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The Energetics of Outflow and Infall from Low to High Mass YSOs

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Abstract. In this review, I present an overview of the physical characteristics of outflows across the mass spectrum and summarize the similarities and differences in the energetics between low and high luminosity young stellar objects. I then discuss how theories and simulations developed for low-mass systems suggest a possible change in the outflow/infall dynamics as the mass accretion rate increases.

1. Introduction

The dynamics of outflow and infall associated with young stellar objects (YSO) affect the large scale energy input and turbulent support of molecular clouds, the dissipation of molecular clouds, the final mass of the central star, the evolution of circumstellar material, and ultimately, the conditions for planet formation. Although outflows in the form of wide-angle winds and/or well-collimated jets are associated with YSOs of all luminosities, there are reasons to believe that massive stars may form differently than low-mass stars: 1) Massive YSOs may evolve to the Zero Age Main Sequence (ZAMS) more rapidly than their lower mass counterparts: O spectral type stars have a Kelvin-Helmholtz timescale $\lesssim 10^4$ years while solar-type stars require more than 10^7 years to reach the main sequence; 2) OB stars reach the ZAMS while still embedded and perhaps still accreting. Once on the ZAMS, UV photons generate an ultracompact HII (UC HII) region and strong winds drastically affect the physical conditions, structure, and chemistry of their surrounding; 3) OB stars form in denser clusters than lower mass stars and a higher fraction of OB stars form in binary or multiple systems. Thus, there may be more dynamical interactions between massive YSOs. In the extreme case, stars with masses well in excess of $10 M_{\odot}$ may arise from the coalescence of lower mass stars (see, e.g. Stahler, Palla, & Ho 2000).

Despite these arguments, independent studies have established correlations of the form: $\dot{M} \propto L_{bol}^{0.6}$ where \dot{M} is the bipolar molecular outflow rate and the ionized mass outflow rate in the wind from $L_{bol} = 0.3$ to $10^5 L_{\odot}$ (e.g. Levreault 1988; Shepherd & Churchwell 1996). There is also a strong correlation between bolometric luminosity and circumstellar mass from $L_{bol} = 0.1$ to $10^5 L_{\odot}$ (Saraceno et al. 1996, Chandler & Richer 2000). These correlations argue that there is a strong link between accretion & outflow for a wide range of L_{bol} . It has been suggested that they argue for a common entrainment and/or driving mechanism for molecular flows from YSOs of all luminosities. However, this is not a compelling argument, given that most physically reasonable outflow mechanisms would generate more powerful winds if the source mass and luminosity increase (Richer et al. 2000).

2. Energetics: Observational Similarities and Differences

Previous reviews that focus mostly on outflows from low-mass YSOs include Lada (1995), Bachiller (1996), Bachiller & Tafalla (1999), and Reipurth & Bally (2001). Massive YSO outflows are reviewed by Garay & Lizano (1999), Churchwell (1999), and Königl (1999). Richer et al. (2000) and Cabrit (2002) examine the similarities between characteristics of massive and low-mass outflows. In this section, YSO characteristics are presented that show trends or differences across the mass spectrum.

Low-mass outflows: spectral types M–F

Young, low-luminosity YSOs ($L_{bol} \sim \text{few } L_{\odot}$) have mass outflow rates $\dot{M}_f = 10^{-8}$ to $10^{-5} M_{\odot} \text{ yr}^{-1}$, momentum rates $\dot{P}_f = 10^{-7}$ to $10^{-4} M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$, and mechanical luminosity $L_{mech} = 10^{-3}$ to $10^{-1} L_{\odot}$. Young stars reach the main sequence at about the same time the outflow terminates (10^7 to 10^8 years). The full opening angle, θ , of flows from low-luminosity YSOs tends to be $10\text{--}30^{\circ}$ close to the central source (< 50 AU) but then re-collimates ($\theta \sim \text{few degrees}$) within 100 AU from the protostar (e.g. Ray et al. 1996; Dougados et al. 2000). The driving jets have a significant neutral component with ionization fractions, $x_e = 0.01$ to 0.1 (e.g. Bacciotti & Eisloffel 1999; Giovanardi et al. 2000).

One of the best examples of a young, low-mass molecular jet is HH 211. The highly collimated jet is roughly 10^4 AU in length (Gueth & Guilloteau 1999; McCaughrean et al. 1994; Chandler & Richer 2001). The morphology of the flow is relatively simple with the highest velocity gas surrounded by a cocoon of lower-velocity gas. Although well-collimated jets continue to be produced even after flows are optically visible (e.g. HH 111: Reipurth & Bally 2001), the molecular outflow morphology tends to become more complex with time and the flow opening angle increases. This could be due to jet precession, as appears to be the case in L1157 (Gueth et al. 1998). Typical precession angles range from a few degrees to $\sim 10^{\circ}$. A wide-angle wind component could also erode the outflow cavity walls, expanding the opening angle (e.g. B5 IRS1: Velusamy & Langer 1998). At least some low-mass YSOs also undergo occasional FU Ori outbursts with rapid disk accretion (up to $10^{-3} M_{\odot} \text{ yr}^{-1}$) accompanied by a strong disk wind with mass-loss rates $\sim 10^{-5} M_{\odot} \text{ yr}^{-1}$ and this likely affects the energetics and morphology of the large-scale flow (e.g. Calvet, Hartmann, & Kenyon 1993; Bell et al. 1995; Hartmann & Kenyon 1996).

In conjunction with the early outflow phase of a low-mass YSO, accretion disks are always present (e.g. Mundy, Looney, & Welch 2000; Haisch, Lada, & Lada 2001; Alves et al. 2002). High velocity gas can generally be traced back to the central $10\text{--}50$ AU region of the disk where the outflow is generated. Thus, it is increasingly clear that outflow and accretion onto the protostar are linked and that the outflow is generated within 50 AU of the protostar.

Intermediate-mass outflows: spectral types A & B

Intermediate-mass YSOs cover a wide range of L_{bol} . For A-type stars $L_{bol} \sim 10\text{--}30 L_{\odot}$. For B-type stars L_{bol} varies 2 orders of magnitude: from $30 L_{\odot}$ several $\times 10^4 L_{\odot}$. Early-B stars ($L_{bol} \sim 10^4 L_{\odot}$) generate UC HII regions and reach the ZAMS while still accreting and generating strong molecular outflows (e.g. Churchwell 1999, Garay & Lizano 1999, and references therein).

Intermediate-mass YSOs have $\dot{M}_f = 10^{-5}$ to a few $\times 10^{-3} M_\odot \text{ yr}^{-1}$, $\dot{P}_f = 10^{-4}$ to $10^{-2} M_\odot \text{ km s}^{-1} \text{ yr}^{-1}$, and $L_{mech} = 10^{-1}$ to $10^2 L_\odot$.

Outflows from A-type YSOs are similar to those from low-mass YSOs although the energetics are roughly an order of magnitude higher. Well-collimated jets are common and the associated molecular flows tend to be collimated for young sources and less collimated for more evolved sources. Evidence for disks around A-type YSOs is extensive (e.g. Thé et al. 1994; de Winter 1996; Mannings & Sargent 1997; Fuente et al. 2002). The frequency of Herbig Ae star disks is between 75 and 100%, similar to T Tauri stars. Disk mass, M_D , increases with stellar mass, M_* , up to A0 spectral type while M_D/M_* remains roughly constant (Natta, Grinin, & Mannings 2000). Given the similarity between disk and outflow properties from A-type YSOs and T Tauri stars, it appears that the dynamics of YSO outflow and accretion is similar for the two groups.

For mid- to early-B stars, there are fewer well-studied examples for which the geometry and energetics within 100–1000 AU of the YSO can be well defined. Thus, statistical properties of these systems are difficult to determine accurately. However, there are a few sources for which our observations are of comparable quality to those of low-mass YSOs and they provide at least a qualitative view of the range of the outflow/infall properties for these energetic sources.

Some mid- to early-B YSOs have ionized or molecular jets that are well-collimated close to the YSO. However, the associated molecular flows have large opening angles and often have complex morphology. One of the best examples is HH 80-81 which has a highly collimated ionized jet with a projected length ~ 5 pc (Martí, Rodríguez, & Reipurth 1993; Heathcote et al. 1998). The truncated CO flow full opening angle is roughly 40° and does not re-collimate (Yamashita et al. 1989). The molecular flow momentum rate ($\dot{P}_f = 6 \times 10^{-3} M_\odot \text{ km s}^{-1} \text{ yr}^{-1}$) is an order of magnitude greater than \dot{P}_j in the ionized jet. If the jet drives the CO flow it must have an ionization fraction, $x_e \sim 0.1$, near the upper range of x_e for jets from low-mass YSOs. Knot spacing within the jet suggests a timescale of 10-30 years, comparable to timescales inferred for T Tauri star jets (Martí, Rodríguez, & Reipurth 1995). Thus, the HH 80–81 jet appears to be a scaled-up version of a T Tauri star jet. The CO flow position angle is misaligned with the jet by roughly 30° . The jet itself has only a slight wobble of a few degrees and thus, jet precession is not likely to cause the wide opening in the molecular flow. The molecular flow may be shaped by a wide-angle wind, it could be the result of multiple flows, or it could be generated by a transverse momentum component due to interactions between working surfaces within the jet. Additional examples of mid- to early-B YSOs that appear to have relatively well-collimated jets are: 1) Ceph A HW2 which has an ionized jet, complex HH objects and multiple molecular outflows (e.g. Sargent 1979; Hartigan et al. 1986; Torrelles et al. 1993; Rodríguez et al. 1994; Garay 1995); and 2) IRAS 20126+4104 which has an ionized and molecular jet which are misaligned from the larger scale molecular outflow by more than 60° (Cesaroni et al. 1999; Hofner et al. 1999; Shepherd et al. 2000). The large precession angle in the IRAS 20126+4104 jet may be due to an interaction with a close binary companion.

At least one early-B YSO, G192.16–3.82, has a poorly collimated ionized wind ($\theta \sim 40^\circ$) within 50 AU of the YSO that expands to $\theta \sim 90^\circ$ 0.1 pc from the source (Shepherd et al. 1998, Shepherd & Kurtz 1999, Shepherd, Claussen,

& Kurtz 2001). The molecular flow represents the truncated base of the larger scale flow that extends more than 10 pc from end-to-end (Devine et al. 1999). The outflow is consistent with being produced by a wind blown bubble and there is no evidence for a collimated jet. Thus, at least some early-B YSOs do not produce well-collimated jets.

Disks around early-B YSOs are significantly more massive than those around A-type and T Tauri YSOs. Further, M_D/M_* is often greater than 0.3 which may cause the disk to be locally unstable and provide an additional means of angular momentum transport from the protostar (e.g. Laughlin & Bodenheimer 1994; Yorke, Bodenheimer, & Laughlin 1995; Shepherd, Claussen, & Kurtz 2001). Early-B YSOs that are actively powering molecular outflows have circumstellar disks with masses ranging from $0.1 M_\odot$ (e.g. R Mon: Natta, Grinin, & Mannings 2000), to several or tens of solar masses (e.g. G192.16–3.82: Shepherd, Claussen, & Kurtz 2001; and IRAS 20126+4104: Cesaroni et al. 1999). The presence of accretion disks around early-B YSOs and outflows that can be traced back to the inner 50–100 AU of the disk in at least a few sources implies that accretion and outflow are linked. The increased M_D/M_* and the existence of less collimated outflows suggests that the detailed dynamics of infall and outflow in early-B YSOs may differ from their lower mass counterparts.

High-mass outflows: spectral type O

O stars with $L_{bol} > 10^4 L_\odot$ generate powerful winds with $\theta \sim 90^\circ$ within 50 AU of the star while accompanying molecular flows can have $\theta > 90^\circ$ (e.g. Orion I, Greenhill et al. 1998). The flow momentum rate ($> 10^{-2} M_\odot \text{ km s}^{-1} \text{ yr}^{-1}$) is more than an order of magnitude higher than what can be produced by stellar winds and L_{mech} exceeds $10^2 L_\odot$ (e.g. Churchwell 1999, Garay & Lizano 1999). For a few sources that are relatively isolated and for which adequate high-resolution data are available, no inner accretion disk (~ 50 AU diameter) has ever been conclusively detected. Instead, collimation close to the protostar appears to be due to pressure confinement from an equatorial torus of dense gas (e.g. Orion I: Greenhill et al. 1988; G5.89–0.39: Acord, Churchwell, & Wood 1998, Feldt et al. 1999; K3-50A: De Pree et al. 1994, Howard, Koerner, & Phipper 1997). Due to the lack of detectable accretion disks, the link between accretion and outflow is in jeopardy for O stars. Either the disks have been photoevaporated by the time the (coasting) outflow is detected (Hollenbach et al. 1994) or the outflow is generated farther from the protostar than in lower-mass YSOs (perhaps in the torus or farther out).

3. A change in outflow/infall dynamics as \dot{M}_{acc} increases?

Observations indicate that the outflow/infall mechanism is similar from T Tauri stars up to B0 protostars. Although there is evidence that the energetics for early-B stars may differ from their low-mass counterparts, the dynamics are still governed by the presence of linked accretion and outflow. This cannot be said for young O stars because no inner accretion disk has ever been detected. Thus, with current observational evidence, there appears to be a break between the dynamics in early-B YSOs and those which govern the formation of O stars. This could simply be a timescale issue: the disks are photoevaporated before they are detected; or O stars form differently than lower mass stars. Assuming the

dynamics of outflow and infall are similar up to early-B YSOs, it is reasonable to examine theoretical predictions and simulations for evidence of a possible change in the dynamics as \dot{M}_{acc} increases.

x-winds: In this model infalling material accretes through the disk until it reaches an inner truncation radius (the x-point) where the material is divided into wind and accretion fractions (Shu et al. 2000 and references therein). The disk magnetic field is locked to the stellar field, regulating the mass and angular momentum balance and controlling outflow and infall dynamics. Shu et al. (1994) noted that high accretion rates push the x-point to the stellar surface, crushing magnetic field lines. For a typical T Tauri star with $M_\star = 0.5 M_\odot$, $R_\star = 2.8 R_\odot$, $B_\star = 380$ G, $\dot{M}_{acc} \sim 10^{-8} M_\odot \text{ yr}^{-1}$ the x-point is $\sim 5R_\star$ from the stellar surface. However, T Tauri stars in FU Ori outburst with $\dot{M}_{acc} \sim 10^{-5} M_\odot \text{ yr}^{-1}$ or a B9 protostar with an accretion rate $\sim 10^{-4} M_\odot \text{ yr}^{-1}$ would force the x-point into the stellar surface. Indeed, FU Ori Stars in outburst have no hot UV continuum emission like T Tauri stars supporting the interpretation that the magnetospheric accretion columns have been crushed onto the stellar surface (Hartmann & Kenyon 1996). Thus, if x-winds from truncated disks drive low-mass outflows, then massive outflows must be driven by a different mechanism: either an x-wind from a rapidly rotating protostar in which the disk abuts against the surface of the YSO (Shu et al. 1994), or a disk-wind in which the outflow is generated in the disk alone (Königl & Pudritz 2000).

Disk-winds: If disks are threaded by open magnetic field lines, then outflows can take the form of centrifugally driven winds (Königl & Pudritz 2000 and references therein). No stellar magnetic field is required and the outflow is generated over a range of disk radii. Simulations of magnetized disk-winds suggest that, for $\dot{M}_w \sim 10^{-8} M_\odot \text{ yr}^{-1}$ at the surface of the accretion disk, disturbances appear to grow, leading to instabilities & shocks and the outflow becomes episodic: knots are produced as observed in T Tauri jets (Ouyed & Pudritz 1999). As \dot{M}_w is increased 3 orders of magnitude, jet behavior shifts from episodic to steady ejection. Thus, if outflows are driven by disk-winds, these simulations suggest that the detailed dynamics could change for the increased \dot{M}_w expected for mid- to early-B YSOs.

Two conditions expected for luminous YSOs are increased disk surface heating (due to increased stellar radiation and shocks) and, perhaps, a higher level of disk turbulence (if $M_D/M_\star > 0.3$). Casse & Ferreira (2000a,b) and Ferreira (2002) have developed a model-independent theory of linked accretion and outflow (Magnetized accretion-ejection structures or MAES) that includes a description of turbulence in the disk and flow. MAES solutions with increased disk surface heating causes increased mass loading (see also Shang et al. 2002 and Garcia et al. 2001). Since winds carry angular momentum away, this means that a warmer, denser wind causes the disk to rotate slower. Also, MAES solutions with higher disk turbulence (larger angular momentum transport through the disk) have increased wind turbulence and the wind carries away less angular momentum and mass relative to the amount that is accreted onto the surface of the star. Thus, MAES solutions suggest a decrease in \dot{M}_w/\dot{M}_{acc} as the luminosity of the protostar increases.

Is there observational evidence for a decrease in \dot{M}_w/\dot{M}_{acc} ? Richer et al. (2000) examine flow energetics as a function of L_{bol} . They define:

$$\frac{\text{Outflow force}}{\text{Accretion force}} = \frac{F_{CO}}{\dot{M}_{acc} v_{kep}} = f \frac{v_w}{v_{kep}} \quad \text{where } f = \frac{\dot{M}_w}{\dot{M}_{acc}}.$$

For x-winds, $f \frac{v_w}{v_{kep}} \sim 0.3 \left(\frac{1}{1}\right)$ while disk-winds have $f \frac{v_w}{v_{kep}} \sim 0.03 \left(\frac{10}{1}\right)$ (because the longer magnetic lever arm accelerates material to many times Keplerian velocity). Fig. 1 shows $f(v_w/v_{kep})$ vs L_{bol} . Black symbols assume $L_{bol} = L_{acc}$; small grey symbols assume $L_{bol} = L_{ZAMS}$ (as may be appropriate for sources above $10^3 L_\odot$). The vertical dashed line illustrates the approximate cutoff between early-B and O star luminosities. If O stars do not have accretion disks, then this comparison is only valid for $L_{bol} < 10^4 L_\odot$. The solid line is a guide only (not a fit) to illustrate that there *may* be a decrease in \dot{M}_w/\dot{M}_{acc} for L_{bol} between 1 and $10^4 L_\odot$. It is important to stress that the possible trend seen in the data of Fig. 1 is, at best, marginal. Further observations are necessary to determine if a trend actually exists.

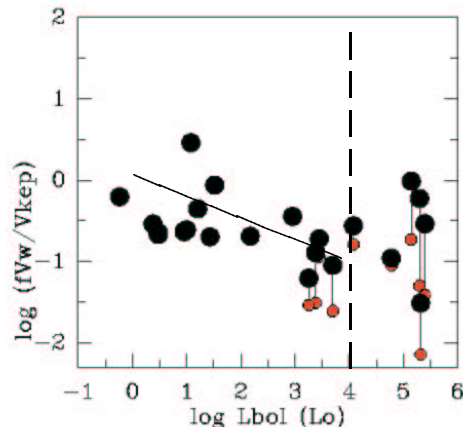


Figure 1. Outflow force/Accretion force vs L_{bol} (Richer et al. (2000)).

An additional reason why one may anticipate a change in the dynamics as the outflow becomes stronger relates to the assumptions inherent in theories developed for conditions appropriate for low-mass YSOs. Both x-winds and disk-winds assume ideal magneto-hydrodynamics (MHD) in which the recombination timescale is much greater than the dynamical timescale and the plasma & magnetic fields are frozen-in. Models of the ionization & density along beams of HH jets indicate that ideal MHD is valid for partially ionized jets from T Tauri stars (e.g.: Bacciotti & Eislöffel 1999). However, the ideal MHD assumption breaks down as: 1) the plasma temperature and density increase; 2) the turbulence in the disk or wind increases; or 3) the toroidal component of the magnetic field, B_ϕ , decreases. As L_{bol} increases plasma temperature and density will increase and the disk may be more turbulent. Thus, ideal MHD assumptions may break down for high-mass outflows and one may expect that energetics and re-collimation could be affected. To be more specific, conditions appropriate for luminous YSO must be included in simulations (e.g. Königl 1999).

4. The formation of O stars

Mid- to early-O stars may form via accretion (McKee & Tan 2002), or coalescence (Stahler, Palla, & Ho 2000 and references therein). If they form by

accretion, then Massive YSOs (MYSO) must have disks and an outflow is expected to be generated in the disk. However, molecular outflows from MYSOs can have masses $> 10M_{\star}$. Given the likely inefficiency of entrainment & momentum transfer by dense jets, the sweeping up of ambient molecular gas by an accretion-driven wind may not be a viable mechanism for O stars (Churchwell 1997). If MYSOs are formed from the coalescence of lower-mass YSOs, then accretion disks are not expected although it is still necessary to explain how an outflow can be generated without a disk.

Do accretion disks exist around O stars? McKee & Tan (2002) suggest that densities and ram pressures associated with infalling gas may be strong enough to overcome stellar radiation pressure and boost \dot{M}_{acc} onto the star, allowing O stars to form via accretion in $10^4 - 10^5$ years. Nine MYSO candidates (early-B to O7.5 ZAMS) have been found which show evidence for circumstellar material, possibly in a disk-like geometry (Hanson et al. 1997; De Pree et al. 1997; Conti & Blum 2002; Conti 2002). However, it is unclear if the material is located in an accretion disk or a torus with an inner hole. Additional surveys are being carried out to search for younger MYSO candidates (e.g. Palla et al. 1993; Molinari et al. 2000; Brand et al. 2001; & Zhang et al. 2001). Out of 260 objects likely to be young OB stars, ~ 12 candidate sources (B2.5 to O8.5) have been identified with outflow and possible disk signatures. Although no disk candidates earlier than O7.5 have been found, follow up observations on these promising candidates may help determine whether late-O stars have accretion disks.

Whether MYSOs form via accretion or coalescence, it is still necessary to explain the large outflow masses. Further, the lack of detectable accretion disks in two MYSOs with outflows (Orion I & G5.89-0.39) begs the question: How can outflows exist without disks? A possible answer lies in a class of models termed ‘‘Circulation models’’ in which flow masses can easily exceed the mass of the star (Fiege & Henriksen 1996; Lery, Henriksen, & Fiege, 1999; Aburrihan et al. 2001; Lery et al. 2002). Most infalling material from the molecular cloud is diverted magnetically at large radii into a slow-moving outflow in the polar direction while infall proceeds in the equatorial plane. Models can generate large outflow masses, explain observed opening angles & velocity structure seen in O stars, and outflow can occur without an accretion disk.

5. Summary

The wealth of observational evidence suggests that outflows from low-mass YSOs are almost certainly powered by disk accretion where magnetic stresses control the balance between inflow and outflow and determine the outflow structure far from the protostar. Intermediate mass protostars, up to early-B stars, can probably also be described by this general picture however the details are not as clear. The presence of accretion disks and outflows traced to within 50–100 AU of early-B YSOs suggests that they are also formed via accretion. Ionized winds from early-B stars can be either jet-like or have wide opening angles that do not re-collimate like their lower mass counterparts. Their associated poorly-collimated molecular flows could be caused by a less collimated wind component and/or jet precession. Assuming the dynamics in early-B and low-mass YSOs are governed by a similar mechanism, then theories and simulations

developed for low-mass YSOs suggest a change in the outflow/infall dynamics as L_{bol} increases: 1) If x-winds from truncated disks drive low-mass outflows, then high-mass outflows are probably driven by a different mechanism: either an x-wind from rapidly rotating protostar in which the disk abuts against the surface of the central object, or a disk-wind in which the outflow is generated in the disk alone; 2) Increased mass-loading expected in the winds of early-B YSOs may produce steady outflow rather than episodic knots as seen in the jets of low-mass YSOs; and 3) Increased plasma temperature and density in the outflow and increased disk turbulence is expected for early-B YSOs. This suggests that ideal MHD assumptions break down and may lead to decreased collimation and allow for significant angular momentum transport in the disk. If this is the case, then \dot{M}_w/\dot{M}_{acc} may decrease as L_{bol} increases from 1 to $10^4 L_{\odot}$.

In the highest luminosity systems (mid- to early-O stars) even the relationship between the outflow and an inner accretion disk is uncertain. Circulation models may be viable mechanisms for O stars where $\dot{M}_f/\dot{M}_{\star} > 10$ and the accretion disk is either non-existent or has already been photoevaporated but the molecular outflow still appears to be driven.

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