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BIPOLAR MOLECULAR OUTFLOWS NEAR HERBIG-HARO OBJECTS

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ABSTRACT. A review of the nature and origin of high velocity molecular gas in the vicinity of Herbig-Haro objects is presented. This gas has been interpreted as arising from the interaction of stellar winds from young stars with the surrounding molecular cloud material. Many of these regions have an asymmetrical spatial distribution of high velocity gas, indicating the presence of bipolar molecular outflows. A discussion of the properties and energetics of these bipolar outflows is presented. In addition, the relationship between the high velocity molecular gas and the Herbig-Haro objects is discussed, as is the physical connection between these two phenomena.

I. INTRODUCTION

The detection of spatially ordered, highly supersonic mass motions in molecular clouds has revealed the existence of a hitherto unexplored phase of stellar evolution. This phase of stellar evolution is characterized by strong stellar winds which are likely to play an important role in nebular dispersal in early planetary systems and in the future evolution of the surrounding molecular cloud. The high velocity molecular gas is most easily detected through the presence of broad emission line wings in rotational transitions of CO. Very broad CO wings were first detected towards the core of the Orion molecular cloud by Kwan and Scoville (1976), and Zuckerman, Kuiper, and Rodríguez-Kuiper (1976). More sensitive observations of this active region show that the full velocity extent of the CO emission is over 180 km s^{-1} (Knapp et al. 1981). Since the first detection of high velocity gas in Orion, numerous additional regions exhibiting broad-winged CO emission have been found; and to date more than 35 regions are known. Properties of many of these regions are summarized by Rodríguez et al. (1982), Bally and Lada (1983), and Edwards and Snell (1983). The broad CO wings seen in these regions have been attributed to the interaction of an energetic outflow of material, associated with star formation, with the ambient molecular cloud.

The high velocity CO emission observed in some regions is distributed anisotropically about a central infrared source. The first such source detected was in the dark cloud L1551 (Snell, Loren, and Plambeck 1980); this source still remains as one of the most remarkable examples of anisotropic high velocity emission. Snell, Loren, and Plambeck interpreted the spatial separation of the redshifted and blueshifted high velocity gas as being due to an outflow confined into two oppositely-directed jets originating at the infrared source IRS 5

(Strom, Strom, and Vrba 1976). Following this detection, two additional "bipolar" outflows were found; these were associated with Ceph A (Rodríguez, Ho, and Moran 1980) and AFGL 490 (Lada and Harvey 1981). Bipolar outflows are now known to be very common, and in fact roughly half of the 35 known regions of high velocity molecular gas are clearly bipolar.

Often the regions exhibiting broad CO wings are associated with luminous infrared sources found in the dense cores of giant molecular clouds. But in addition, many high velocity molecular gas regions are associated with low luminosity infrared sources in nearby dark clouds. Often these latter regions are in the vicinity of Herbig-Haro objects. The association of high velocity molecular gas, Herbig-Haro objects, high velocity H_2O masers, and molecular hydrogen emission have suggested that the interaction of winds from young stars with the ambient molecular cloud may give arise to all of these phenomena. It is the purpose of this review to summarize the properties of molecular outflows that are found in the vicinity of Herbig-Haro objects and to discuss the physical relationship between the high velocity gas and the Herbig-Haro objects. Not only are the molecular observations of interest for studying molecular clouds but these observations can be useful in elucidating the origin and nature of the Herbig-Haro objects.

II. HIGH VELOCITY MOLECULAR GAS

A. Nature of the High Velocity Gas

High velocity CO emission is observed towards many regions of star formation in molecular clouds. The full velocity extent of the CO emission observed in these regions varies from ~ 10 to 180 km s^{-1}. In all of these regions the gas motions observed are highly supersonic, and require the presence of very energetic activity in these regions of star formation. A spectrum of the J=2-1 rotational transition of CO towards the core of the Orion molecular cloud is shown in Figure 1. This spectrum shows both a narrow emission feature at 9 km s^{-1}, due to the ambient molecular cloud, as well as very broad CO wings that originate in a region with a spatial extent of ~ 40 arcsec (Solomon, Huguenin, and Scoville 1981; Knapp et al. 1981). The narrow-velocity component from the ambient cloud is detectable over several square degrees.

All high velocity molecular gas regions have in common the properties that their velocity dispersion is much greater than that produced only by the ambient molecular cloud and that the spatial size of the region of high velocity molecular emission is very small compared with the size of the emission from the ambient molecular cloud.

The very broad CO wings are generally accepted to arise from mass outflow from young stars; but are energetic outflows necessary to explain the observations? Lada and Harvey (1981) have addressed this question for the bipolar source AFGL490. They considered three possible gas motions that could produce the observed broad CO wings; rotation, collapse, and expansion. Both rotation and collapse must satisfy the requirement that the central mass be $> V^2r/2G$. The small spatial sizes and the large observed velocities in most regions then require that the central mass be much larger than is estimated for these small regions.

Therefore, gravitationally bound motions such as rotation and collapse are unlikely to be the cause of the observed broad CO wings. However, if the motion is due to expansion, there is then no requirement on the amount of mass that need be present in the region of high velocity emission. Expansion motions, therefore, alleviate the necessity of very massive cores and can also explain the spatial distribution of high velocity gas that is observed. Lada and Harvey concluded that expansion was responsible for the gas motions in AFGL 490. The coincidence of high velocity molecular gas with young, embedded stars has suggested to many workers that the expansion of the molecular material may be driven by winds from these young stars. This hypothesis is strengthened by the additional correlation of other phenomena, such as H_2 emission and the high velocity H_2O masers, that require the presence of stellar winds in these same regions. Though similar to the T Tauri star winds, the energetics of the winds producing the observed molecular outflows must be orders of magnitude larger. The momentum and energy deposited by these winds can play a significant role in the evolution of both the star and the molecular cloud.

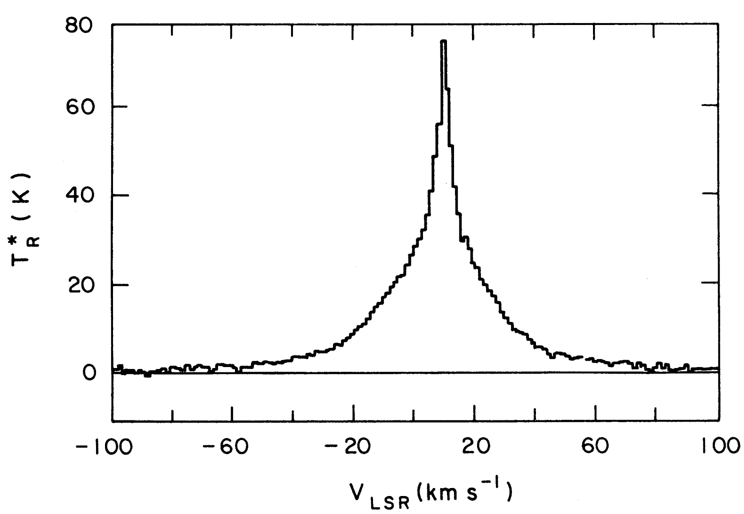
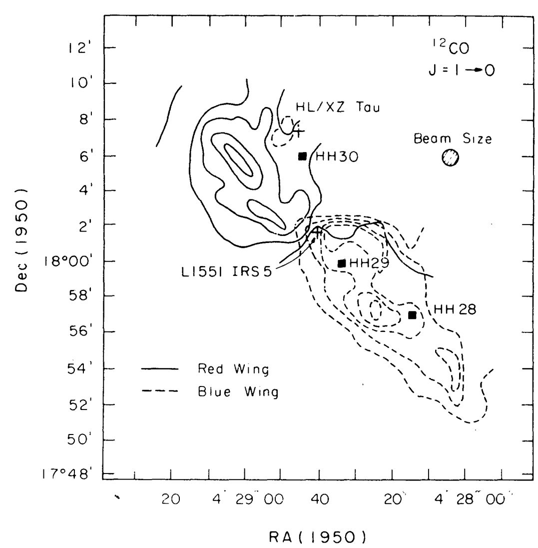


Figure 1 - Spectrum of the J=2-1 transition of CO obtained at the Five College Radio Astronomy Observatory towards the core of the Orion molecular cloud.

B. Bipolar Outflows

The best example of a bipolar outflow is that associated with the dark cloud L1551. In this outflow the redshifted and blueshifted high velocity CO emission is spatially separated and symmetrically placed about a low luminosity infrared source IRS 5 (Strom, Strom, and Vrba 1976). A high spatial resolution map of the redshifted and blueshifted CO emission in this source is presented in Figure 2 from Snell and Schloerb (1983). This map shows the location of the high velocity redshifted and blueshifted CO emission, the location of IRS 5, and the positions of the Herbig-Haro objects HH 28, 29, and 30. Also located in this region near IRS 5 is a larger, more diffuse Herbig-Haro object, HH 102 (Strom, Grasdalen, and Strom 1974). The luminosity of IRS 5, presumably the source driving the outflow, has been estimated by Fridlund et al. (1980) to be 25 $L_\odot$. Near IRS 5 there is a second source of outflow associated with the T Tauri stars HL/XZ Tau (Calvet, Cantó, and Rodríguez, 1983).

Examples of CO spectra taken towards IRS 5 and towards the redshifted and blueshifted lobes of emission are shown in Figure 3. Note that the outflow velocity is only 12 km s^{-1}, much less that that observed in Orion, but significantly larger than the narrow velocity component that arises from the ambient cloud. This outflow has the highest degree of collimation among known bipolar outflows. Also, unlike the high velocity wings in Orion, the wings in L1551 are distinctly separated from the ambient molecular emission (see Figure 3). Snell, Loren, and Plambeck (1980) interpreted these wings as arising from a shell of molecular gas swept up by the stellar wind. Such velocity features are seen only in one other high velocity source, T Tauri. The detection of these distinct velocity features only in L1551 and T Tauri is probably due to the proximity of these sources which allows higher spatial resolution.



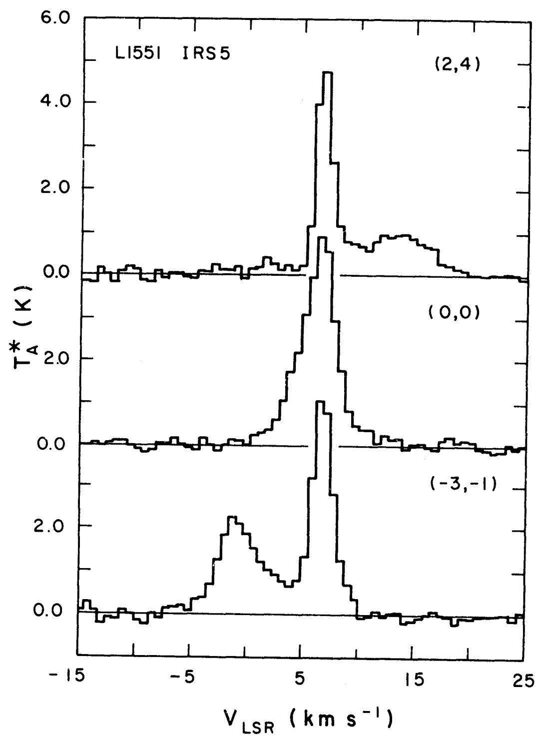


Figure 2 (left) - Contour map the integrated intensity in the redshifted and blueshifted high velocity molecular gas associated with L1551 IRS 5. This data was obtained by Snell and Schloerb (1983) using the 14 m telescope of the Five College Radio Astronomy Observatory.

Figure 3 (right) - Individual spectrum obtained towards IRS 5 and locations in the lobes of redshifted and blueshifted high velocity molecular emission.

It is important to realize that for collimated outflows, the projection of the flow axis on to the plane of the sky affects our ability to detect the high velocity gas, to determine if the outflow is bipolar, and to determine its true velocity and size. At present, there are 18 known outflows which show clearly bipolar structure; maps of many of these regions are presented in Bally and Lada (1983). Most high velocity gas regions have highly asymmetrical spatial distributions of high velocity emission. It is probable that most of these regions not identified as bipolar outflows are bipolar outflows either observed at a poor inclination angle with respect to our line of sight, or in which one jet has been stopped or retarded by an encounter with dense molecular material. Higher spatial resolution observations of the high velocity molecular emission is necessay to test this conjecture. The high velocity source in Orion can be used as an example of the necessity of high spatial resolution; the Orion outflow was until recently believed to be isotropic, but higher spatial resolution observations by Erickson et. al. (1982) showed the high velocity emission to be clearly bipolar. Most bipolar outflows do not show the degree of collimation observed in L1551, but this must in part be due to poorer spatial resolution.

Since most molecular outflows may be bipolar, some focusing mechanism for stellar winds is required. Some workers have suggested that the stellar wind is initially anisotropic at the stellar photosphere, an effect that may be produced either by rotation of the star (Hartmann and MacGregor 1982) or by magnetic fields (Draine 1983). However, other authors have suggested that the wind is initially isotropic and is collimated by an external structure. Snell, Loren, and Plambeck (1980) suggested that a circumstellar disk about L1551 IRS 5 might be responsible for collimating the outflow into two jets. On the other hand, Cantó et al. (1981) and Königl (1982) proposed that density gradients can focus the stellar wind. Observations by Plambeck et al. (1982) and by Torrelles et al. (1983) have indicated that dense toroidal clouds surrounding the central object may be the focussing mechanisms for bipolar flows. The size of the toroids that these authors found are 10^{17} cm or larger. In L1551 the bipolar flow is collimated at size scales of 10^{15} cm, as is shown by the radio continuum maps of Cohen, Bieging, and Schwartz (1982). Therefore, in at least in this latter case, the focusing occurs close to the source of the wind.

C. Relationship with Herbig-Haro Objects

Many of the molecular outflows are found in the vicinity of Herbig-Haro objects or suspected Herbig-Haro objects. Table 1 lists all known outflows of this type. A total of 21 outflows have been found in the vicinity of Herbig-Haro objects and suspected Herbig-Haro objects; of this total, 13 are known to be bipolar. We will examine in more detail the physical relationship between the Herbig-Haro objects and the molecular outflow for four of these regions, L1551 IRS 5, HH 7-11 IR, R Mon, and Orion IRc 2.

The most remarkable bipolar source known is that associated with L1551 IRS 5. Not only is it the best-resolved and collimated outflow yet studied, but both radial velocities and proper motions have been measured for the Herbig-Haro objects in this region (Strom, Grasdalen, and Strom 1974; Cudworth and Herbig 1979). The proper motion vectors for the two Herbig-Haro objects, HH 28 and 29, are directed away from the infrared source IRS 5 (see relative positions

TABLE 1

High Velocity Molecular Outflow Sources in the Vicinity of Herbig-Haro Objects

HH Objects	Number of Outflows	Suspected Source of Molecular Outflows	Nature of Outflow	Ref
Known HH Objects:				
HH 1-3,35,36	1	V380 Ori	Predominately redshifted gas	6
HH 4-18	2	SVS13 (HH 7-11 IR)	Bipolar	14
		SVS12 (HH 12 IR)	Confused with HH 7-11 IR	5
HH 19-23	1	Unknown		6
HH 24-27	2	SSV59 (HH 26 IR)	Bipolar	15
		SSV63 (HH 24 HVS)	Bipolar	15
HH 28-30,102	2	SSV5 (L1551 IRS 5)	Bipolar	13
		HL/XZ Tau	Confused with L1551 IRS 5	2
HH 32	1	AS 353 A	Asymmetrical	4
HH 39	1	R Mon	Bipolar	3
HH102, GGD 32,35	2	LkHα 234	Predominately redshifted gas	5
		NGC 7129 FIR	Bipolar	5
GGD 18	1	CRL 961	Bipolar	9
NGC 1555	1	T Tau	Predominately blueshifted gas	4
RNO 43	2	unknown	Both possible bipolar	6
M42 HH objects	1	Orion IRc2	Bipolar	7,12
Suspected HH Objects:				
GGD 12-15	1	unknown	Bipolar	11
GGD 24	1	NGC 6334 FIRS V	not known	8
GGD 29	1	unknown	Bipolar	1
GGD 37	1	Cep A	Bipolar	10

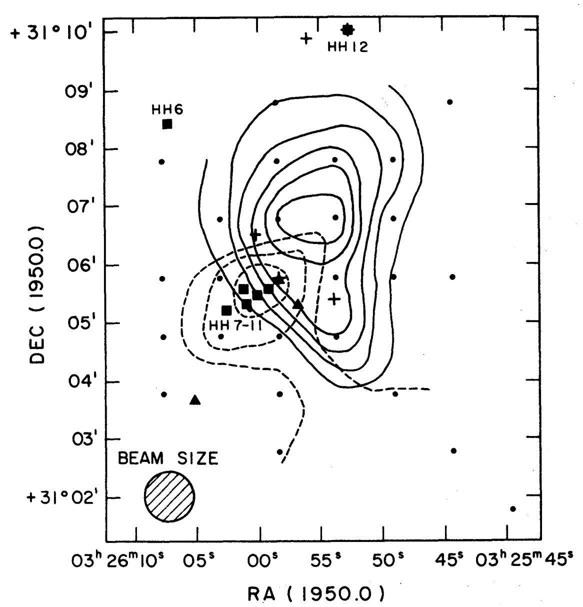
Table 1 references:

1 Bally and Lada (1983)
2 Calvet, Cantó, and Rodríguez (1983)
3 Cantó et al. (1981)
4 Edwards and Snell (1982)
5 Edwards and Snell (1983)
6 Edwards and Snell, in preparation
7 Erickson et al. (1982)
8 Fischer (1981)
9 Lada and Gautier (1983)
10 Rodríguez, Ho, and Moran (1980)
11 Rodríguez et al. (1982)
12 Scoville and Kwan (1976)
13 Snell, Loren, and Plambeck (1980)
14 Snell and Edwards (1981)
15 Snell and Edwards (1982)

in Figure 2) and lie within the blueshifted bipolar CO flow, and their radial velocities are also blueshifted. Therefore, both molecular gas and Herbig-Haro objects are comoving in the same collimated outflow originating at IRS 5. In addition, high spatial resolution observations of CO were obtained during a lunar occultation of L1551, allowing measurement of the location of the high velocity gas with a spatial resolutions of 7 arcsec (Snell and Schloerb 1983). These observations show that HH 102 is coincident with the boundary of the blueshifted high velocity CO emission present to the southwest of IRS 5, and may delineate the location of the shock front responsible for both the optical emission and the high velocity molecular gas.

Large proper motions have also been measured by Jones and Herbig (1982) for the Herbig-Haro objects HH 39. The motion of HH 39 lies along the axis of symmetry of the fan-shaped nebula, NGC 2261, associated with the star R Mon. CO observations by Cantó et al. (1981) indicate the presence of a bipolar molecular outflow also aligned with this symmetry axis. In addition, the radial velocity of the CO high velocity emission to the north of R Mon has the same sense as the radial velocity of NGC 2261 (Stockton, Chesley, and Chesley 1975). As is the case of L1551 IRS 5, both the motions of the Herbig-Haro object and the high velocity molecular gas are coincident, and both originate from the young star, R Mon.

The Herbig-Haro objects, HH 7-11, are aligned along the axis of the bipolar molecular flow driven by HH 7-11 IR (SVS 59; Strom, Vrba, and Strom 1976). A contour map of the locations of the redshifted and blueshifted high velocity gas is shown in Figure 4 from Snell and



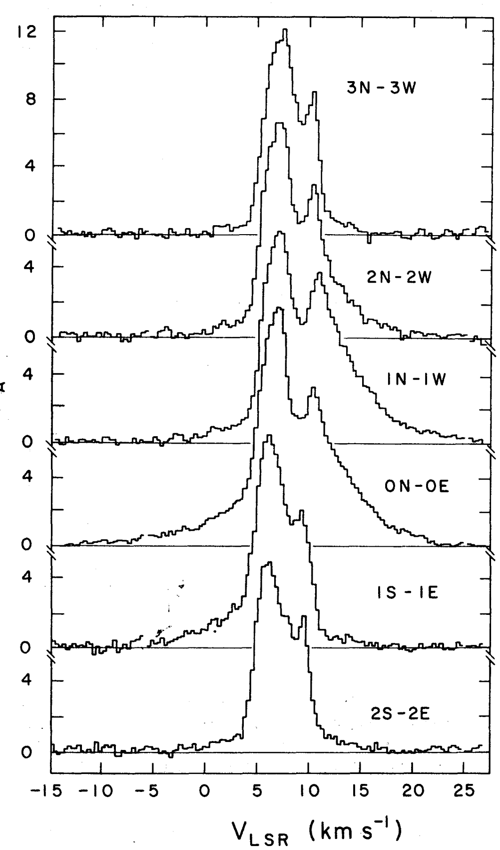


Figure 4 (left) - Contour map of the integrated intensity of the redshifted and blueshifted high velocity gas near HH 7-11 from Snell and Edwards (1981). Positions of the Herbig-Haro objects, H_2O masers, and infrared sources are also shown.

Figure 5 (right) - Spectrum of the J=2-1 transition of CO along the axis of the bipolar flow (Snell and Edwards 1981) showing the bipolar nature of the CO emission and its symmetrical distribution about HH 7-11 IR (0N-0E).

Edwards (1981). The string of negative radial velocity Herbig-Haro objects is coincident with the blueshifted high velocity molecular gas. A series of CO spectra obtained near HH 7-11 are shown in Figure 5 and show the bipolar structure of the high velocity molecular gas in this region. Towards HH 7-11 IR the full velocity extent of the CO emission is 40 km s^{-1} (Snell and Edwards 1981). Similarily, in Orion the negative radial velocity Herbig-Haro objects (Münch 1977; Cantó et al. 1980; Axon and Taylor 1983) are asociated with the blueshifted high velocity molecular gas in the bipolar flow originating near IRc 2. In this source the velocities of the Herbig-Haro objects exceed 300 km s^{-1}. The locations of the high-velocity blueshifted and redshifted CO, and the locations of some of the Herbig-Haro objects are shown in Figure 6. Axon and Taylor (1983) proposed that the Herbig-Haro objects and the high velocity molecular gas are driven by a bi-conical stellar wind collimated by a dense molecular disc. In all four of these regions, the striking spatial and kinematic relation between the Herbig-Haro objects and the high velocity molecular gas suggests that dynamical interaction between winds from young stars and the ambient molecular material produces the shocks necessary to excite the Herbig-Haro objects (Schwartz 1975) and to accelerate the molecular gas.

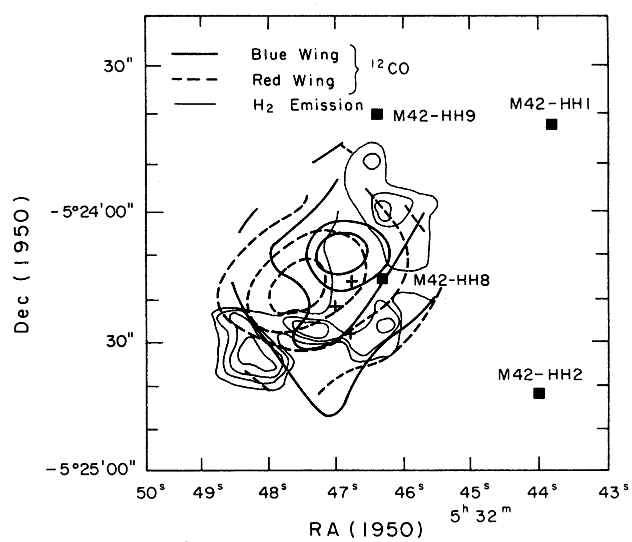


Figure 6 - Contour map of the integrated intensity of the redshifted and blueshifted high velocity gas towards the core of the Orion molecular cloud (Erickson et al. 1982). Also shown is the location of the Herbig-Haro objects and the H_2 emission in this region.

A survey of high velocity molecular gas in the vicinity of 53 Herbig-Haro objects has been presented by Edwards and Snell (1983). Many of these Herbig-Haro objects are found near sources of high velocity molecular outflow but often lie beyond the boundaries of detectable high velocity CO emission. It is conceivable that these more distant Herbig-Haro objects are excited by the sources driving the molecular outflows, although this would require Herbig-Haro excitation mechanisms to operate at distances as great as 2 pc from the source. Edwards and

Snell (1983) have compared the radial velocities of Herbig-Haro objects with the velocities of the high velocity molecular gas; they find that many of the Herbig-Haro objects have directional velocity coincidence with the molecular gas. This result provides strong evidence that both are driven by the same stellar winds. Strom, Grasdalen, and Strom (1974) and Canto (1981) have noted that most Herbig-Haro objects are blueshifted relative to the ambient gas. The coincidence of the high velocity molecular gas with only blueshifted Herbig-Haro objects would result if the redshifted Herbig-Haro objects produced by receding shocks are generally more obscured by interstellar material and thus less likely to be detected.

D. Relationship with H_2O Masers and H_2 Emission

H_2O masers have been detected towards nine of the outflows that are listed in Table 1 (Knapp and Morris 1976; Haschick et al. 1980; Rodríguez et al. 1980; Sandell and Oloffson 1981; Haschick et al. 1983). The H_2O masers in Orion have been shown by Genzel et al. (1981) to be expanding from the infrared source IRc 2, which may also be responsible for the bipolar molecular outflow. It has been suggested that the production of both the H_2O masers and Herbig-Haro objects are related (Norman and Silk 1979; Rodríguez et al. 1980), and originate in the interaction of a stellar wind with the ambient cloud material. If the H_2O masers originate in high velocity flows, then the occurrence of water masers near nine of the molecular outflows that are associated with Herbig-Haro objects is not surprising.

Also associated with many of the molecular outflows listed in Table 1 is the detection of molecular hydrogen emission (Gautier et el. 1976; Fischer, Righini-Cohen, and Simon 1980; Elias 1980; Simon and Joyce 1983). This emission is thought to arise from shocked molecular gas produced by winds from young stars. Similar to the Herbig-Haro objects, the H_2 emission found by Simon and Joyce (1983) is also preferentially found associated with blueshifted high velocity emission. Their explanation for this phenomena is the same as was discussed earlier for the Herbig-Haro objects. The coincidence in many regions of high velocity molecular gas, Herbig-Haro objects, H_2O masers, and H_2 emission all suggest that energetic winds from embedded young stars interact with the surrounding molecular gas producing these observed phenomena.

III. SOURCES RESPONSIBLE FOR HIGH VELOCITY MOLECULAR OUTFLOWS

In many of the high velocity molecular outflows summarized by Bally and Lada (1983) the stellar source thought to be responsible for the outflow is a luminous infrared source and presumably a young, massive star. But many regions of high velocity molecular emission are also associated with T Tauri and FU Ori stars (Kutner et al. 1982; Edwards and Snell 1982; Calvet, Cantó, and Rodríguez 1983; Levreault 1983), low luminosity infrared sources (Snell, Loren, and Plambeck 1980, Snell and Edwards 1981, 1982; Edwards and Snell 1983), or with nearby dark clouds (Frerking and Langer 1982). In all of these instances the source of the high velocity molecular outflow is thought to have a low luminosity and are thus presumably low mass, young stars. Many of the outflows listed in Table 1 are associated with low luminosity infrared sources. In Figure 7 is a histogram showing the distribution of total luminosity for the sources suspected of driving the outflows listed in Table 1; as can be seen in this figure, most of the sources driving outflows near Herbig-Haro objects have total luminosities less than 100 $L_\odot$.

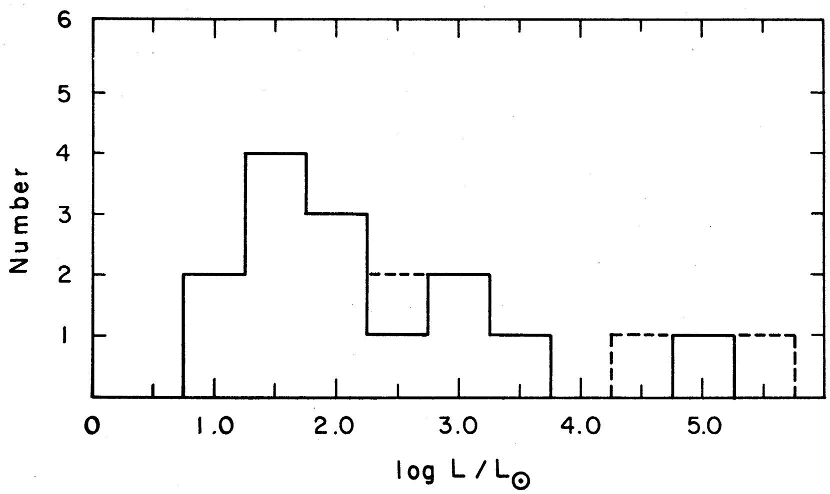


Figure 7 - Histogram showing the distribution of total luminosities of the sources presumable responsible for producing molecular outflows near Herbig-Haro objects (solid lines) and suspected Herbig-Haro objects (dashed lines).

Knowledge of the formation rate of high velocity outflows is important in assessing the impact these outflows have on both stellar evolution and also on molecular cloud dynamics. The birthrate of high velocity sources has been estimated by Rodríguez et al. (1982), Beckwith, Natta, and Salpeter (1983), and Snell and Edwards (1983). Their results indicate that many low mass stars must pass through this energetic evolutionary phase. Better statistics are now available which show that there are 28 high velocity molecular sources within 1 kpc of the sun. The lifetime of the high velocity outflow phase has been estimated to be between 10^4 and 10^5 years (Bally and Lada 1983; Snell and Edwards 1983). Snell and Edwards attempted to correct the dynamical ages for geometrical projection effects and they find a mean lifetime of 2×10^4 years. If we assume that energetic outflows occur only once in the lifetime of a star and that the lifetime of this energetic phase is 2×10^4 years, the birthrate of stars that produce outflows is roughly 5×10^{-4} stars yr^{-1} kpc^{-2}. Comparing this rate to the stellar birthrates determined by Miller and Scalo (1979) indicate that all stars with masses greater than ~ 1.5 solar masses must undergo a phase of energetic outflow. But the volume of space within 1 kpc of the sun that has been surveyed for high velocity molecular emission is very small; therefore, one would expect the true number of sources to be much greater than the 28 known sources. It is likely that if stars undergo this energetic phase only once during their lifetime, then all stars with masses greater than 1 $M_\odot$ must have very strong stellar winds during their lifetime.

IV. ENERGETICS OF THE MOLECULAR OUTFLOWS

Based on the CO high velocity emission, the total mass, momentum, and energy in the high velocity molecular gas can be computed (i.e. Snell and Edwards 1981). The computed mass, momentum, and energy of the high velocity gas are usually lower limits to the true values since the CO high velocity emission is usually assumed to be optically thin, the contribution of high velocity gas at radial velocities coincident with the ambient gas are excluded, and no attempt is usually made to include projection effects in calculating the gas velocity. The dynamical timescale for the outflow is usually computed from the spatial size of the outflow measured in the plane of the sky divided by the radial velocity of the high velocity gas. For highly collimated flows, the dynamical timescale as well as other parameters can be seriously in error unless geometrical projection effects are accounted for.

It is assumed that ultimately the energy source for these outflows originates at the central stellar source. We will consider the possibility that high velocity molecular gas is driven by an expanding stellar wind. This mechanism was proposed by Snell, Loren and Plambeck for the motions in L1551. The rate of momentum transfer in a steady stellar wind can be estimated, assuming conservation of momentum in the interaction between the stellar wind and the molecular gas. A momentum flux can then be determined from the observed momentum of high velocity molecular gas and the dynamical timescale of this gas. Further, if the velocity of the stellar wind is known, the mass loss rate can also be computed. The properties of many of the outflows listed in Table 1 have been summarized by Rodríguez _et al_. (1982) and Edwards and Snell (1983). Edwards and Snell have attempted to correct, in a statistical sense, for projection effects by assuming that the outflows are randomly oriented in space. The median properties of the outflows that they investigated are presented in Table 2. To derive the mass loss rate given in Table 2, it was assumed that the stellar wind velocity was 200 km s^{-1}. Edwards and Snell also found in their limited sample, that the distribution of radial velocities and dynamical timescales are consistent with the distribution that would be expected if all flows were characterized by outflow velocities of 20-30 km s^{-1} and lifetimes of ~ 10^4 years and were randomly oriented in space. It should be emphasized that one parameter of the flows that is

TABLE 2

Mean Properties of Molecular Outflows in the Vicinity of Herbig-Haro Objects

Parameter	Value
Outflow velocity	30 km s^{-1}
Radius	0.5 pc
Lifetime	$2x10^4$ years
Kinetic energy	$1x10^{45}$ ergs
Mass loss rate	$7x10^{-6}$ $M_\odot$ yr^{-1}

geometry independent is the mass of high velocity gas. The sample of outflows summarized by Edwards and Snell had masses of high velocity gas that varied from 0.003 to 24 $M_\odot$. Clearly, the mass, momentum, and energy of these outflows varies enormously from source to source.

A histogram of the distribution of mass loss rates derived for the central sources presumably responsible for the molecular outflows listed in Table 1 is shown in Figure 8. These mass loss rates were derived assuming a wind velocity of 200 km s^{-1}. Most of the outflows in Table 1 require a very large continuous mass loss to produce the observed motion of the molecular gas.

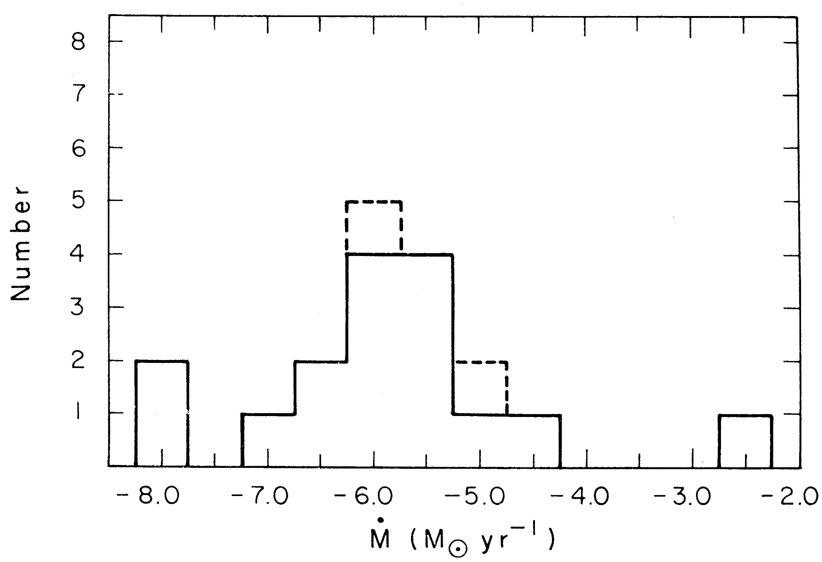


Figure 8 - Histogram showing the distribution of mass loss rates for molecular outflows associated with Herbig-Haro objects (solid lines) and suspected Herbig-Haro objects (dashed lines).

Rodríguez et al. (1982), Bally and Lada (1983), and Edwards and Snell (1983) have suggested that there is a correlation between the total photon luminosity for the central sources and the mechanical luminosity or momentum flux in the wind. In Figure 9 is shown the relation between the photon luminosity of the central sources and the mechanical luminosity for the outflows from Table 1 (filled circles). [The open circles in Figure 9 are additional sources found in Bally and Lada (1983).] A nearly linear relation exists between the mechanical and photon luminosity of these sources, but as can be seen in Figure 9, the mechanical luminosity in these outflows is only a small fraction of the photon luminosity. A comparison of the momentum flux in the outflow to the momentum flux in the available stellar photons reveals that in all sources the momentum in the outflow is always greater than the photon momentum. As pointed out by Solomon, Huguenin, and Scoville (1981), the photon momentum limit is valid only for the case of an optical depth of order 1. More momentum can be imparted to the outflow if multi-scattering of the photons occurs. In many cases the momentum in the outflow is several orders of magnitude greater than the photon momentum. Bally and Lada concluded that in many sources an excessive number of scatterings would be necessary to drive the molecular outflow by radiation pressure from the star.

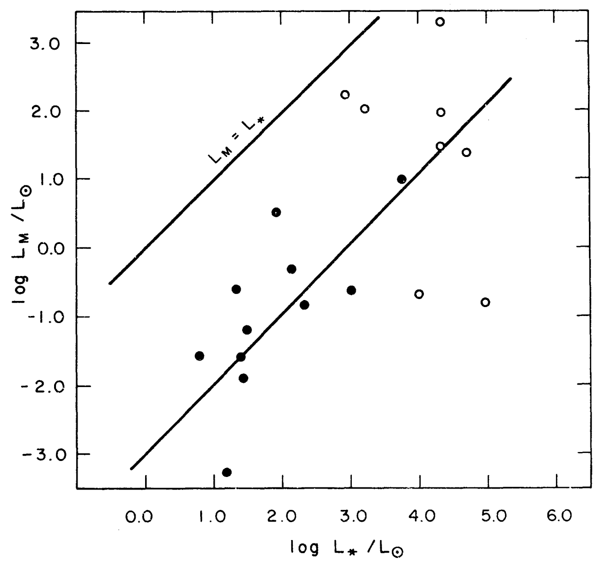


Figure 9 - A plot of the stellar luminosity (L_*) versus the mechanical luminosity in the outflow (L_M). The filled circles are for outflows associated with Herbig-Haro objects (Edwards and Snell 1983) and the solid circles are additional sources from Bally and Lada (1983). The upper line show the location of equal luminosities.

An assessment of the dynamical impact of the observed flows have on molecular clouds is subject to much uncertainity. The observed correlation between flow luminosity and photon luminosity implies that the energetics of the outflow may depend on the mass of the central stellar source. Since little is known of the mass-luminosity relation for pre-main sequence stars of low luminosity, it would be difficult to estimate the integrated effect that the formation of stars of all masses have on molecular clouds. As pointed out by Snell and Edwards (1981) the kinetic energy of the high velocity molecular gas in the HH 7-11 region is comparable to the total kinetic energy in the much more massive cloud fragment where the outflow is occuring.

V. SUMMARY

Herbig-Haro objects are often found in the same regions containing high velocity molecular outflows thought to be driven by strong winds from central stellar objects. This association supports the shocked cloudlet model of Herbig-Haro objects proposed by Schwartz (1975). The striking spatial and kinematic relationship between the Herbig-Haro objects and the high velocity molecular gas in many of these regions suggests that both phenomena are produced by the same stellar wind. This model is supported by the additional observations of high velocity H_2O masers and H_2 emission in the same regions. In most, if not all of these cases, the stellar winds are focused, producing bipolar molecular outflows. The focusing mechanism for the wind may be in many cases due to interstellar toroidal clouds surrounding the central object. A large number of Herbig-Haro objects is found near molecular outflows, but beyond the boundary of the high velocity molecular emission, suggesting that the excitation mechanism of the Herbig-Haro objects can act over distances as large as 2 pc. Further measurements of the radial velocities and the proper motions of the Herbig-Haro objects are necessary to unambigously associate a Herbig-Haro object with a particular molecular outflow. The statistics of high velocity molecular outflows suggest that all stars with masses greater than 1 $M_{\odot}$ must undergo a phase of mass loss characterized by a mass loss rate of > 10^{-7} $M_{\odot}$ yr^{-1} for a period of ~ 10^4 years.

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DISCUSSION

Rodríguez: Both your model and Cantó's model predict that the high velocity CO is coming from the walls of a cavity. You would expect then to observe limb brightening in the high velocity CO data. However, your L1551 cuts do not show this. How do you account for this situation?

Snell: We do not see any evidence for limb brightening. I think this suggests that our models are too simple and CO emission arises from both swept up gas in the cavity walls and from material within the cavity.

Rodríguez: The notion that *all* types of stars power outflows in their early life is supported by interesting data from Lichten which show CO outflows even in clouds where only low mass stars are forming.

Bok: (*Comment*) The papers dealing with South-hemisphere objects (Graham, Reipurth and others) show that we have no solid CO information for the Magellanic clouds, the Globules (such as Coalsack Globule, ESO 210-6A, Cometary Globules and Dark Nebulae of the South).This is a disgraceful situation. We obviously need *urgently* a modern 12 to 15 meter millimeter radio telescope with good auxiliary equipment.

Pişmiş: You showed us that there were a score of HH-objects that showed bipolar outflows. How do the intensities of radiation of the lobes compare with one another? What is the range of the difference in energy contained in them? Were one of the lobes very faint we would not be able to realize the bipolarity of the nebula.

Snell: The bipolar outflow in L1551 has equal mass, momentum, and energy in the redshifted and blueshifted lobes, but for most bipolar flows the intensity is very unequal. Ratios of energy in the two lobes greater than 10 are observed on some sources. You are correct, we may miss some bipolar flows because the emission in one of the lobes is below our detection threshold.

Cohen: May I ask what is the origin for your estimates of luminosity for your luminosity histogram? My own distribution -presumably for the same objects- is rather different for stars/infrared sources truly associated with proven HH-objects.

Snell: The luminosities are based primarily on far-infrared observations. The distributions may differ because the sources I included are presumable driving the molecular outflows in the vicinity of HH-objects but not necessarily the exciting source for the HH-objects.

Kuhi: Can you clarify the velocity data that you showed? Is there any evidence for a velocity gradient along the axis of ejection i.e., the axis of the two CO lobes.

Snell: There are variations in the velocity structure along the axis of the bipolar but no evidence for systematic velocity gradients.

Herbig: What is the reason that the CO observations always give outflow velocities of 20-30 km s^{-1}, yet HH-motions in these same lobes are 100-300 km s^{-1}? Have the CO spectra extended to large enough velocities to be sure there is nothing at such velocities?

Snell: We have the velocity coverage to detect CO emission at 100's of km s^{-1}, but it is not seen. Either we do not have the sensitivity to detect the very high velocity CO emission or it is not present. I think the CO outflow velocities of 20-30 km s^{-1} are what is expected for dense gas swept up by a stellar wind and the high velocities of the HH-objects are more difficult to explain.

Königl: (*Comment*) I would like to make two comments. First, the transverse velocity profile that you measured in L1551 seems to me to be consistent with the jet picture, in which the outflow is collimated along the axis of the lobes. Second, the so-called momentum discrepancy does not necessarily imply that the flow cannot be radiatively accelerated, only that the acceleration region cannot be optically thin. As long as the kinetic power does not exceed the bolometric power, the optically-thick radiatively-driven wind remains a viable alternative.

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