MASS OUTFLOWS ASSOCIATED WITH YOUNG STELLAR OBJECTS

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ABSTRACT. The fundamental properties of optical and molecular outflows associated with young stellar objects are reviewed. Particular emphasis is placed on a discussion of new results concerning outflow energetics, collimating structures and the relationship between outflow properties and the magnetic field geometry characterizing their host molecular clouds. IRAS observations of YSO mass outflows reveal extended far-IR emission associated with high velocity molecular gas; in the case of L1551 IRS5, the luminosity of the extended emission is $\sim$10 times the mechanical luminosity inferred from observation of the molecular flow (and thus $\gtrsim$0.1 the bolometric luminosity of the YSO driving the outflow). Circumstellar disks of size $\sim$100 au appear to be a common, if not certain outcome of the stellar birth process for stars of $\sim 1 M_{\odot}$. In a few cases, it has been possible to resolve disk-like structures associated with YSO outflow sources. In such cases, the disk axes appear to lie along the direction of molecular outflows or stellar jets. The mass outflows (and by inference, the axes of circumstellar disks) show a remarkable tendency to align along the direction of the magnetic fields which thread their host molecular clouds. This suggests that the cloud magnetic field must play an important role in determining the flattening (and perhaps the rotation) of protostellar structures.

1. INTRODUCTION

For almost three decades, astronomers have recognized that stars undergo extensive mass loss as they approach the main sequence. The evidence includes:

- the observation of P Cygni profiles in Herbig Ae/Be and in T Tauri stars (Herbig 1960; Kuhi 1964). Mass loss rates for the Ae/Be stars are estimated to lie in the range 10^{-6} to $10^{-8} M_{\odot}$/yr; for the T Tauri stars, mass loss rates in the range 10^{-7} to 10^{-9} $M_{\odot}$/yr obtain. Outflow velocities range from 150 to 450 km/s.

- the recognition that the emission spectra characterizing Herbig-Haro objects are produced by shock excitation, resulting either from the interaction of supersonic stellar winds with "cloudlets" of ambient molecular gas (Schwartz 1975), or as "interstellar bullets" (Norman and Silk 1979) are decelerated by the surrounding molecular gas; the interstellar bullet model requires a strong stellar wind to accelerate clumps of circumstellar material to the observed velocities of several hundred km/s.

The interaction between YSO winds and ambient gas also results in a near-IR analog of the HH phenomenon: the excitation of 2.3μ molecular hydrogen emission (Elias 1980;

M. Peimbert and J. Jugaku (eds.), Star Forming Regions, 255–273.

Fischer et al. 1980).

• proper motion observations of individual HH knots (Cudworth and Herbig 1979; Jones and Herbig 1982); the tangential velocities of HH emission knots can reach values as high as 350 km/s (comparable to the largest wind velocities characterizing YSOs). Extrapolation of the observed proper motion vectors reveals an ejection site coincident with an embedded or visible YSO. High velocity water masers associated with embedded YSOs reveal similar behavior. Strelnitsky and Sunyaev (1972) first proposed that the compact knots thought responsible for producing the maser emission are accelerated to high velocities by a stellar wind. VLBI observations of water masers provide direct evidence of expansion of masering knots away from a central YSO (Genzel et al. 1981).

• molecular line observations of YSO environs. Transfer of momentum from stellar winds to ambient molecular gas can accelerate the nearby material to velocities far in excess of those characterizing undisturbed cloud material. Low spatial resolution CO observations of such wind-cloud interactions reveal broad (typically $\sim$ 10 km/s) lines (Loren 1975; Zuckerman et al. 1976; Kwan and Scoville 1976; Edwards and Snell 1982; Calvet et al. 1983). At higher spatial resolution, these outflows are often seen to be collimated and bipolar (see section 1.1).

• cm wavelength observations of a small sample of T Tauri stars and embedded YSOs known to drive molecular outflows. Multi-wavelength radio observations (e.g. Cohen, Bieging and Schwartz 1982; Rodriguez and Canto 1983) reveal spectral indices characteristic of outflowing ionized material; the mass outflow rates deduced from radio continuum observations fall in the range determined from optical studies.

1.1. Properties of Molecular Outflows

At present (see Lada 1985), over 70 molecular outflow regions have been mapped at moderate (2') to high ($\sim$20") spatial resolution. A synthesis of the derived flow characteristics suggests that:

• the flows are usually collimated, with length/width ratios of up to 6:1; the degree of collimation may prove to be even greater when flows are examined at higher angular resolution.

• outflows are often, but not always bipolar; the powering source is typically located at the center of symmetry of the outflow.

• the mechanical luminosity of the molecular outflow is large; typically, L(wind) lies between 0.01 and 0.1 times the bolometric luminosity (L(bol)) of the YSO responsible for driving the outflow. There is a rough correlation between bolometric and mechanical luminosity: higher luminosity YSOs drive higher (mechanical) luminosity flows.

• the wind momentum, p(wind), is large; p(wind) is typically 100 to 1000 times L(bol)/c (thus ruling out radiative acceleration of the outflows except for a few cases associated with high luminosity YSOs).

• typical molecular outflow velocities are $\sim$10km/sec; in rare cases, values of $\sim$100 km/s are observed.

• the outflow lifetimes, estimated as the size of the disturbed cloud region (typically $\sim$0.1 to $\sim$1 pc) divided by the average velocity of the molecular gas (typically $\sim$10 km/s), lie between 10^4 and 10^5 years.

• the mass of gas asociated with or swept up by the flow is $\sim$ several $M_\odot$.

• the estimated flow lifetimes and momenta, combined with the observed density of YSOs/pc^3, suggest that mass outflows from young stars can supply a significant fraction of the internal turbulent pressure necessary to support molecular clouds agains gravitational collapse (Norman and Silk 1980).

• in regions where the direction of the magnetic field has been determined from polarimetric observations (e.g. Vrba, Strom and Strom 1976; Snell, Loren and Plambeck 1980; R.J. Cohen, Rowland and Blair 1984) the flows appear to be directed parallel to the field.

1.2. Optical Manifestations of Mass Outflows Associated with YSOs

Recently, optical manifestations of collimated mass outflows have been seen in deep monochromatic CCD images at Hα and [S II] (two of the strongest shock-excited features anticipated for the observed range of YSO wind velocities and ambient cloud densities). In addition to locating low surface brightness HH emission regions, such images reveal a new phenomenon: stellar jets of length $\sim$1000 au and opening angles much smaller than 10° (Mundt and Fried 1983). Strom, Strom and Stocke (1983) discuss a larger-scale analog of stellar jets: highly collimated, sometimes sinuous outflows of length $\sim$0.1 pc.

Results of recent imaging and spectroscopic programs aimed at defining these new phenomena suggest (see K.M. Strom et al. 1986 for a review) that:

• optical outflows are often highly collimated. In some cases (e.g. L1551/IRS 5) the optical outflow appears to be much more highly collimated than the associated (resolved) molecular outflow.

• optical outflows are often bipolar. However, in some cases, the red-shifted component may be obscured by intervening molecular cloud or circumstellar material; in others the blue-shifted component is weak or absent possibly because the density on the earthward side of the molecular cloud is too low to produce observable emission.

• in some cases (e.g. Haro 6-10, Haro 6-13), optical jets or HH objects are not accompanied by molecular outflows; in others (e.g. LkHα 198), the molecular and optical outflows are not well aligned.

• several objects (e.g. HH 12, Haro 4-249, HH 101) show hints of helical structures.

• the momentum input from the ionized component of the optical outflows is $\sim$0.1 times the momentum estimated for the molecular outflows (Snell et al. 1985)

• both HH objects and stellar jets show outflow velocities in the range 100 to 400 km/s, that is, $\sim$ 10 times the velocities characteristic of molecular outflows.

• in some cases, the driving sources for molecular outflows associated with low luminosity stars appear to be highly variable and perhaps spectroscopically similar to the FU Ori class of eruptive pre-main sequence variables (Graham and Frogel 1985; Mundt et al. 1985; section 5 below).

• the HH phenomenon is not restricted to low mass stars. HH objects are now known to be associated with the intermediate mass ($\gtrsim 2M_\odot$) objects R Mon, LkHα 198 and V380 Ori.

• as is the case for molecular outflows, there is a strong tendency for optical outflows to be aligned along the direction of the magnetic field threading the host molecular cloud complex (see section 4 below).

1.3. Current Questions

A number of question must be adressed in order to further our understanding of mass loss during the early phases of stellar evolution. Among the most pressing are:

• do optical and molecular outflows have the same origin? Most current pictures (Snell et al. 1980; Snell and Schloerb 1985) presume that molecular outflows result as ambient molecular gas is swept up by a stellar wind having its origin at the surface of a young star. However, as noted above, the estimated momentum input from the observed ionized wind is insufficient to drive the molecular flow; moreover the wind mechanical luminosity represents a significant fraction of the bolometric luminosity of the YSO driving the outflow. Several recent theories (e.g. Pudritz and Norman 1983; Uchida and Shibata 1984) propose an alternative: molecular outflows result from centrifugally driven hydromagnetic winds emanating from the outer regions of large ($\gtrsim$ 0.1 pc) molecular accretion disks; the optical outflows result as ionized gas is driven from the hot, inner regions of the disk (Torbett 1984). Which of these pictures -- swept up gas or disk-driven winds -- best fits the observations?

• why is the mechanical luminosity of the optical and molecular outflows such a large fraction of the bolometric luminosity of the star which presumably powers the outflow? Why is the wind mechanical luminosity correlated with the YSO bolometric luminosity? Do these facts force us to conclude that YSO outflows are driven by phenomena associated with accretion of circumstellar material? Does a large fraction of the observed bolometric luminosity of YSOs driving mass outflows result from accretion?

• what accounts for the collimation of the molecular and optical outflows? Is the mechanism the same in each case? Does the outflow leave the vicinity of the stellar surface already well collimated or does an initially isotropic wind become focussed or collimated by a circumstellar disk or a larger scale molecular disk?

• what is the relation between the outflow properties and the global properties (kinematics, density distribution, magnetic field strength and geometry) of the host molecular cloud? Do most outflows align with the cloud magnetic field? If so, does this suggest that collimating structures are aligned over scales of many parsecs? that protostellar and/or stellar angular momentum vectors in young clusters may be aligned?

• how do mass outflows from YSOs affect the subsequent star-forming history of the molecular cloud complexes? Does the increase in cloud turbulent motion induced by winds affect the shape of the initial mass function? Can winds trigger episodes of star formation?

In the remainder of this review, we will focus our attention on recent observations which bear on the questions of outflow energetics and collimation, the relationship between YSO outflows and the properties of the host molecular cloud, and the properties of the YSOs responsible for driving energetic mass outflows.

2. FLOW ENERGETICS: FAR INFRARED EMISSION ASSOCIATED WITH MOLECULAR FLOWS

Examination of IRAS "skyflux" and coadded survey data in the vicinity of YSO mass outflow regions reveals several objects for which extended infrared emission corresponds morphologically with optical and molecular tracers of outflows from young stars (Strom

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et al. 1985; Clark and Laureijs 1986). The far infrared luminosity of these extended emission regions is $\sim$10 times the mechanical luminosity estimated from the observed velocity, size and mass associated with the high velocity molecular gas. It thus appears as if the mechanical luminosity inferred from the expanding molecular gas significantly underestimates the true magnitude of the YSO wind energy.

The archetypical outflow associated with L1551/IRS5 provides an excellent example. IRAS survey data for 24 individual passes have been coadded to produce a $1^\circ \times 1^\circ$ intensity map of a region centered on IRS5 (Edwards et al. 1986). In figure 1a, we present an R-band image of the L1551 region on which we superpose the 60μ contours derived from the IRAS coadded survey data. For comparison (figures 1b and 1c) we provide an overlay of the contours of emission arising from ^{12}CO high velocity gas (Snell and Schloerb 1985) and the overall ^{12}CO emission associated with the undisturbed molecular gas in the L1551 cloud (Snell 1981). For reference, the location of several YSOs in the L1551 region is indicated in these figures. Edwards et al. (1986) conclude that:

- extended 60μ emission is aligned along the outflow axis defined by the collimated supersonic molecular gas; extended emission is also seen at 100μ but not at 12μ and 25μ. The extended infrared emission bears little resemblence to the roughly spherical L1551 cloud (defined both by its optical appearance and the ^{12}CO contours for the undisturbed gas), but is instead closely aligned with the axis of the molecular outflow.

- the morphological correspondence between the outflowing molecular gas and the collimated IR emission is not exact. A comparison of the molecular gas and the IRAS maps at comparable spatial resolution reveals that the 60μ emission is more extended than the outermost contour of the integrated high velocity molecular emission. Along the outflow axis, the 60μ emission continues for more than 5' (0.2 pc at the distance to L1551) beyond the observed extent of the high velocity gas.

- the integrated 60μ and 100μ luminosity of the extended IR emission around IRS5 is $3L_\odot$. Extrapolation based on an observed color temperature of 24°K yields a bolometric luminosity of $7L_\odot$ for the extended IR emission region. This exceeds the mechanical luminosity in the high velocity molecular gas (Snell and Schloerb 1985) by more than a factor of 10 and represents nearly 20 percent of the observed bolometric luminosity of IRS5.

- the observed color temperature is roughly uniform (24°K) along the outflow axis; perpendicular to the outflow, we observe a cylindrical "halo" of cooler (20°K) emission.

- the extent of the far-IR emission region ($\sim$1 pc) argues that radiative heating from IRS 5 cannot be a major source of dust excitation. The equilibrium temperature for "standard" interstellar grains located at a distance of 1 pc from IRS 5 is only 12°K.

- the most attractive models for explaining the far-IR emission rely on emission from dust grains heated through dissipation of mechanical energy of a wind emanating from IRS5. This could occur either via 1) collisional heating of grains at the wind-cloud interface or 2) radiative heating from the shock-cooling region at the wind-cloud interface. The observed extension of the infrared emission beyond the boundary of the expanding molecular gas finds more natural explanation in the context of the radiative heating picture. Optical or ultraviolet photons arising in the shock-cooling region should penetrate beyond the wind-cloud interface before their ultimate absorption by more distant dust grains.

• the observed far-IR luminosity is comparable to the mechanical luminosity estimated from the mass loss rates and velocities thought to characterize the material leaving the surface of IRS5 (Mundt et al. 1985; Snell et al. 1985). Hence, it seems likely that only 10 percent of the initial wind luminosity is manifest in the high velocity molecular outflow; the remaining 90 percent is dissipated, perhaps in radiative losses arising in the shock-region located at the wind-cloud interface.

Extended far-IR emission is also associated with the outflows driven by the YSOs R Mon, Haro 6-10 and R CrA. These preliminary results offer the hope that the IRAS data base can be used to locate YSOs currently undergoing massive outflows, and to provide thereby a means of assessing the true frequency of this important phase of pre-main sequence evolution.

3. COLLIMATION OF YSO MASS OUTFLOWS

The physical mechanism(s) responsible for the high degree of collimation observed for molecular outflows and the even more remarkable stellar jets associated with YSOs have yet to be identified. Proposed collimating mechanisms fall into one of two broad categories: 1) those which assume that the winds leaving the YSO surface are initially isotropic and are later confined and/or focused by circumstellar or molecular cloud material and 2) those which assume that mass ejection is intrinsically anisotropic. Included in the first category are

• circumstellar disks or toroids (Snell et al. 1980; Choe 1984; Shu, Lizano and Adams 1987) of dimension $\sim 10^2$ to $10^{3.5}$ au

• molecular disks or toroids (Canto et al. 1981; Barral and Canto 1981) of dimension $\gtrsim 10^4$ au

• large scale ($\gtrsim 10^4$ au) density gradients in the nearby molecular cloud material (Konigl 1982)

In the second category are

• models which posit anisotropic outflows originating in a circumstellar accretion disk. Included in this category are centrifugally-driven hydromagnetic winds (Pudritz and Norman 1983; Uchida and Shibata 1984) and models which rely on the energy liberated in a boundary layer shock (as accreting disk material impacts on a YSO photosphere) to drive the vertical density structure of the boundary layer out of hydrostatic equilibrium (Torbett 1984).

• models in which protostellar objects exhibit strong, rotationally driven winds. Hartmann and MacGregor (1982) show that for plausible rotational velocities and magnetic field strengths, it may be possible to drive anisotropic mass outflows by means of centrifugally and magnetically accelerated winds; in their picture, the winds are directed outward along the equatorial plane of circumstellar disks.

Considerable effort has been invested in attempts to find observational evidence of proposed collimating structures.

3.1. The Search for Molecular Disks and Toroids

Torreles et al. (1983) report NH_3 observations of several well-resolved molecular outflows. Their maps typically reveal high density (n $\sim 10^4$ molecules/cm^3) structures elongated in a direction perpendicular to the CO outflow direction; they identify these structures as molecular disks or toroids. High angular resolution CS observations of the L1551 IRS5 region obtained recently with the Nobeyama 45-m telesocpe (Kaifu et al. 1984) appear to show morphological and kinematical evidence of a high density (n $\gtrsim 10^4$ molecules/cm^3) disk surrounding IRS5 (though see Batrla and Menten 1985).

While this work seems to confirm the presence of large-scale structures capable of collimating the outflows, there is in our view little conclusive evidence which at present supports their identification as disks or toroids. Heyer et al. (1986) report CS observations of the regions surrounding the YSOs driving a number of well-resolved, well-collimated molecular outflows. In general, the YSOs reside near the center of dense CS "cores"; however, neither the core morphology nor kinematic behavior suggests the presence of rotating disks of dimension on the order of 10^3 to 10^4 au. The data suggest instead that the winds from the YSOs have broken through the "weak points" in a dense, but irregular circumstellar structure. Moreover, recent CS observations by Moriarty-Schieven (1986) at FCRAO clearly demonstrate that although L 1551 IRS 5 is indeed located near the center of a dense structure of size $\sim$0.1 pc, there is no clear kinematic or structural signature of a disk.

Mapping the morphology and kinematics of dense structures associated with YSO outflow regions is considerably complicated by the lack of agreement between maps made in different tracers of high density gas. Most glaring is the disparity between the CS and NH_3 maps of the region surrounding L1551 IRS 5; the CS structure is aligned perdendicular to the flow direction while NH_3 traces a structure along the outflow (Torreles et al. 1983; Kaifu et al. 1984)! In some cases, KAO observations of far-IR continuum emission from circumstellar dust associated with outflow sources may provide a basis for resolving the ambiguities which arise from comparison of multiple molecular tracers of dense circumstellar material.

The apparent lack of convincing evidence in favor of rotating molecular disks appears to present serious difficulties for models which posit that such disks represent the source of molecular outflows (e.g. Pudritz and Norman 1983). Furthermore, the mass of molecular material involved in a typical molecular outflow is quite large compared with the proposed disk masses (Snell 1987); this latter result is also inconsistent with a "pure" disk origin for the observed outflowing molecular gas.

3.2. The Search for Smaller Scale Circumstellar Collimating Structures

While molecular disks or large-scale density gradients may play a role in collimating molecular outflows (of dimension $\sim$ 1 pc), the observations of stellar jets which appear to be highly collimated at distances no more than 100 au from the stellar surface (Mundt and Fried 1983) suggest that smaller scale structures must be responsible for focusing or confining these jets.

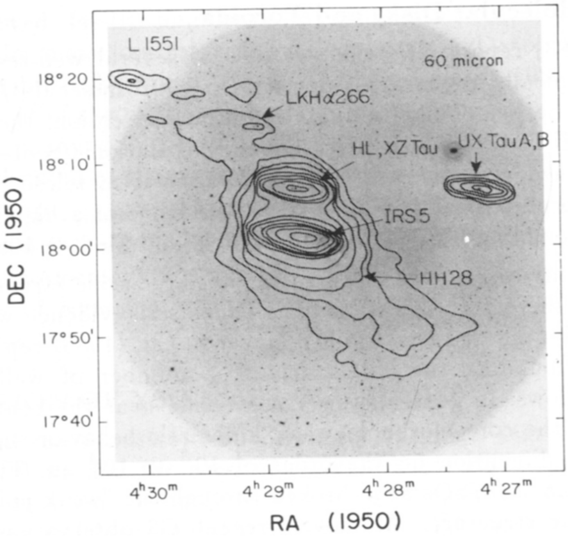

Figure 1a: A broad-band R image of the L1551 region obtained with the prime focus camera of the Mayall 4-m telescope. The circular field has a diameter of ~50'; North is at the top and East to the left. Superposed on this image is the IRAS 60μ intensity map constructed from coadded survey data. The contour levels correspond to 4,8,12,20,34,96,192,384,768,1535 and 3070 times the background noise level of $1.0\mathrm{x}10^6$Jy/ster. Also noted are the locations of the YSOs L1551 IRS5, HL and XZ Tau, UX Tau AB, and LkHα 266 and the Herbig-Haro object HH 28.

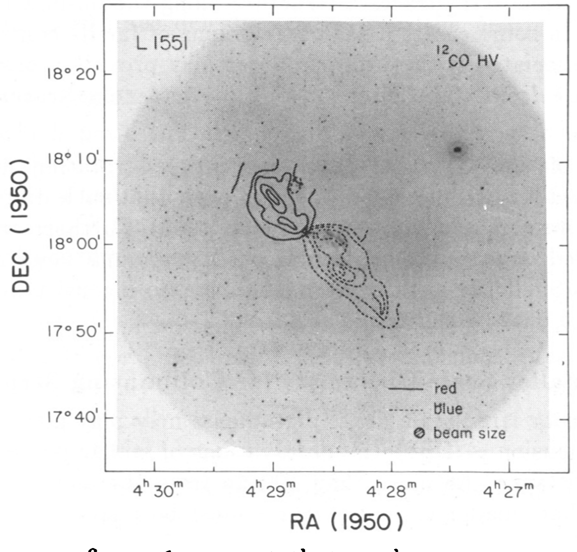

Figure 1b: Same as figure 1a except that we here superpose contours representing the integrated intensity of the high velocity blueshifted (dashed lines) and redshifted (solid lines) molecular (^{12}CO) gas; contours are plotted at intervals of 5 °K km/s (Snell and Schloerb 1985); the lowest contour level corresponds to 5 °K km/s. Note that the 60μ contours are aligned along, but extend beyond the high velocity molecular gas.

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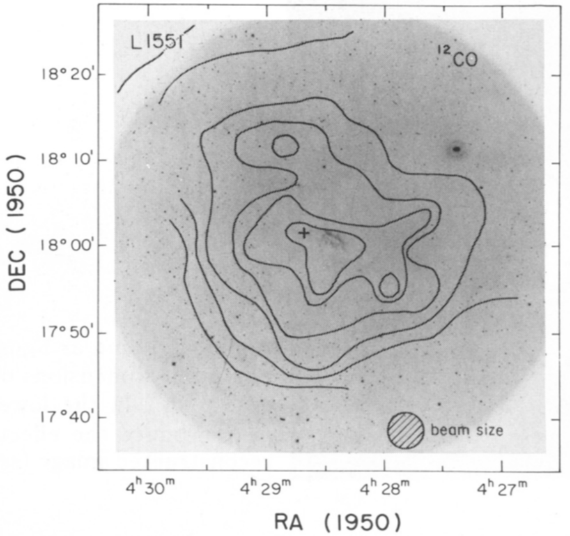

Figure 1c: Same as figure 1 except that we display contours of the integrated intensity of the ^{12}CO J=1-0 line over all velocities; the contour intervals begin at a level of 2°K km/s and are displayed at intervals of 2°K km/s. Note that the integrated ^{12}CO contours follow the roughly circular outline of the optical obscuration which defines L1551. The morphology of the extended 60μ emission bears no resemblance to the cloud shape (thus ruling out the possibility that it traces heated dust at the cloud surface rather than the mass outflow region).

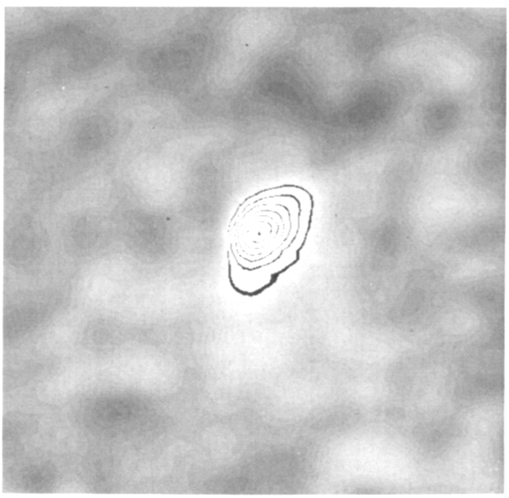

Figure 2: A maximum entropy reconstruction image of the YSO L1551 IRS 5 derived from a heavily oversampled, high signal/noise picture obtained at the IRTF under conditions of excellent seeing; the outer dimensions of the image are 12"x12"; North is at the top and East to the left. Note that the axis of the disk lies along the direction of the mass outflow (illustrated in figure 1b) and approximately along the direction of the magnetic field as defined by the polarization observations reported by Vrba, Strom and Strom (1976).

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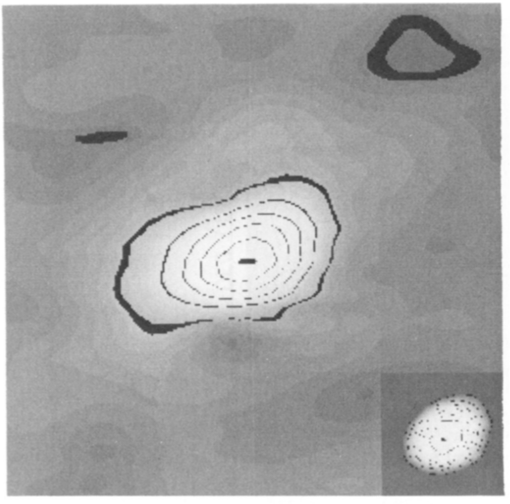

Figure 3: Same as figure 2 except for HL Tau. The outer dimensions of the image are in this case 6"x6". In the lower right hand corner we reproduce the effective beamsize for the reconstructed image (see Grasdalen et al. 1984).

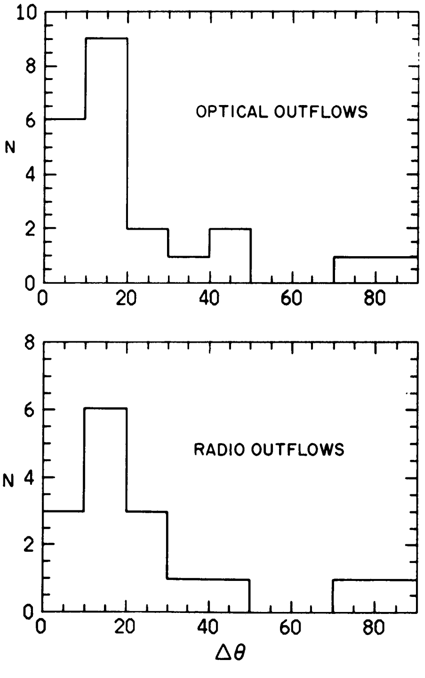

Figure 4a (top): A histogram depicting the frequency distribution of the absolute value of the difference, $\Delta\theta$, between the position angle of the magnetic field direction and the outflow direction determined for well collimated molecular outflows.

Figure 4b (bottom): Same as figure 4a except for YSO outflows defined by optical tracers of wind-cloud interactions (see K.M. Strom et al. 1986).

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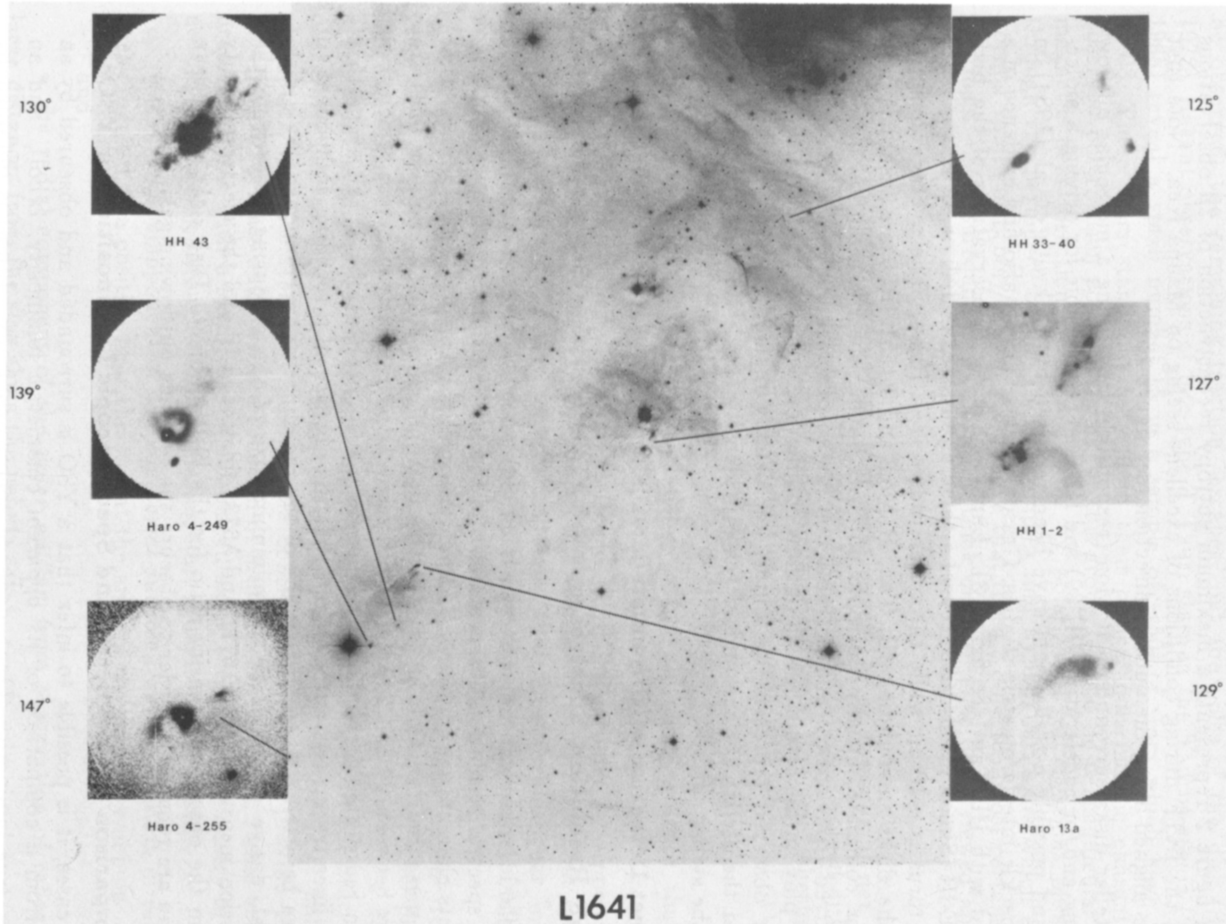

Figure 5:
A series of [S II] images of YSO outflow regions located within the L1641 GMC arranged around a wide-fiedl image of the cloud complex. Note the strong tendency for the outflow axes to be parallel one to another and to the direction of the magnetic field (which defines a position angle ~140°; Vrba 1986). The scale over which outflow axes are aligned within L1641 is ~15 pc.

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3.2.1. Direct Detection of Circumstellar Disks

Searches for circumstellar disks associated with YSO outflow sources have begun to bear fruit. Strom et al. (1985) report the detection of a circumstellar disk (of diameter ~500 au and seen via dust-scattered light) surrounding L1551 IRS5. The image of IRS5 reproduced in figure 2 represents a maximum entropy reconstruction of 2μ observations obtained with the IRTF during conditions of excellent seeing on Mauna Kea. Note that the disk axis is aligned along the outflow direction (see figure 1b).

Circumstellar disks surrounding R Mon (responsible for driving a molecular outflow and for ejecting and/or accelerating HH 39) and HL Tau (responsible for driving a molecular outflow and possibly a stellar jet) have been reported by Beckwith et al. (1984) on the basis of speckle interferometric studies; Grasdalen et al.(1984) also find evidence of a disk associated with HL Tau (see figure 3). Lunar occultation observations of the high mass star M8E-IR (Simon et al. 1985) reveal a thick circumstellar disk or torus; the inner radius of the torus is ~10 au while the outer radius is ~ 70 au. The average densities inferred for the disks surrounding HL Tau, R Mon and L1551 IRS5 are insufficient to confine and/or collimate initially isotropic outflows having the mass outflow rates and velocities inferred from optical and/or radio continuum observations of these stars. For these disks to play an important role in outflow collimation, we must posit that the structures thus far observed represent the outer, low density regions of disks which extend inward toward the stellar surface and increase in density (by $\gtrsim$ 100 times) at distances $\lesssim$10 au from the stellar surface.

3.2.2. Indirect Detection of Circumstellar Disks

3.2.2.1. High Resolution Spectroscopy of YSOs Showing Strong Forbidden Lines

Appenzeller, Jankovics, and Ostreicher (1984) and Edwards et al. (1986) have obtained high spectral resolution observations of a sample of 15 T Tauri stars and Herbig emission objects characterized by strong forbidden emission. Appenzeller et al. note that the velocities measured for [O I] λ6300Å and [S II] λ6717 and λ6731Å emission lines are blue-shifted by between 20 and 240 km/s with respect to the stellar systemic velocity; in most cases, no red-shifted forbidden-line emission is seen. Appenzeller et al. argue that the forbidden lines trace mass outflows and that the absence of a receding component to the outflow can be attributed to obscuration of the red-shifted flow component by a disk. Edwards et. al. derive estimates of the minimum size of the obscuring disks from the observed emission measure in the λ6717 and λ6731 lines of [S II] and the electron density estimated from the observed intensity ratio for the [S II] doublet. Disk sizes of between ~30 and 150 au are required in order to obscure the receding outflowing gas.

3.2.2.2. Comparison of Bolometric and Spectroscopic Luminosities for YSOs

In some cases, it is possible to infer that a YSO is surrounded and obscured by an edge-on disk from a comparison of its ***apparent*** bolometric luminosity, L(bol), and an estimate of its ***true*** luminosity, L(sp), deduced spectroscopically. L(bol) is obtained by integrating the observed YSO spectral energy distribution from 0.4μ to 100μ while L(sp) is obtained from measurement of gravity- and temperature- sensitive spectroscopic features (e.g. hydrogen line wings and helium line strengths for early-type YSOs and CaH and TiO band strengths for late-type young stars; Strom et al. 1972; Mould and Wallis

1977). If we assume that every young star is surrounded by an optically thick circumstellar disk, then YSOs viewed equator-on will appear to have unusually small values of L(bol)/L(sp). In such cases, to a first approximation, only that fraction of starlight absorbed by the disk and returned to the observer in the form of infrared photons can be observed; the remaining fraction "escapes" out the poles of the disk (Strom et al. 1972). Recent observations of late-type T Tauri stars in the Taurus region (Strom et al. 1985) reveal a small number (5 in a sample of $\sim$50) of stars which have L(bol)/L(sp) $\lesssim$0.03. These stars stand out as well in their optical polarimetric characteristics: the observed polarization position angles for this group tend to lie perpendicular to the local magnetic field direction as defined both by polarization observations of stars viewed through the periphery of the Taurus complex and by T Tauri stars which exhibit more normal values of L(bol)/L(sp). We believe that these 5 objects almost certainly represent low mass YSOs surrounded by optically thick circumstellar disks viewed approximately equator-on.

The above summary suggests that disks appear to be common if not certain outcomes of the stellar birth process. Moreover, the axes of spatially resolved disks appear to lie along the direction of stellar jets or molecular outflows. However, whether these circumstellar disks play a direct role in collimating YSO mass outflows is not yet certain.

3.3. Current Limits on the Size of the Collimation Region

Observations of YSOs driving stellar jets provide clear evidence that these jets become collimated on scales $\lesssim$100 au (Mundt and Fried 1983).

Analysis of blueward-displaced [O I] and [S II] line profiles by Appenzeller et. al. (1984) and Edwards et al. (1986) (see section 3.2.2.1) demonstrates that outflows from these stars must be collimated on scales $\lesssim$100 au (indeed, several appear "closely nebulous" on high quality optical photographs) and that the receding parts of the collimated flows are obscured by circumstellar disks of dimension $\gtrsim$100 au.

Young stars associated with "cometary" reflection nebulae appear to provide a laboratory for probing the wind geometry within ***a few stellar radii*** of YSO photospheres. Since the observed radial velocity component of the outflowing wind in the direction of a given point in the reflection nebula depends on the angle between the star, nebula and observer, spectroscopic observations of stellar outflow signatures (e.g. narrow "shell" absorption lines) scattered by dust in the cometary nebula, can provide the basis for modeling YSO mass outflows as a function of latitude. For example, radial velocity measurements made with a spectrograph slit placed along the axis of symmetry of a cometary nebula and passing through the illuminating star, provide a measure of

• the ***radial*** component of the ***equatorial outflow*** from observation of reflected shell lines observed at a position near the star at the apex of the cometary nebula

and

• the radial component of the ***polar outflow*** from observation of reflected light at large distances from the star along the nebula axis.

Jones and Herbig (1982) report the results of such a study for R Mon, a YSO which appears to drive a bipolar molecular outflow (as well as to excite and accelerate HH object 39) and which is located at the apex of the cometary reflection nebula NGC 2261. Deep, narrow Balmer "shell" absorption features, formed in an expanding envelope surrounding R Mon, are quite prominent. A low resolution, long slit spectrum taken along the symmetry axis of the reflection nebula (and passing through R Mon) reveals that the Balmer shell lines exhibit an apparent velocity gradient. The velocities measured along the axis of NGC 2261 lie near -50 km/s within a few arc seconds of R Mon, and decrease monotonically to a value of -250 km/s at progressively greater distances from the star. Jones and Herbig attribute this velocity gradient to a latitudinal variation of wind velocities close to the stellar surface. The observed velocity gradient is well modeled by a wind characterized by a relatively small ($\lesssim$100 km/s) velocity in the equatorial plane of the star, and by a much larger velocity ($\sim$300 km/s) near the poles. If their model is correct, it suggests that mass loss in R Mon takes place primarily along its polar axis. Moreover, because the Balmer "shell" features are probably formed within a few stellar radii of the surface of R Mon, the wind anisotropy must have its origin at or near the stellar surface. This conclusion is consistent with the belief that the material comprising stellar jets, with characteristic velocities of several hundred km/s, must be accelerated near the surface of a star (where the escape velocity is on this order) rather than at distances of $\sim$astronomical units from the surface of the star.

4. THE RELATIONSHIP BETWEEN YSO MASS OUTFLOWS AND MOLECULAR CLOUD MAGNETIC FIELDS

Several observers (Snell et al. 1980; Cohen et al. 1984; Strom and Strom 1985) have noted that collimated mass outflows from YSOs appear to be directed parallel to the magnetic field threading the molecular cloud complexes which host the outflow sources. If so, then the magnetic field must either 1) play a direct role in collimating the flows or 2) must determine the orientation of the structures (e.g. circumstellar or molecular disks; larger-scale density gradients) which collimate the outflows.

In order to test the hypothesis that the outflow and magnetic field directions are aligned, we have embarked on a program aimed at determining the outflow and magnetic field directions. A determination of the outflow direction depends on

• identification of the YSO driving an optical or molecular outflow (from extrapolated proper motion vectors measured for HH emission knots, location at the center of symmetry of a bipolar molecular outflow, polarization measurements of scattered-light-dominated regions associated with the mass outflow, or unusual infrared properties)

and

• a flow direction defined either by a high angular resolution molecular line map, or a CCD image of shocked gas (which, together with the source location, describes the locus of wind-cloud interactions)

The magnetic field direction is derived from optical polarimetry of stars viewed through the periphery of the molecular cloud hosting the outflow(s) (Vrba, Strom and Strom 1976).

In figure 4a, we plot a histogram depicting the distribution of the quantity

$$\Delta\theta = | \text{ flow position angle - magnetic field position angle } |$$

for all well-collimated flows mapped at mm wavelengths. Figure 4b presents a similar histogram for flows imaged at optical wavelengths (see K.M. Strom et al. 1986 for a summary).

There is a strong tendency for the outflow and magnetic field directions to be aligned; more than 70 percent of the outflows are aligned within 30° of the cloud magnetic field.

A more dramatic presentation of this tendency is afforded by figure 5 in which we locate and illustrate 6 optical outflows associated with the giant molecular cloud (GMC) Lynds 1641. The position angle of each outflow is listed adjacent to its [S II] 6731Å image. Preliminary results of a survey of ~200 stars associated with this GMC (Vrba 1986) suggest that the magnetic field (as mapped by the subset of our sample stars showing polarization values in excess of 2 percent at R) defines a position angle of ~140°. These outflows are well aligned both with the cloud magnetic field and with one another despite the fact that their driving sources are separated by ~15 pc.

As noted in sections 3.1 and 3.2.1, the axes of disk-like structures associated with YSOs driving mass outflows tend to lie along the directions defined by the outflowing gas. This result, combined with the above discussion strongly suggests that the magnetic field plays an essential role in determining the flattening and perhaps the rotation of protostellar structures.

5. THE NATURE OF THE EMBEDDED YSOs RESPONSIBLE FOR DRIVING MASS OUTFLOWS

The YSOs responsible for driving energetic mass outflows are generally deeply embedded within their parent molecular cloud complexes and still shrouded by disks or cocoons of circumstellar dust and gas. Direct observation of these stars at optical wavelengths is therefore difficult and often impossible. Fortunately, the powerful winds emanating from these objects have apparently "excavated" cavities in the surrounding molecular material. In turn, these cavities provide paths, not only for escaping gas, but for photons emerging from the optically obscured YSO and its environs. These photons are, in favorable circumstances, scattered by dust near the surface of the surrounding molecular cloud. Observations of this scattered "light at the end of the tunnel" can provide a glimpse of a YSO at an early and active phase of its evolutionary development.

An excellent illustration of this circumstance is provided by the outflow region associated with L1551 IRS5. The approaching half of the bipolar molecular outflow has produced and optically thin cavity (within which are entrained or accelerated a number of clumps of gas, shocked by the highly supersonic wind emanating from IRS 5 and characterized by Herbig-Haro emission spectra). The walls of the cavity are illuminated by light escaping from IRS5 (as demonstrated from polarimetric observations of these regions; Ward-Thompson et. al. 1985, Stocke et al. 1986).

Mundt et. al. (1985) obtained a long slit spectrum of the brightest portion of the scattered light "rim" located to the north, northwest of IRS5. The resulting spectrum shows weak Hα emission, a strong, violet-displaced P-Cygni component at Hα (the deepest part of the absorption component falls at a velocity of -300 km/s), a blend of metallic lines at λ 6500Å and an indication of a broad feature at λ 6707Å (Li I). The spectrum appears similar to those of FU Ori and V 1057 Cyg, two members of the FU Ori class of eruptive pre-main sequence variable stars. If the assignment of L1551 IRS5 to the FU Ori class can be confirmed from observation of a strong variation of spectral type with wavelength, it will represent the second example of an FU Ori star associated with a collimated mass outflow (see Graham and Frogel 1985 who find the powering source for HH 57 to be an FU Ori-like object). In this regard, it is noteworthy that

Hartmann and Kenyon (1986) ascribe the variation of spectral type with wavelength characterizing objects of this class to the contribution of the inner regions of a circumstellar accretion disk to the observed (composite) spectrum.

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FELLI: The 2.2 μm map in L1551 seems to be crucial in the understanding of the collimation agent of the bipolar outflow. But, what is the true nature of the IR emission: dust, reflected stellar radiation or gas emission?

STROM: Gary Grasdalen (unpublished) has obtained 2.2 μm polarimetric observations of L1551/IRS5 and its associated extended structure. These observations suggest that the observed structure results from light scattered by dust.

UCHIDA: Is it possible by present-day techniques to measure the tilt of the spectral line across the optical jet corresponding to the rotation of the jet around its axis, or has somebody already measured it? I am keen to know whether the optical jet has a helical velocity which is indicative of the importance of magnetic field in the process.

STROM: Yes. Imaging through narrow-band filters (e.g. [S II] λ6731), tilted to change the wavelength of maximum transmission, permit crude velocity maps to be made; of particular interest is the map reported by Morgan, Wolff, Strom and Strom (1984, Astrophys. J. Letters) for H-H 101, which suggests a "helical" velocity field. However,Hartigan and Lada have challenged the interpretation in this case. Others, e.g. Haro 4-249,could be studied using multiple long-slit spectra and "tomographic" representations of the velocity field.

ZINNECKER: 1) Regarding circumstellar disks such as the one in L1551-IRS5, are the results obtained with the maximum entropy method (2.2 μm map) and the infrared speckle interferometry in agreement with each other? 2) Regarding the possible connection between global cloud properties and the occurrence or structure of CO-outflows, could you comment on the fact that of the many CO-outflows, reported so far, none seems to occur in the Rho Ophiuchi star forming region?

STROM: 1) Yes, both the derived shape and mass for HL Tau are in good agreement. 2) Charlie Lada has detected a flow in one of the sources in this cluster. As I recall, it is aligned along the local field and is extended in the far-IR. However, Charlie should confirm both statements!

ZINNECKER: Concerning outflows in the Rho Ophiuchi cloud, I think we can say that in the core region, where more than 30 buried infrared sources are found, we have not yet found an outflow comparable to that of L1551-IRS5, although we have not yet searched every candidate. The only prominent outflow we have been able to find is associated with a very cold IRAS source well outside the core region of the cloud. Perhaps the lack of outflow activity in the core is due to the fact that the bulk of the stars there are of low mass, and flows from low mass stars are difficult to detect. Perhaps the lack of outflows has something to do with the high star formation efficiency in the cloud. Perhaps we have not searched hard enough for such activity in the cloud. Certainly more work on this cloud is needed to address this question.

PUDRITZ: Your observations of L1641 is extremely interesting. Taking the Taurus flow/sheet structure as an analogy, one might expect to find sheet like structures oriented perpendicular to the global magnetic field on planes bissecting the position of the outflow sources. Are you searching for such structure?

STROM: Yes. A graduate student at U. Mass, Robert Seaman, Gary Grasdalen and we are carrying out a program of near IR (1.6 μm and 2.2 μm) imaging of 200 sources in L1641 in order to search for circumstellar structures and to determine their orientation, our other goal is to constrain the location in the HR diagram of these embedded sources.

BASTIEN: I would like to caution those who make polarization observations of stars to map the magnetic field in a given region to very careful in discriminating between background and embedded stars. The T Tauri star RY Lupi is a good example of a star with an intrinsic, variable, polarization which cannot be explained by grains aligned by a magnetic field. If embedded stars are used to map the magnetic field, one should *at least* check that the polarization does not vary.

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