that may be the stellar wind itself or at least be very closely associated with it.

The ionized gas component can also be studied via its free–free emission, and radio observations of this continuum emission from the HH objects and their exciting sources is also developing into a powerful technique to study the outflow phenomenon in star–forming regions. Some examples of radio continuum emission from Herbig–Haro objects are discussed.

Key words: **HERBIG–HARO OBJECTS — NEBULAE–INDIVIDUAL — RADIO SOURCES–GENERAL — STARS PRE–MAIN–SEQUENCE**

I. INTRODUCTION

Our understanding of the Herbig–Haro phenomenon has advanced greatly in the last decade. To make this evident it is enough to take an undergraduate astronomy textbook several years old and read what it had to say about Herbig–Haro objects. A rather popular textbook published in 1979 affirmed: *"Certain curious types of young stars, known as Herbig–Haro objects and T Tauri stars, may be examples of protostars in or near this (accreting) stage of evolution "*. Even as recently as 1983, another undergraduate textbook defined Herbig–Haro objects as *"bright nebulous + regions of gas and dust that may be stars in formation "*. Obviously, the authors of these textbooks did not know about the many studies, the first being the seminal paper of Strom, Grasdalen, and Strom (1974), that showed that the HH objects are not protostars or young stars themselves, but are the result of the interaction of the collimated winds of such stars with the surrounding gaseous medium. Sometimes the exciting star can be as far as a few pc from the HH object (Cantó *et al.* 1981; Rodríguez and Reipurth 1989).

But we should not despair. My review of recent undergraduate textbooks indicates that HH objects are receiving more comprehensive and accurate treatment. An example can be given by quoting a 1987 book that states; *"near the T Tauri stars, small, bright, star–like nebulae, the Herbig–Haro objects, have been discovered. These are thought to be produced in the interaction between a stellar wind and the surrounding interstellar medium* ". I believe that this general definition is satisfactory for most of us. The details, however, are a matter of considerable controversy.

In this review I will concentrate on recent radio observations of Herbig–Haro objects, their exciting sources, and the interstellar medium directly associated with both. For radio observations prior to 1983, we refer the reader to Snell (1983) and Moran (1983). A review of theoretical models of Herbig–Haro objects is given by Cantó (1989) in this volume. As a convenient frame for the discussion I will assume that the main characteristics of the HH–object phenomenon can be described in terms of a *unified* model, that incorporates not only the HH–objects but also the molecular outflows and the optical jets. It is now firmly established that the three phenomena are closely related. The ingredients of this *unified* model (Figure 1) are five:

1) A young star undergoing a vigorous episode of mass loss, with $\dot{M} \simeq 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$ and velocities of order a few hundred km s^{-1}.

2) A collimating mechanism that provides the bipolar geometry seen often in molecular outflows, Herbig–Haro objects, and optical jets. The precise nature of this mechanism has been the subject of considerable study but a consensus has not been reached. Observational results and theoretical considerations appear to favor disks and/or toroids but their characteristics, even their dimensions, are not clearly established.

3) Herbig–Haro objects and optical jets in the surroundings of the exciting star. While the HH objects can be detected over angular dimensions of several arcmin (tenths of pc at the typical distances of near star–forming regions) from the exciting star, the optical jets are only seen much closer, usually a few to a few tens of arcsec from the star. Both the HH objects and the jets have optical spectra characteristic of shocked gas and velocities that can reach up to a few hundred km s^{-1}.

4) High–velocity molecular gas with bipolar geometry and radial velocities of a few tens of km s^{-1}, present on a scale of several arcmin.

5) A molecular cloud, inside of which these phenomena occur. Heavy extinction is frequently present, making the infrared and radio observations of great value.

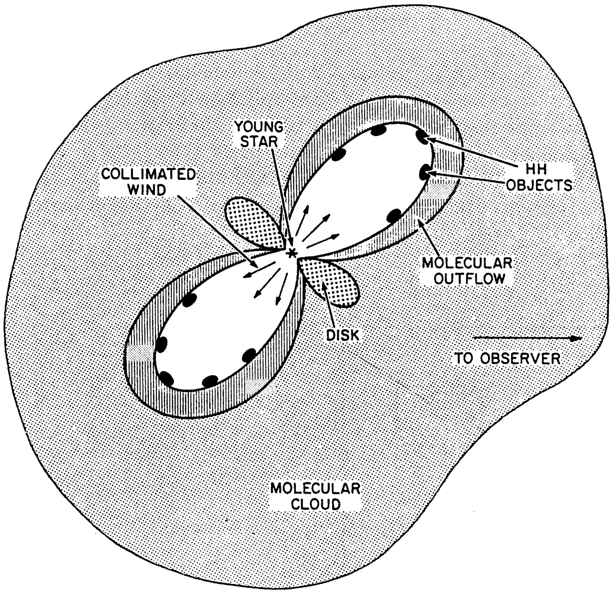
This review will be structured as follows. In §II I discuss the mapping of bipolar molecular outflows associated with HH objects. Until recently, most radio observations of HH objects concentrated on the bipolar molecular outflows and on the dense gaseous structures around the exciting stars. A very exciting development in the field has been the detection, in atomic hydrogen and carbon monoxide, of extremely–high velocity gas that seems to be the stellar wind itself. These new results are presented in §III, while in §IV a brief review of the denser, more quiescent gas observed around the exciting objects is given. In the last few years it has been possible to detect and study in the radio continuum the HH objects themselves and their exciting sources. The more recent radio continuum observations, all made with the Very Large Array, of several Herbig–Haro objects and their presumed energy sources are presented in §V. Radio observations of H_2O maser emission have been used to investigate the HH objects and their environment, and they are briefly referenced in §V. The conclusions are given in § VI.

II. MOLECULAR OUTFLOWS AND HH OBJECTS

The most systematic effort to detect high–velocity molecular gas near Herbig–Haro objects was made by Edwards and Snell (1983; 1984). Using the J = 1-0 rotational transition of CO, they detected several energetic molecular outflows in the vicinity of Herbig–Haro objects. A compilation of 17 such sources is given by Edwards and Snell (1984). The HH objects usually appear spatially associated with the blueshifted lobes, as expected since obscuration will be larger toward the redshifted lobes (see Figure 2). The best studied sources, by them and other authors, are L1551 (associated with HH28, 29, and 102; Uchida *et al.* 1987; Moriarty–Schieven and Snell 1988), HH7–11 (Grossman *et al.* 1987; Liseau, Sandell and Knee 1988), and Cepheus A (associated with GGD37; Hayashi, Hasegawa and Kaifu 1988). Attempts to detect high–velocity CO in the HH1–2 system have proved inconclusive (Edwards and Snell 1983; Levreault 1988).

A major development in the studies made by these last groups has been the angular resolution of the morphology of the blue CO lobes in L1551 and HH7–11. Remarkably, the lobes exhibit *limb brightening* with what appears to be holes in their centers. Furthermore, as noted by Liseau, Sandell and Knee (1988) for HH7–1 and Rodríguez *et al.* (1989*b*) for L1551, the HH objects appear projected along the inner walls of the high–velocity CO shells (Figure 3). Clearly, we seem to be dealing with shock excitation produced as the stellar wind impinges on and accelerates molecular gas.

The bipolar flow in HH7–11 has been detected also in H I by Rodríguez *et al.* (1989*d*) using the *VLA*, and in OH by Mirabel *et al.* (1987) using Arecibo. The H I map of Rodríguez *et al.* (1989*d*) is shown in Figure 4. There we can see the bipolar outflows associated with HH7–11 and HH12. In both cases the HH objects appear projected along an edge of the H I blueshifted lobe, supporting the notion that these HH objects could be chains of nebulosities along the wall of a cavity and not jetlike phenomena, as has sometimes been proposed.



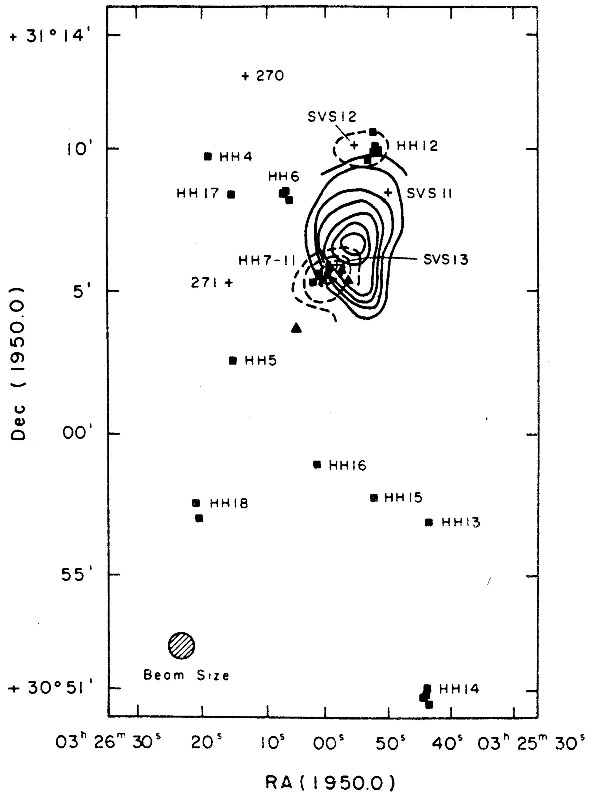


Fig. 1. The five ingredients of the *unified* model for outflows and HH objects are depicted in this figure. A young star is losing mass in the form of a powerful wind. This wind is collimated to a bipolar geometry, possibly by a flattened structure around the star. In some cases the collimation seems to be present very close to the star (at the sub arcsec scale) and optical and radio jet are created. On larger scales, the collimated wind interacts with the ambient cloud, giving rise to the HH objects and the molecular outflows. This activity is usually taking place inside a molecular cloud and large obscuration could be present.

Fig. 2. High-velocity CO map of the NGC 1333 region from Edwards and Snell (1983). The solid contours mark the location of the redshifted gas and the dashed contours mark the location of the blueshifted gas. The filled squares give the positions of the HH objects, the triangles that of the H_2O masers, and the crosses that of the Hα stars or near-IR sources in the region.

III. H I AND CO OBSERVATIONS OF EXTREMELY HIGH VELOCITY GAS IN HH7–11

The observations discussed in the previous section refer to gas moving at velocities of a few tens of km s^{-1}. This gas is almost certainly coming from the molecular cloud and has been accelerated by a much faster, but less massive, wind. For several years since the detection of the bipolar outflows it was not clear if the postulated wind was actually present. The exciting stars of molecular outflows are almost always heavily obscured and undetectable at optical wavelengths. Furthermore, searches for an ionized wind had showed that even when ionized gas could be present in close association with the stars, these ionized component appeared insufficient to drive the molecular outflows (Rodríguez and Cantó 1983; Snell *et al.* 1985; Strom *et al.* 1986).

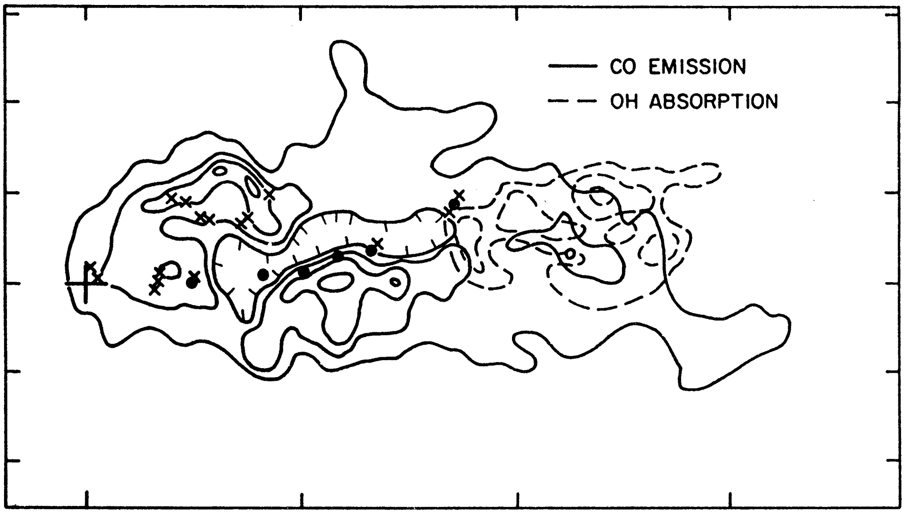


Fig. 3. Blueshifted lobe of the L1551 bipolar outflow. The solid lines are selected contours from the high-velocity blueshifted CO map of Moriarty-Schieven and Snell (1988). Note the depression in the center of the lobe, that indicates a possible shell-like morphology for the high-velocity CO. The dashed contours mark the location of the high-velocity OH, observed in absorption by Rodríguez *et al.* (1989*a*). The large cross indicates the position of L1551 IRS5, the presumed exciting source of the system. The positions of the HH nebulosities discussed by Stocke *et al.* (1988) are marked with an X, and the positions of the HH-like nebulosities discussed by Rodríguez *et al.* (1989*b*) are marked with a solid circle. Note that most of the HH objects appear projected along the inner walls of the cavity. The horizontal axis of this figure is aligned at a position angle of 45° in the sky. The tick marks in the horizontal axis are separated by 5 arcmin.

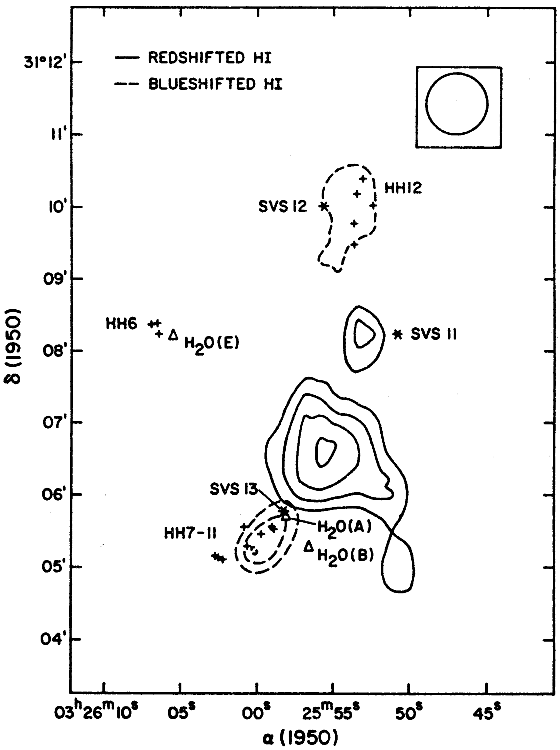


Fig. 4. High-velocity H I map of the HH7–11 (NGC 1333) region from Rodríguez *et al.* (1989 *d*). The solid contours mark the location of the redshifted gas and the dashed contours mark the location of the blueshifted gas. The crosses give the positions of the HH objects, the triangles that of the H_2O masers, and the asterisks that of the near-IR sources in the region.

An estimate of the mass loss rate required from the exciting star can be obtained as follows. Assume as typical values for an outflow a mass of $M_o = 1\ M_\odot$, a velocity of $v_o = 10\ \mathrm{km\ s^{-1}}$, and a radius of $R_o = 0.5$ pc. The momentum rate in the outflow is defined as

$$\dot{P}_o = \left[\frac{M_o v_o}{\tau_o}\right], \tag{1}$$

where τ_o is a characteristic time, that we take equal to R_o/v_o. We then have

$$\dot{P}_o = \left[\frac{M_o v_o^2}{R_o}\right], \tag{2}$$

from where we derive $\dot{P}_o = 2 \times 10^{-4}\ M_\odot\ \mathrm{yr^{-1}\ km\ s^{-1}}$, since $R_o/v_o = 5 \times 10^4$ years. Assuming that the momentum rate in the wind is $\dot{P}_w = \dot{M}_w v_w$, that $\dot{P}_w = \dot{P}_o$, and that the velocity of the wind is $v_w = 200\ \mathrm{km\ s^{-1}}$, we derive $\dot{M}_w = 10^{-6}\ M_\odot\ \mathrm{yr^{-1}}$. As we mentioned before, until recently there was no solid evidence for the presence of such a fast and energetic wind.

The evidence for the wind was reported by Lizano *et al.* (1988), who detected very broad (≥ 300 km $\mathrm{s^{-1}}$) wings in the H I and CO emission at the position of the infrared source SVS13, the exciting source of HH7-11. Their spectra are shown in Figure 5. They interpret this broad emission as arising in the stellar wind itself and show that this extremely-high velocity gas can account for the massive, lower-velocity outflow observed at typical velocities of $\sim 10\ \mathrm{km\ s^{-1}}$.

Other searches for extremely high-velocity CO by Koo (1989) and Margulis and Snell (1989) have shown that sources like AFGL 490 and NGC 2071 have CO wings with total widths exceeding 100 km $\mathrm{s^{-1}}$. However, no other source comparable with HH7–11 has been found.

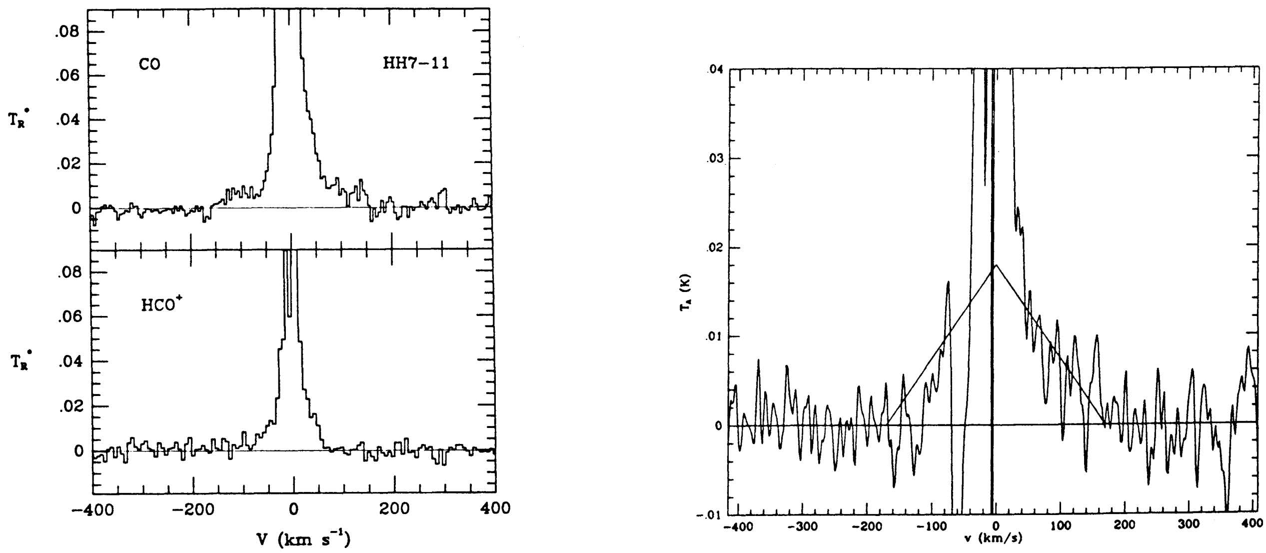


Fig. 5. Spectra of CO (top), HCO^+ (middle), and H I (bottom) toward SVS13, the exciting star of the HH7–11 outflow, taken from Lizano *et al.* (1988). Note the extremely wide ($\sim 300\ \mathrm{km\ s^{-1}}$) in the CO and H I spectra.

IV. DENSE GAS ASSOCIATED WITH THE EXCITING SOURCES

In the two previous sections we have discussed recent results on two gaseous components: the ~ 10 km $\mathrm{s^{-1}}$ gas that is typical of molecular outflows, and the $\sim 100\ \mathrm{km\ s^{-1}}$component, present at least in HH7–11, that may be tracing the stellar wind itself or be a component more directly associated with it. In this section we will discuss a third molecular component. This component is dense ($n_{H_2} \geq 5 \times 10^3\ \mathrm{cm^{-3}}$), relatively quiescent (with line widths of 1 km s^{-1} or less), and is best traced by molecules such as NH_3 and CS. This dense gas is almost invariably found in close association with the presumed exciting stars of the outflows and HH objects (Torrelles *et al.* 1986; Anglada *et al.* 1989).

The close association of these dense cores (with typical dimensions of ~ 0.1 pc) with the exciting stars of outflows has one inmediate implication: the stars must be very young. Since the dimensions of the cores are ~0.1 pc and typical random velocities of newly–formed stars are expected to be in the order of 1 km s^{-1}, one reachs the conclusion that, since the star is still embedded in its parent core, it must have formed less than 10^5 years ago since otherwise it would have drifted away from the core.

An important area of research has been trying to ascertain the nature of the interaction between this dense gas and the outflow. In many sources (see Torrelles *et al.* 1983 and review by Rodríguez 1988) the major axis of the core is aligned perpendicular to the outflow axis, suggesting that the outflow is collimated by the dense structure. For example, in the case of HH1–2, Marcaide *et al.* (1988) have mapped in ammonia what appears to be a rotating and expanding toroid around *VLA* 1, the exciting source of the system (Figure 6). The structure has its major axis aligned approximately perpendicular to the outflow axis. However, there is also evidence for collimation on both much smaller and much larger size scales. On one hand, the optical (e.g. Mundt 1986) and radio (e.g. Rodríguez *et al.* 1989*c*) jets indicate collimation on scales smaller than one arcsec (hundreds of AU at the typical distances involved). On the other hand, Mirabel *et al.* (1987) present evidence that, at the pc scale, the outflow lobes in L1551 and HH7–11 are elongated in the direction of the steepest density gradients in the ambient cloud, suggesting that even the large scale structure of the cloud plays a role in determining the morphology of the outflow. Rodríguez (1988) suggests that different collimating mechanisms may be operating at different scales.

Another quiescent component of great importance has been detected recently by Rudolph and Welch (1988). They detected, using the Hat Creek millimeter interferometer, dense clumps of HCO^+ that appear downstream of several of the HH objects in the HH7–11 chain. They propose that the coincidence of quiescent, almost stationary ambient gas with the fast–moving, shock–excited HH objects suggest that HH7–11 are the shocked surfaces of stationary dense ambient cloudlets buffeted by a high velocity stellar wind.

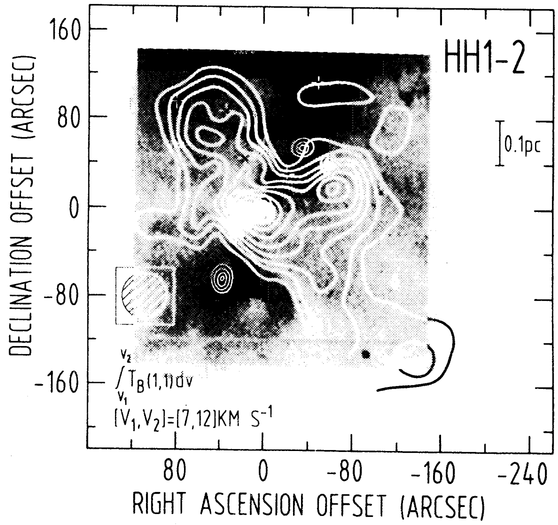


Fig. 6. Map or the integrated ammonia emission for the H1–2 region (solid contours; Marcaide *et al.* 1988) superposed on the R plate of Strom *et al.* (1985). The ammonia structure is well centered on the *VLA* source and is roughly perpendicular to the line connecting HH1 and HH2.

V. RADIO CONTINUUM OBSERVATIONS

The detection of radio continuum emission from the Herbig-Haro objects 1 and 2 and their central source of energy (Pravdo *et al.* 1985), and the subsequent detailed *VLA* study of the region (Rodríguez et al. 1989*c*) have produced a significant advance in our understanding of the HH phenomenon. Among other results, it has been possible to identify the central source of energy of the system and to show that the radio radiation mechanism from the HH objects themselves is optically-thin free-free emission and to estimate the shock parameters from these data (Curiel, Cantó and Rodrí guez 1987). When observed with sub arcsec angular resolution, the central source (*VLA* 1) appears

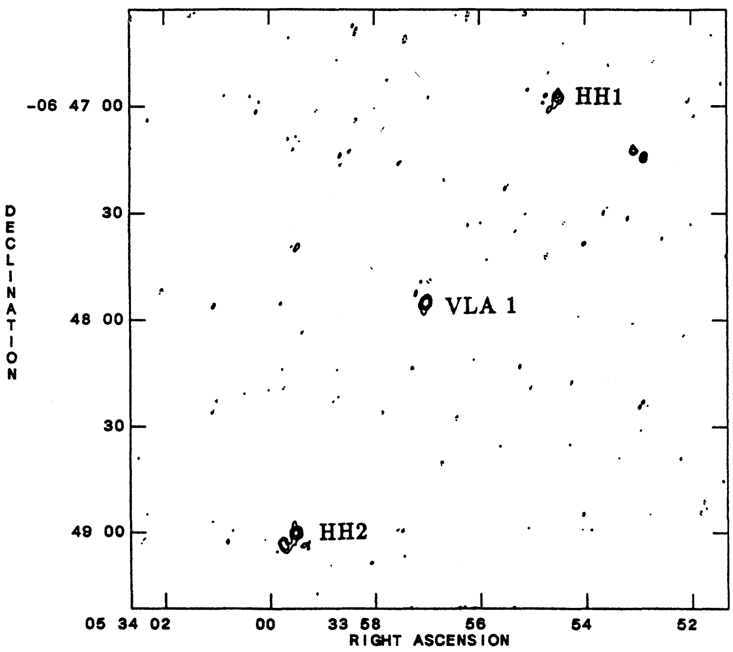


Fig. 7. *VLA* map of the 6-cm emissiom from the HH1–2 region (solid contours; Marcaide *et al.* 1988) superposed on the R plate of Strom *et al.* (1985). The ammonia structure is well centered on the *VLA* source and is roughly perpendicular to the line connecting HH1 and HH2.

elongated and its major axis is aligned within a few degrees with the HH1–2 axis (Rodríguez *et al.* 1989*c*). Finally, the proper motions of the HH objects, first observed in the optical by Herbig and Jones (1981) have been confirmed by comparing the radio data taken two years apart. In Figure 7 we show a 6–cm VLA map of the HH1–2 region made by Rodríguez *et al.* (1989*c*).

The same techniques applied to HH1-2 and its central source of energy can, in principle, be applied to other HH-object and their energy sources. The radio measurements could be particularly valuable in the case of HH objects that are heavily or totally obscured at optical wavelengths. However, the fact that the Hα intensities (that are expected to be correlated with the radio continuum emission) of other known *classic* HH objects are about ten times weaker than HH1 and HH2 has impeded these studies. In here I am using the term *classic* to refer to HH objects that are being excited by a low–luminosity, solar–type, young star. Indeed, searches for radio continuum toward other classic HH objects have produced only upper limits (Curiel *et al.* (1989), with the possible exceptions of the tentative detections of HH101 in the Corona Australis molecular cloud by Brown (1987) and of the southernmost knot of HH12 by Snell and Bally (1986).

This distressing situation is certainly changing with the study of HH objects associated with more massive stars than the classic HH objects. The HH objects associated with massive stars, which have received scant attention until recently, are significantly more luminous than the classic HH objects and can be more easily detected in the radio continuum. Along these lines of research, HH80–81 (Rodríguez and Reipurth 1989), M42/HH3–4 (Yusef-Zadeh 1989), and M16/HH1 (Curiel *et al.* 1990) have been detected recently. One drawback in the study of this type of HH objects is that in some cases their nature as real HH objects is controversial. However, at least in the case of HH80–81 the HH nature is firmly established (Reipurth and Graham 1988; Heathcote and Reipurth 1989). These HH objects are being excited by a 10^4 $L_\odot$ IRAS source, IRAS 18162-2048, also detectable in the radio continuum (Figure 8). This source exhibits elongated morphology (see Figure 8) and its major axis points approximately to HH80–81. This geometry is similar to that found for the central sources of the L1551 (Bieging and Cohen 1985;Rodríguez *et al.* 1986) and HH1–2 (Rodríguez *et al.* 1989*c*) systems, but in HH80–81 the angular size of the major axis of the radio source associated with the presumed exciting source is $\sim 2'$ ($\sim$ 1 pc at a distance of 1.7 kpc), while in L1551 and HH1–2 it is only a few arcsec (of order 0.01 pc at the distances of these sources).

In general, it is believed that the observed ionization, both in the HH objects and in their exciting stars can be provided by shock–induced ionization. From the formulation of Cox (1972) and Daltabuit and Cox (1972), we find that the shock-induced ionization rate from a stellar wind with mass loss rate $\dot{M}$ and terminal velocity v_∞ (for $v_\infty \geq$ 200 km s^{-1}) is approximately

$$\left[\frac{N_S}{s^{-1}}\right] \simeq 1 \times 10^{45} \left[\frac{\dot{M}}{10^{-6}\ M_\odot\ yr^{-1}}\right] \left[\frac{v_\infty}{200\ km\ s^{-1}}\right]^2 . \quad (3)$$

For $\dot{M} \simeq 10^{-6}\ M_\odot\ yr^{-1}$ and $v_\infty \simeq 200$ km s^{-1}, we obtain $N_S \simeq 1 \times 10^{45}$ s^{-1}. For optically-thin plasma with an electron temperature of 10^4 K, this ionizing rate will produce, at a distance of 1 kpc, a radio continuum flux density of ~10 mJy, of the same order of magnitude that is observed.

We end by noting that H_2O maser emission has been detected in the vicinity of several HH objects (Haschick *et al.* 1983; Henkel, Haschick, and Güsten 1986). At present it is still unclear if the emission from these H_2O maser spots marks the position of young stars in the field, or if it could arise from moving cloudlets of similar origin and nature than that of the HH objects. A detailed proper motion study of these H_2O masers is required to clarify this issue.

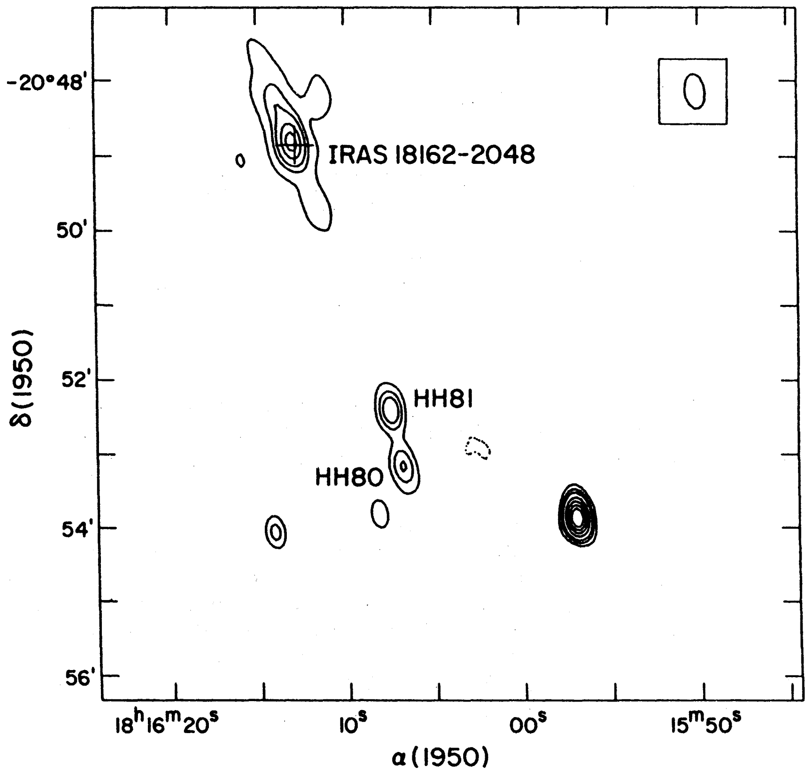


Fig. 8. *VLA* map of the 6-cm emission from HH80–81 region, from Rodríguez *et al.* (1989*c*). The position of HH1 and HH2 as well as that of *VLA* 1, the exciting source of the system, are indicated in the figure. This map has an angular resolution of about 2 arcsec.

VI. CONCLUSIONS

The radio observations of Herbig–Haro objects and their exciting sources as well as their environment have produced a significant advance in our understanding of the phenomenon. In this review I presented some examples of this research. In general, it seems that the *unified* model discussed in the Introduction can account qualitatively for several aspects of the outflow phenomenon. The radio observations presented here can help us to sharpen and consolidate this description significantly.

The recent results discussed here can be summarized as follows. There is now evidence that the stellar wind that powers the HH objects and molecular outflows may be largely neutral. Collimation and ionization (probably partial) can occur rather close to the star, giving rise to the optical and radio jets. The nature of the mechanism for this small scale collimation is unknown. At the same time, there is a less collimated, more powerful bipolar outflow that produces the classic molecular outflows. The collimation of the outflows may be provided by toroids of interstellar scale (0.1 pc), as well as by density gradients in the ambient cloud. In the best studied cases, the outflows seem to have shell-like morphologies and the classic HH objects appear sometimes projected along the inner walls of the cavities.

I thank S. Curiel, J. M. Moran, A. Raga, and F. Yusef-Zadeh for useful comments. Support from a Guggenheim Fellowship is gratefully acknowledged.

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