MASSIVE BIPOLAR OUTFLOWS AROUND YOUNG STARS

John Bally, A T & T Bell Laboratories, New Jersey.

1. *Introduction*

Collimated outflows have been found in a large variety of astronomical sources ranging from pre-main sequence stars to post-main sequence stars, planetary nebulae, collapsed, degenerate stars, galactic nuclei, and radio galaxies. Although the physical scale on which these outflows occur vary over many orders of magnitude, there are numerous morphological similarities between the various types of outflow. Here, I will review the outflows associated with pre-main sequence objects and point out similarities with the mass loss seen in post-main sequence stars.

Within the last 20 years, it has been recognized that most star formation in our Galaxy takes place in the cold and dusty environment of the Giant Molecular Clouds. Although star formation is believed to be a process of gravitational collapse and fragmentation of the molecular gas, the first visible sign of the birth of a new star is the detection of hypersonic *outflow* often in the form of two oppositely directed twin-exhaust jets. Outflows are observed to emanate from stars of all luminosities and masses and occur so frequently in regions of recent star formation, that essentially *every* star must go through an outflow phase during its pre-main sequence evolution.

Evidence for outflows has been obtained using a variety of observational techniques:

(1) High velocity components seen in both OH and H_2O masers surrounding luminous protostellar infrared sources (Reid and Moran 1981).

(2) High velocity line wings seen in the millimetre-wave spectra of molecules such as CO (Bally and Lada 1983) in the direction of star forming cloud cores.

(3) Shock excited molecular hydrogen emission in the near infrared (2–3 μm) portion of the spectrum (Shull and Beckwith 1982).

(4) Shock excited optical nebulosities, the Herbig-Haro (HH) objects found in the vicinity of pre-main sequence stars. These nebulae often exhibit proper motions and radial velocities up to 500 km s^{-1} in amplitude (Schwartz 1983).

(5) Deep optical CCD images of HH objects and their surroundings have shown the presence of highly collimated optical jets emanating from young stellar objects and pointed in the direction of nearby HH objects (Mundt and Fried 1983).

Because of the shape of the Initial Mass Function, a greater number of low mass, late spectral type stars form than massive, early spectral type stars. Thus, it is not surprising that outflows associated with pre-main sequence, late type stars greatly outnumber their early spectral type counterparts. The nearest most easily studied outflows are associated with low-mass sources.

2. *Bipolar molecular outflows*

The unambiguous interpretation of the kinematics of a source of high velocity gas as outflow requires that the flow velocity exceed the local gravitational escape velocity; if this is not the case, rotation or collapse are viable source models. In order to estimate the relevant escape velocity, $v_{esc} \sim (2GM/R)^{1/2}$ the spatial extent of the high velocity gas must be resolved to provide an estimate of R. An optically thin tracer of the H_2 column density (such as $C^{18}O$) can be used to estimate the mass inside the flow zone, M. If it is assumed that *all* gas along the line of sight within the angular extent of the high velocity flow lies within a distance R of the flow center, the mass estimate becomes an upper limit. In most outflow zones the mass of stars is negligible when compared with the mass of gas lying along the line of sight. Gas which is observed to have a radial velocity $v > v_{esc}$ is almost certainly outflowing material.

In many directions in the galactic plane, there are numerous molecular clouds at different distances, superimposed along the line of sight; care is required to avoid misinterpretation of a background cloud as an outflow. The requirement that the high velocity gas be confined to the approximate vicinity of a dense cloud core eliminates most chance superpositions of background clouds except in the inner regions of the Galaxy.

Carbon monoxide has proven to be the best indicator of the existence of energetic outflow in regions of recent star formation. Observations in the 115 GHz ($\lambda = 2.6$ mm) line of ^{12}CO have led to the discovery of over 60 regions exhibiting molecular outflow with velocities ranging from $v \sim 10$ to 130 km s^{-1} and sizes ranging from $r \sim 10^{17}$ to 10^{19} cm. Although the total number of known H_2O masers associated with star forming regions is larger, most of these sources are unresolved and an unambiguous case for outflow cannot be made. Presence of maser activity, however, does indicate a high probability that a search for high-velocity CO will be successful. Maps of the high-velocity CO emission can be used to estimate the mass, energy, momentum, and lifetime of a flow. The lifetime can be estimated from the flow size R and flow velocity v by the approximate relation $t_D \sim R/v$. This parameter ranges from 10^3 yrs for the Orion IRC 2 flow to 2×10^5 yrs for the energetic and evolved Mon R2 outflow. If the gas density in the flow diminishes with distance from the outflow sources, t_D may provide only a lower limit on the actual age of the flow since CO is not excited into emission if $n(H_2) \leqslant 10^2$ cm^{-3}. The ^{13}CO species can be used to estimate the line opacity in ^{12}CO. In most sources, the ^{12}CO line is found to have moderate opacity ($\tau \sim 1$ to 10). Mass and other kinematic parameters of the outflow can be estimated from the CO emission by conversion of the CO column densities to total gas column density using the approximate ratio $n(H_2)/n(^{13}CO) \sim 10^6$. Table 1 summarizes the properties of four extensively studied outflows.

A remarkable property of most CO outflows is their bipolar morphology. Figure 1 shows the CO distribution in the intermediate mass outflow in NGC 2071; the red-shifted and blue-shifted components of the emission are displaced from each other. Taken together the two velocities define a highly collimated twin exhaust jet emanating from a cluster of three stars still buried in the molecular cloud. Although most outflows ($\sim$80 percent) are bipolar, most are not as well collimated as NGC 2071. Jet opening angles range from 5° to 50°.

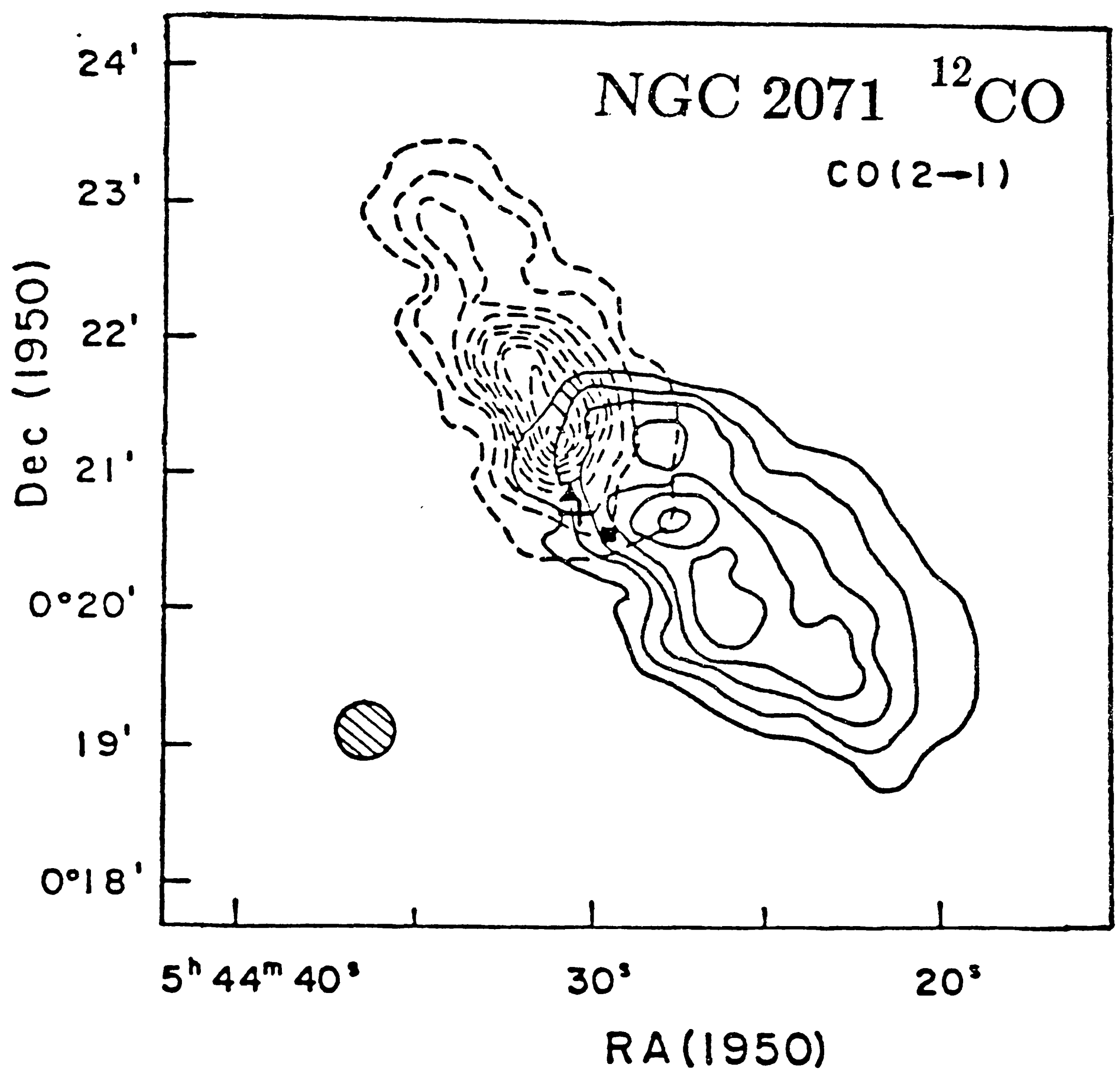


Figure 1. A J = 2 – 1 ^{12}CO map of the bipolar outflow associated with a small cluster of stars buried behind the reflection nebula NGC 2071. This map was made by Snell *et al.* (1984) using the FCRAO 14-metre antenna. Dashed contours represent blue-shifted gas. Solid contours represent red-shifted gas. The (+) symbol marks the position of the infrared cluster. Beam size is 25″.

Table 1

Source	Distance (pc)	Luminosity ($L_\odot$)	Mechanical Luminosity ($L_\odot$)	H_2 Luminosity ($L_\odot$)	Size (pc)
L 1551	175	38	0.2	<1	0.6
NGC 2071	500	10^3	175	10	0.4
Orion IRC 2	460	10^5	2,600	200	0.05
Mon R2	850	10^5	240	<10	2

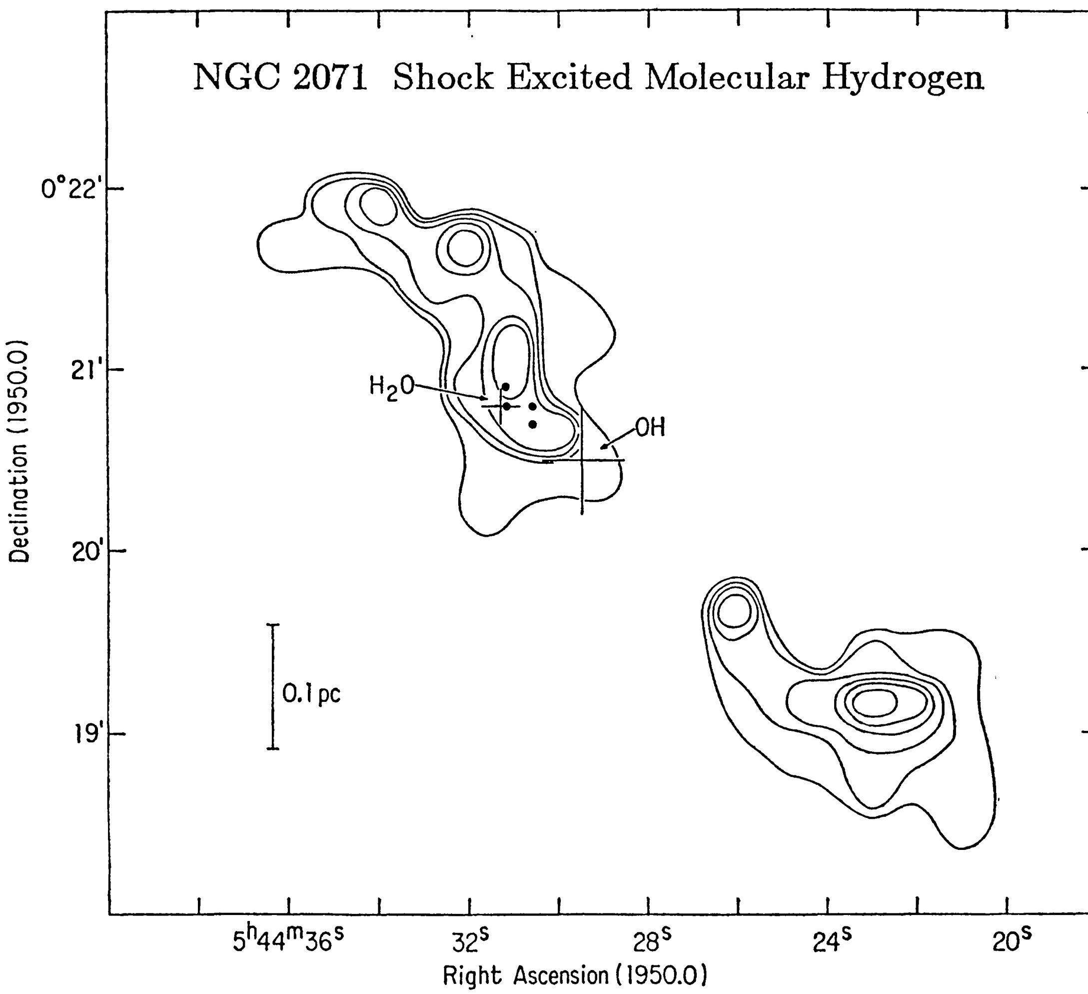


Figure 2. 2.12 μm map of the S(1) line in the rotation-vibration spectrum of H_2 showing the morphology of shock waves in NGC 2071 (see Lane and Bally 1986). The most prominent difference between the H_2 and CO maps is the gap in the H_2 map seen to the south-west of the infrared cluster. Beam size is 25″.

Properties of 4 Well studied Outflows

Velocity	Mass	Dynamical Lifetime	Masers	H-H Objects	Compact Jets
($km\ s^{-1}$)	($M_\odot$)	(years)			
15	0.3	2×10^4	none	yes	optical, radio
15	20	2×10^4	OH, H_2	no	radio(?)
100	5.0	1×10^3	OH, H_2O, SiO	yes	no
7	100	2×10^5	OH, H_2O	no	no

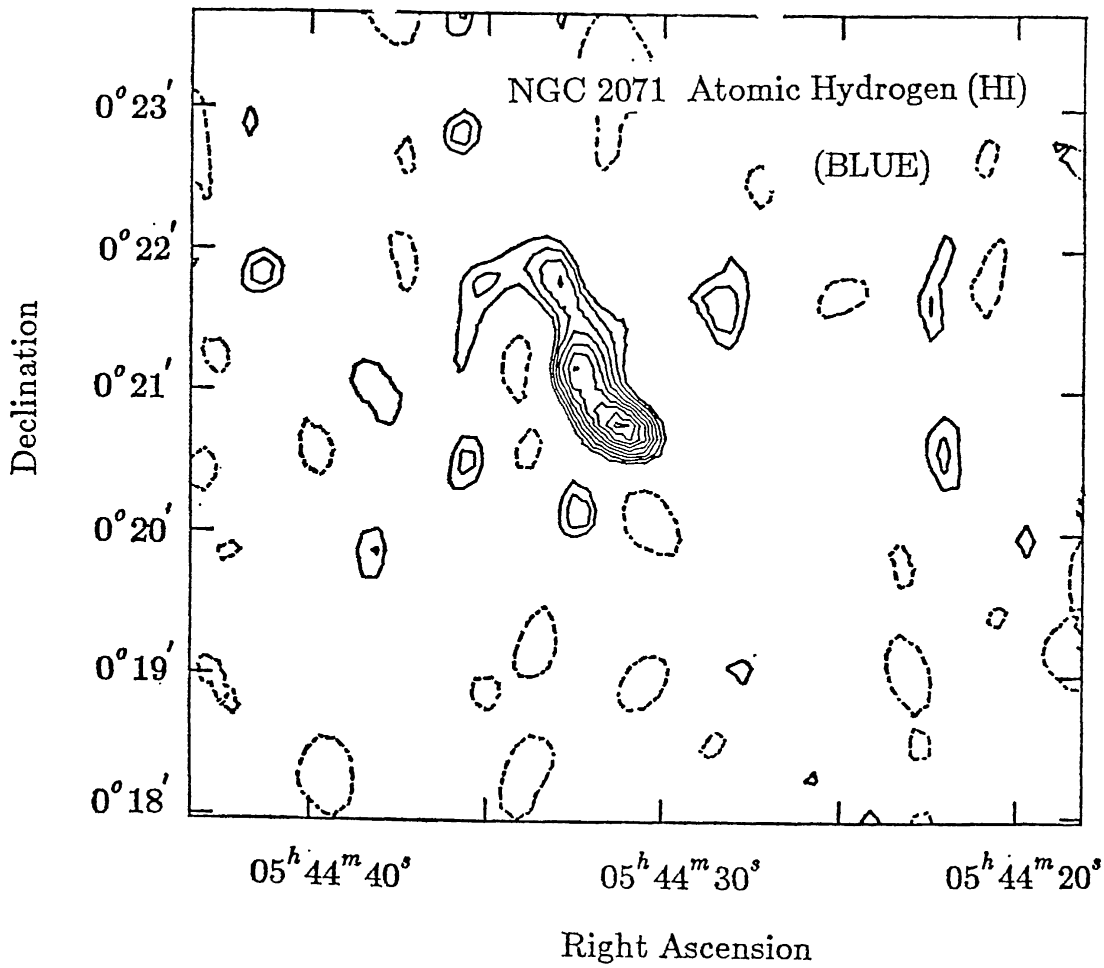
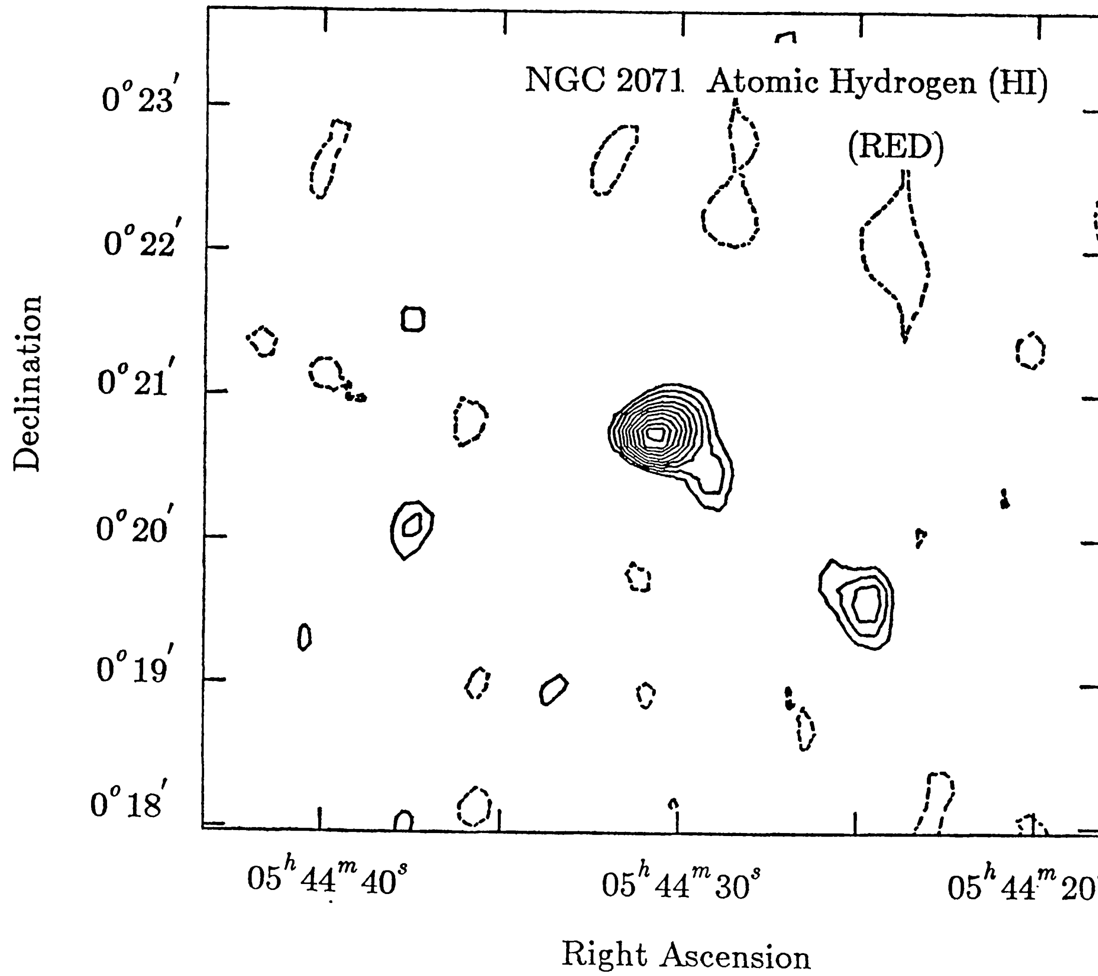


Figure 3. 21 cm atomic hydrogen (HI) emission associated with the NGC 2071 outflow. (Obtained at the VLA by Bally and Stark 1983). Left panel shows emission in the range $-20 < v_{LSR}\,(\mathrm{km\,s^{-1}}) < 0$, corresponding to the blue-shifted part of the outflow. The ambient cloud is centred at $v_{LSR} = 10$ km s^{-1}. Right panel shows emission in the range $20 < v_{LSR}\,(\mathrm{km\,s^{-1}}) < 40$, corresponding to the red-shifted part of the outflow. Contour levels are in steps of 0.9×10^{-3} Jy/beam. Beam size is 20″.

The mechanical luminosity and flow momentum, derived from CO, are roughly correlated with the radiative luminosity of stars located at the origin of the outflow (Bally and Lada 1983). The mean value of the mechanical luminosity is usually about an order of magnitude less than the source radiative luminosity. The flow momentum, however, almost always exceeds the radiative momentum by a factor 10^2 to 10^3. Radiation pressure involving single scattering from an opaque medium cannot drive the outflows.

Our knowledge of the flow structure is limited by the poor angular resolution of single dish millimetre wave telescopes which, at best have beams bigger than 15″. Maximum entropy reconstruction, a lunar occultation experiment, and recent observations made with the new 45-metre telescope at Nobeyama, Japan, show that in the nearest outflow to the Sun, L 1551, the high velocity gas forms a thin shell at the



exterior surface of two nearly empty cavities (Snell 1985, Kaifu 1985). Analysis of the emission lines from other sources indicates that the observed molecular gas in the outflows fills only a small fraction of the available volume.

3. *Shock waves*

Near infrared (2 μm) lines of H_2 are excited into emission behind shock waves moving with a velocity $v_{\rm shock}$ $\sim$7 to 30 km s^{-1} into dense ($n \geqslant 10^5$ cm^{-3}) gas. In some outflow sources, the 2 μm emission provides a high angular resolution tracer of the shock wave morphology. In some sources the total H_2 luminosity, corrected for extinction, is comparable to the total outflow mechanical luminosity; H_2 may provide most of the energy dissipation at the interface where bulk mechanical energy is being converted into radiation. The evidence suggests that the strongest H_2 emission arises in the dynamically youngest outflow sources such as the Orion IRC2 flow. Some flows do not exhibit detectable H_2 emission, possibly because the ambient cloud density through which the shock waves are propagating is too low. In addition to the outflows seen by their CO (and maser) emission, the brighter Herbig-Haro Objects also show strong H_2 emission lines. Figure 2 shows the morphology of the 2.12 μm S(1) line of molecular hydrogen in the NGC 2071 outflow.

An inevitable consequence of passage of fast shock waves is the dissociation of H_2 into atomic hydrogen. Remarkably, the linewidths of the H_2 lines in some sources such as Orion A (IRC 2) and NGC 2071 exceed 100 km s^{-1}, indicating flow velocities in excess of 50 km s^{-1}. All H_2 should dissociate for flow velocities above v_{shock} = 30 km s^{-1}; the survival of H_2 at higher velocities may indicate the presence of a magnetic field which cushions the gas. Some HI *is* observed in the NGC 2071 flow. A VLA map of the $\lambda = 21$ cm line, obtained by Bally and Stark (1983) is shown in Figure 3. The morphological similarity of the HI emission to the H_2 emission suggests a close connection between the shock excited H_2 emission and the observed atomic hydrogen. The total amount of HI observed is about 0.1 ($M_\odot$), much less than the amount of cold H_2 inferred from CO. Since most of the HI in the CO jets has a velocity $|v| < 30$ km s^{-1}, atomic hydrogen is dynamically unimportant. Within 1 arcminute of the infrared cluster in the core of NGC 2071, a small amount of very high velocity HI (producing a 120 km s^{-1} line profile) is seen. This gas may be part of the wind driving the outflow. However, the amount of HI in this wind is too small to provide, by itself, the momentum and energy observed in the NGC 2071 outflow.

4. *Herbig-Haro objects and optical jets*

Small nebulosities are often found in the vicinity of recent star formation sites which exhibit optical emission line spectra best explained by collisional excitation in high velocity shock waves. Radial velocity and proper motion determinations indicate that many HH nebulosities have space motions up to 500 km s^{-1} relative to the molecular cloud in which they originate. In some well studied sources such as the HH1 and HH 2 region, the HH 7–11 region, and the HH 46–47 region, the high velocity Herbig-Haro objects delineate highly collimated outflows from nearby infrared sources (Schwartz 1983). Edwards and Snell (1983, 1984) have found that a large fraction of known HH objects is associated with the blue shifted portion of CO outflows. Along with the frequent detectability of H_2 emission lines, this demonstrates the close connection between the CO outflows, shock excited H_2 emission, and the Herbig-Haro phenomenon.

Deep CCD imagery of nearby star forming regions frequently reveal highly collimated and sometimes sinuous jets of partially ionized gas (Mundt and Fried 1983). The spectra and velocity fields of the optical jets suggest very high velocities and shock excitation, like the HH objects. The surface brightness of the jets, however, is much less than most HH objects studied so far. If H_2 emission is associated with optical jets and scales with source luminosity, it would be undetectable with current instruments.

Optical jets exhibit the best collimation of all the tracers of mass outflow from young stars. The inferred mass and kinetic energy flowing in the jets is much less than the total mass and energy in the cold gas associated with the CO outflows estimated either from CO observations or from measurements of shocked H_2 luminosity. At present, it appears that optical jets and high velocity CO are not directly related although both are observed in similar circumstances. It is possible that the optical jets represent the lowest mass but highest excitation manifestation of outflow while CO represents the most massive and lowest excitation manifestation.

5. *Outflow sources*

The stellar sources lying at the centre of outflow regions exhibit large optical extinctions, $A_v \sim 10-100$ magnitudes, and are mainly seen as infrared stars. Most sources with a luminosity greater than 100 ($L_\odot$) are surrounded by compact (sub-arc second diameter) ionized zones producing milli-Jansky radio continuum fluxes at centimetre wavelengths and Brackett α and γ hydrogen recombination lines at near infrared wavelengths. In the few cases where it has been measured, the $B\alpha$ or $B\gamma$ lines are very broad, with $\Delta v \sim 200$ to 400 km s^{-1}. The radio spectra of most of these sources are flat (optically thin free-free emission) or rise with frequency (optically thick free-free emission). The source of ionization is not understood since the Lyman continuum flux from main sequence stars of the same luminosity is insufficient to photo-ionize the observed radio sources. In most cases, if the ionized gas is interpreted as part of an outflowing wind, the mass loss parameters fail to explain the energetics of the large scale CO flows by several orders of magnitude. Therefore, ionized stellar winds do not drive the CO outflows.

6. *Outflow mechanisms*

The mechanical luminosity and momentum flux in the CO outflows exceeds what can be produced by single scattering radiation pressure by a factor of 10^2 to 10^3. Either the opacities of the gas and dust are unusually large near the source stars or a mechanism other than radiation pressure is responsible for the outflow.

Theories of both the energy source, and the collimation mechanism fall into two categories: (1) the flow acceleration and collimation occurs at the central star and (2) flow acceleration and collimation occurs in a disc of gas surrounding the star.

One possible energy source model utilizes the very high molecular opacities in the stellar envelope to make the envelope Eddington-unstable at the luminosity of the star. The dust opacity at short wavelengths ($\lambda < 1 \mu$m) can be very large; however, degradation of the mean photon energy by re-radiation of absorbed light by cooler dust shifts the wavelengths to $\lambda > 1$ μm where the radiation can escape in the absence of other sources of opacity. This infrared leak may be stopped by the absorption bands of asymmetric-top molecules such as H_2O, whose spectra contain millions of molecular lines lying in the range $\lambda \approx 1$ μm to $\lambda \sim 1$ mm at temperatures $200 < T < 3{,}000$ K (Carson 1976). If most of the available C, N, and O is tied up in common molecules such as H_2O, then the fractional abundance of such species may be in the range $X \sim 10^{-3}$ to 10^{-4}. The mass loss rates deduced from CO observations, along with an estimate of the outflow velocity, constrain the column density of gas in the stellar envelope. If the envelope expands at a velocity of $v_w \sim 100$ km s^{-1} and is losing mass at a rate $dM/dt \sim 10^{-5}$ $M_\odot$ yr^{-1}, the column density of hydrogen above the stellar photosphere ($r \sim 3 \times 10^{11}$ cm) is about $N \sim 10^{25}$ cm^{-2}. For $T > 200$ K the superposition of millions of molecular lines, Doppler broadened by orbital motion about the star, produces an effective continuous opacity $\kappa \sim 200-1{,}000$ cm^2 g^{-1} throughout the far-infrared portion of the spectrum, effectively preventing the direct escape of photons. With such large opacity, stars with $M \geqslant 1$ $M_\odot$ may have Eddington-unstable envelopes when they are near the top of their Hayashi tracks ($L \geqslant 100$ $L_\odot$

and $L \propto (M/M_{\odot})^{2.2}$). Radiation pressure may, under these conditions, play an important role in radial acceleration and dynamic evolution of circumstellar gas.

Two attractive bipolar flow energy generation mechanisms have been proposed which use magnetic fields and tap the rotational angular momentum of a circumstellar disc to drive the outflows. The first model due to Draine (1983) argues that as gas collapses towards the centre of mass and circulates in the disc, the frozen-in magnetic field is wrapped up in a toroidal configuration. Eventually, the magnetic pressure builds sufficiently so that a magnetic bubble forms, ejecting gas tied to the field lines along the rotation axis of the disc. The bubble derives its energy from rotation and the gravitational field of the system.

The recent model of Pudritz (1985) uses the poloidal component of a field frozen into a circumstellar disc to drive a centrifugally accelerated magnetohydrodynamic wind. In this model, gas is assumed to move mostly along the field lines, whose axis of symmetry is aligned with the disc axis. Radial collapse pinches the field lines in the plane of the disc, producing an "hourglass" configuration. Centrifugal forces accelerate charged particles in the radial direction, away from the central protostar and along the poloidal magnetic field. This mechanism also taps the rotational energy of the disc to drive the outflow and may solve the long standing angular momentum problem in star formation. A feature of this model is that dissipation of angular momentum leads to accretion of gas onto the protostar through an accretion shock. Luminosity of the shock regulates the heating and ionization of the disc, thereby regulating the mass loss rate, and by feedback, the accretion rate. The model reproduces the observed correlation between the outflow mechanical luminosity and the source luminosity. Ionizing radiation generated by the accretion shock provides an explanation for the highly collimated optical jets and the compact ionized regions seen in some outflows.

7. *Comparisons with post-main sequence outflows*

A large variety of post-main sequence objects exhibit outflow sometimes into highly collimated jets. Spherical mass loss is observed in red giants, OH/IR stars, and carbon stars. Planetary nebulae may be the photoionized relics of this mass loss stage. Several extremely young planetary nebulae such as CRL 618, the Egg Nebula (CRL 6888) exhibit high velocity, highly collimated outflows of ionized gas. Many evolved planetaries are bipolar. Some of the post-main sequence bipolar nebulae such as NGC 6302, the "Bug Nebula" and the R Aquarii system contain ultra high velocity ($v \sim 800$ km s^{-1}) and highly collimated jets. The central stars, like the pre-main sequence outflow sources, are highly obscured objects which emit most of their radiation at far infrared wavelengths. There are some striking morphological similarities between the post-main sequence and pre-main sequence outflows. The source of the Orion outflow, the infrared source IRC 2, exhibits infrared colours, and maser activity so similar to the late type giant stars, that some workers have suggested the IRC 2 is a post-main sequence star, coincidentally seen superimposed on the core of the Orion molecular cloud. Although this interpretation seems unlikely, it does point out the existence of similar physical conditions during the birth and death of stars.

Both the pre-main sequence and post-main sequence bipolar outflow sources appear to be undergoing a stage of gravitational collapse, are rotating, and partly because of mass loss, are buried inside dusty and molecule rich environments. Both categories of sources may share common mechanisms for the driving and collimation of their outflows. Perhaps by studying *both* categories of sources, we may better understand the mechanisms responsible for energetic mass loss in outflow sources.

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J. Bally, A T & T Bell Laboratories,
Holmdel, NJ 07733, USA.

HIGH RESOLUTION SPECTROSCOPY OF HERBIG-HARO OBJECTS AND ITS INTERPRETATION

K. H. Bohm, University of Washington, Seattle.

J. Solf, Max-Planck-Institut fur Astronomie, Heidelberg.

A. Raga, University of Washington, Seattle.

1. *Introduction*

During the last few years the interest in Herbig-Haro (HH) objects has increased rapidly. One of the main reasons for this development is the use of HH objects as tracers of the jet-like bipolar outflows from T Tauri stars, Herbig Ae, Be stars and protostars (cf. Mundt 1985, Cohen 1986, Bally 1986, Strom *et al.* 1985). At the same time physical processes in and near HH objects, as shown by their optical,