Massive Star Birth: A Crossroads of Astrophysics
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Massive star outflows

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Abstract. Molecular outflows in the form of wide-angle winds and/or well-collimated jets are associated with young stellar objects of all luminosities. Independent studies have established that the mass outflow rate is proportional to $L_{bol}^{0.6}$ for $L_{bol} = 0.3$ to 10^5 $L_\odot$, suggesting that there is a strong link between accretion and outflow for a wide range of source luminosity and there is reasonable evidence that accretion-related processes are responsible for generating massive molecular flows from protostars up to spectral type B0. Beyond $L_{bol} \sim 10^4$ $L_\odot$, O stars generate powerful wide-angle, ionized winds that can dramatically affect outflow morphology and even call into question the relationship between outflow and accretion.

Recently Beuther & Shepherd 2005 have proposed an evolutionary scenario in which massive protostellar flows (up to early B spectral type) begin collimated. Once the star reaches the Main Sequence, ionizing radiation may affect the balance between magnetic and plasma pressure, inducing changes in the flow morphology and energetics. Here I review the properties of outflows from young OB stars, discuss implications and observational tests of this proposed evolutionary scenario, and examine differences between low-mass and massive star formation.

Keywords. stars: formation, stars: winds, outflows, ISM: HII regions, accretion disks

1. Introduction

The dynamics of outflow and infall associated with young stellar objects (YSOs) affect the turbulent support and dissipation of molecular clouds, the final mass of the central star, and ultimately, the conditions for planet formation. Outflows in the form of wide-angle winds and/or well-collimated jets are associated with YSOs of all luminosities. However, the conditions and timescales associated with massive star formation differ from their low-mass counterparts, e.g.: 1) Massive stars evolve to the Zero Age Main Sequence (ZAMS) more rapidly than low-mass stars: 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 a hyper-compact HII (HC 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 (proto)stars (e.g. Bonnell, Bate, & Vine 2003).

Two scenarios have been proposed to explain the formation of massive O stars. The first scenario relies on non-spherical accretion which over comes radiation pressure even from the most luminous stars (e.g., Norberg & Maeder 2000, Behrend & Maeder 2001, Yorke & Sonnhalter 2002, McKee & Tan 2003). However, the most massive star that can form in the 2D models of Yorke & Sonnhalter is about 30 $M_\odot$ – even when 120 $M_\odot$ of gas is available in the initial cloud. A solution to this problem was presented by Krumholz *et al.* (2005). Using a 3D Monte Carlo radiative transfer code (Whitney *et al.* 2003) modified to

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account for time-dependent hydrodynamics Krumholz *et al.* found that the optically thin outflow channels carried away significant radiation, allowing the surrounding envelope to remain relatively cooler. This made it easier for the core to collapse to form very massive stars. The wider the outflow cavity, the more easily radiation can escape. Thus, the presence of a cavity created by a bipolar outflow may be critical for the formation of the most massive stars. Yet, the accretion-based formation of massive stars may differ from low-mass scenarios. In particular, recent simulations suggest that nearly 90% of the mass of massive stars is not due to accretion from an initial clump or envelope but from subsequent competitive accretion of material much farther from the stars (e.g., Bonnell, Vine, & Bate 2004).

The second scenario proposed for the formation of O stars involves the coalescence of lower mass (proto)stars at the centers of dense clusters (e.g., Bonnell, Bate, & Zinnecker 1998, Stahler, Palla & Ho 2000, Bonnell & Bate 2002). The mergers would likely destroy any accretion disks around the lower mass components and disrupt their outflows. The resulting massive star will likely have rotating circumstellar material but accretion is not a necessary criteria for formation. Simulations by Bonnell, Bate, & Vine (2003) suggest that, while true mergers of (proto)stars may be rare outside of binary systems, dynamical interactions between stars in dense star forming clusters are not: nearly 1/3 of all stars and most stars with $M_\star > 3\,M_\odot$ suffer disruptive interactions that can truncate circumstellar disks and bring the accretion and outflow process to an abrupt and possibly explosive halt (Bally & Zinnecker 2005). While the competitive accretion model predicts molecular outflows with properties that may be similar to low-mass outflows, it is unlikely that highly-collimated structures could exist in the coalescence scenario and the outflow energetics may be significantly different.

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), Königl (1999), and Beuther & Shepherd (2005). Richer *et al.* (2000), Cabrit (2002), and Shepherd (2003), examine the similarities between massive and low-mass outflows. Here we examine new results associated with massive flows, discuss a possible evolutionary scenario, and examine evidence for morphological and dynamical differences between massive and low-mass flows.

2. Outflow Energetics

Young, low-luminosity YSOs ($L_{bol} \sim$ few $L_\odot$) have mass outflow rates $\dot{M}_f = 10^{-8}$ to 10^{-5} $M_\odot\,yr^{-1}$, momentum rates $\dot{P}_f = 10^{-7}$ to 10^{-4} $M_\odot\,km\,s^{-1}yr^{-1}$, 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 10–30° close to the central source (<50 AU) but then re-collimates ($\theta \sim$ few degrees) within 100 AU from the protostar (e.g. Ray *et al.* 1996; Dougados *et al.* 2000). Intermediate-mass YSOs cover a wide range of L_{bol}. For A-type stars $L_{bol} \sim 10$–30 $L_\odot$. 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. 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 $\times 10^{-3}$ $M_\odot\,yr^{-1}$, $\dot{P}_f = 10^{-4}$ to 10^{-2} $M_\odot\,km\,s^{-1}yr^{-1}$, and $L_{mech} = 10^{-1}$ to 10^2 $L_\odot$. Outflows from early-B and late O

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stars can be well-collimated when the dynamical times scale is less than $\sim 10^4$ years although poorly collimated flows are more common in both young and old sources. O stars with $L_{bol} > 10^4$ $L_\odot$ generate powerful winds with $\theta \sim 90°$ within 50 AU of the star while accompanying molecular flows can have $\theta > 90°$. The flow momentum rate ($>10^{-2}$ $M_\odot$ km s^{-1}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 both well-collimated and poorly collimated flows, 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, Cabrit & Bertout 1992, Shepherd & Churchwell 1996, Anglada 1996, Henning *et al.* 2000, Beuther *et al.* 2002a, Wu *et al.* 2004). 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 suggest that there is a strong link between accretion & outflow for a wide range of L_{bol} - even into the mid-O star range.

CO outflows from both low and high mass stars show a mass-velocity relation in the form of a power law $dM(v)/dv \sim v^\gamma$ with γ ranging from -1 to -8. The slope, γ, steepens with age and energy in the flow (e.g. Rodríguez *et al.* 1982, Lada & Fich 1996, Shepherd *et al.* 1998, Richer *et al.* 2000). A similar relation of H_2 flux-velocity also exists with γ between -1.8 and -2.6 for low and high-mass outflows (Salas & Curz-González 2002).

For a few early B (proto)stars with outflows that have a well-defined jet, the jet appears to have adequate momentum to power the larger scale CO flow although this relation is not as well established as it is for lower luminosity sources. For example, IRAS 20126+4104 has a momentum rate in the SiO jet of $2 \times 10^{-1}(\frac{2\times10^{-9}}{\mathrm{SiO/H_2}})$ $M_\odot$ km s^{-1}yr^{-1} while the CO momentum rate is 6×10^{-3} $M_\odot$ km s^{-1}yr^{-1} (Cesaroni *et al.* 1999, Shepherd *et al.* 2000). Although the calculated momentum rate in the SiO jet is adequate to power the CO flow, the uncertainties in the assumed SiO abundance makes this difficult to prove. Another example is IRAS 18151–1208 in which the H_2 jet appears to have adequate momentum to power the observed CO flow (Beuther *et al.* 2002a, Davis *et al.* 2004). For sources that have a weak jet component coupled with a wide-angle flow, it has not been determined what fraction of the momentum rate is supplied by the jet. Despite the detection of jets toward massive protostars, the molecular flows themselves tend to be less collimated than their low mass counterparts. Wu *et al.* (2004) find that the average collimation factor (major/minor radius) for outflows from sources with $L_{bol} > 10^3 L_\odot$ is 2.05 compared with 2.81 for flows from lower luminosity sources. This is true even for sources in which the angular size of the flow is at least five times the resolution. Thus, the generally poorer collimation for massive flows is not due to low resolution of the observations.

There are an increasing number sources for which our observations are of comparable quality to those of low-mass YSOs and they provide a quantitative view of the range of the outflow/infall properties for these energetic sources. Wu *et al.* (2004) provide a statistical overview of the general properties of both massive and low-mass outflows. In the following sections, selected outflows from early B and O (proto)stars are discussed and compared.

3. Well-Collimated Outflows from Early B (Proto)Stars

Collimated, ionized jets can be generated by early-B protostars. The youngest sources ($\sim 10^4$ years or less) can be jet-dominated and can have either well-collimated or poorly collimated molecular flows. In a few sources, jets tend to have opening angles, θ,

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between 25° and 30° but they do not re-collimate. Other sources appear to generate well-collimated jets ($\theta \sim$ few degrees) that look like scaled up jets from low-luminosity protostars. Jet activity can continue as long as 10^6 years although associated molecular flows have large opening angles and complex morphology. Below are some examples of sources with outflows that are at least partially driven by a jet.

One of the best examples of an early B ZAMS star with a jet is HH 80-81 which has a highly collimated ionized jet with a projected length ~5 pc and age ~10^6 years (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 ($\dot{P}_f = 6 \times 10^{-3}$ $M_\odot$ km s^{-1}yr^{-1}) is an order of magnitude greater than $\dot{P}_j$ in the ionized 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 luminosity of the driving source is uncertain. The total luminosity of the system is ~2×10^4 $L_\odot$ however there is at least one early B star near the jet center that could account for a third or more of the luminosity (Stecklum *et al.* 1997). Thus, HH 80-81 appears to be powered by a B3-B1 ZAMS star. A similar situation is seen toward Ceph A HW2 - an early B star with 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, and Garay 1995).

While HH 80-81 looks like a scaled T-Tauri star with a jet that stays well-collimated far from the central source, a growing number of sources are being discovered which have jets with wider opening angles that do not appear to re-collimate. In particular, IRAS 20126+4104 (B0.5 spectral type, age ~ few $\times 10^4$ years) has an ionized and molecular jet which are misaligned from the larger scale molecular outflow by more than 60° (Cesaroni *et al.* 1999, Cesaroni *et al.* 2005, Hofner *et al.* 1999, Shepherd *et al.* 2000). The large precession angle in the IRAS 20126 jet appears to be due to an interaction with a close binary companion. The full opening angle of the ~0.1 pc SiO jet is roughly 40°. This agrees with recent estimates based on water maser studies that suggest the jet full opening angle is ~34° roughly 200 AU from the central source (Moscadelli *et al.* 2005).

Another relatively wide-opening angle, ionized jet is IRAS 16547−4247 (Brooks *et al.* 2003, Garay *et al.* 2003, Rodríguez *et al.* 2005). The luminosity of the source suggests a B0-O8 spectral type. The molecular mass outflow rate is unknown but the radio luminosity of the ionized jet is consistent with being powered by a late O star. Based on the extent of the H_2 emission, the flow appears to be ~7,000 years old. Rodríguez *et al.* estimate the full opening angle of the jet to be ~25° out to about 10,000 AU (~3″ at D = 2.9 kpc). Again, this is a wide-opening angle jet relative to the typical 1-3° opening angles often seen toward low-mass jets. Two other examples of early-B (proto)stars with well-collimated flows are: 1) IRAS 05358+3543 which is an early B star cluster (age ~4×10^4 years) that has multiple collimated molecular outflows (Beuther *et al.* 2002b, Sridharan *et al.* 2002); and 2) IRAS 18151−1208 which harbors two H_2 jets, one of which appears to be from an early B star (Davis *et al.* 2004).

4. Wide-Angle Outflows from Early B (Proto)Stars

Molecular outflows from early B (proto)stars are on average less collimated than low-mass flows (Wu *et al.* 2004). Low collimation factors can occur in molecular flows even when there is a well-defined ionized jet (see previous section). In at least some sources, both the ionized wind near the central source and the larger scale molecular flow are poorly collimated and there is no evidence for a jet. Several examples are given below.

The early-B YSO, G192.16–3.82, has a poorly collimated ionized wind ($\theta \sim 40°$) within 50 AU of the YSO that expands to $\theta \sim 90°$ 0.1 pc from the source (Shepherd *et al.* 1998, Shepherd & Kurtz 1999, Shepherd, Claussen, & Kurtz 2001). The 100 $M_\odot$ molecular flow is a few $\times 10^5$ years old and forms 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. A source that appears to be similar to G192.16 is AFGL 490. It has a wide angle wind and outflow from an early B star (e.g. Snell *et al.* 1984, Mitchell *et al.* 1995, Schreyer *et al.* 2005). The age of the CO flow is estimated to be $\sim 2 \times 10^4$ years old, the outflow opening angle is roughly 50° and the collimation factor is about 1.0. The central star, detected in the near-IR (e.g. Davis *et al.* 1998) is surrounded by a 20,000 AU CS torus that appears to have an inner accretion disk that is less than 500 AU in diameter (Schreyer *et al.* 2002). There is no obvious sign of a collimated jet from the central object.

As a final example consider W75 N. At the center of the CO outflows is a cluster of UC HII regions. One, VLA 2, appears to power a wide-angle, red-shifted CO flow to the south-west (Davis *et al.* 1998, Shepherd 2003, Shepherd *et al.* 2004). Proper motions of water masers associated with the outflow from VLA 2 show that the opening angle of the flow appears to be nearly 180° within 100 AU of the star (Torrelles *et al.* 2003). The larger scale CO flow opening angle is roughly 50°, consistent with a wind-blown bubble. There is no indication near the star that a well-collimated jet exists. The infrared line emission suggests that only slow, non-dissociative J-type shocks exist throughout the parsec-scale outflow. Fast, dissociative shocks, common in jet-driven outflows from low-mass stars, are absent in W75 N. Interestingly, VLA 1, just 2,000 AU from VLA 2, is a jet that drives a collimated CO flow. Torrelles *et al.* (2004) suggest that the increased collimation may be because VLA 1 is at a different evolutionary state than VLA 2.

5. Mid to Early O Star Outflows

To date, extremely collimated outflows have not been observed toward sources earlier than B0. It is possible that this is simply a selection effect because O stars form in dense clusters and reach the ZAMS in only a few $\times 10^4$ years. Thus, any collimated outflows may be confused by other flows. For a few sources that are relatively isolated and for which adequate high-resolution data are available, no inner accretion disk ($\sim$50 AU diameter) has been conclusively detected. In a few sources, collimation close to the protostar appears to be due to pressure confinement from an equatorial torus of dense gas (e.g. K3-50A: De Pree *et al.* 1994, Howard, Koerner, & Pipher 1997). This may also be the case for the Orion I outflow (e.g. McCaughrean & Mac Low 1997, Greenhill *et al.* 1998) however, there is now strong evidence that Source I and the BN object are moving away from each other and that they were within 225 AU of each other about 500 years ago (Rodríguez *et al.* 2005). Source I and BN may have been members of a multiple system or BN may have been a companion of θ^1 Ori C and made a close approach to Source I after it was ejected (Tan 2003). The poorly collimated, explosive-looking outflow seems to have occurred $\sim 1,000$ years ago. Could it have been caused by the event that ejected the BN object? If so, then the outflow is not actively powered by Source I and the geometry of the circumstellar material around Source I need not be linked to the large-scale flow. Such explosive events may not be uncommon as evidenced by the 'fingers' of shocked gas seen in Spitzer images of the ionized outflow associated with G34.26+0.15 (Churchwell, personal communication).

As a final example, consider G5.89–0.39. The UC HII region appears to be powered by an O5 star. The star has a small excess at 3.5μm suggesting the presence of circumstellar

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material (Feldt *et al.* 2003). The O5 star is along the axis of two H_2 knots that appear to trace a collimated N-S flow (Puga *et al.*, poster presented at this conference). There is also a N-S $C^{34}S$(J=3-2) and the UC HII region is expanding in the N-S direction (Cesaroni *et al.* 1991, Acord *et al.* 1998). Although still circumstantial, the evidence is mounting that the O5 star in G5.89 produced the N-S outflow and thus is forming via accretion. Note, there is also an SiO flow (with a NE-SW orientation) that is powered by a star to the S-W of the O5 star (Sollins *et al.* 2004, Puga *et al.* this conference) and a larger scale E-W CO flow for which the driving source has not been identified (Watson *et al.* 2002).

Additional evidence that O stars form via linked accretion and outflow comes from 7 mm continuum observations of very young O stars (van der Tak & Menten 2005). Models of the derived sizes, flux densities, and radio spectra of sources with luminosities up to $\sim 10^5 L_\odot$ suggest that at least one star has a dust disk and all are accreting material. Although not conclusive, this supports the accretion-based formation scenario for even mid-O stars.

6. Evidence for an Evolutionary Scenario

Current observations indicate that the outflow/infall mechanism is similar from T Tauri stars up to early B protostars. Although there is evidence that the energetics for at least some early-B stars may differ from their low-mass counterparts, the dynamics are still governed by the presence of linked accretion and outflow. A few young O stars show evidence for accretion as well. Although there are clearly explosive events, these may be due to close encounters that disrupt the accretion process. However, dynamical mergers of (proto)stars to create the most massive stars may still be a viable formation mechanism.

There are both well-collimated and poorly collimated molecular flows from massive stars. Well-collimated molecular flows tend to be in systems with ages less than a few times 10^4 years old where the central object has not yet reached the main sequence. Hence the effects of increased irradiation on the disk and disk-wind due to the stellar radiation field are minimized. Observed jets often have opening angles between 25° and 30° with little evidence for recollimation of the jets on larger scales. This could be due to a change in the balance between magnetic and plasma pressure. Poorly collimated flows (opening angle greater than 50° that show no evidence for a more collimated component) are associated with more evolved sources that have detectable UC HII regions and the central star has reached the main sequence. Thus, the disk and outflow are subject to significantly more ionizing radiation.

To account for the differences seen in flow morphologies from early B to late O stars Beuther & Shepherd (2005) proposed two possible evolutionary sequences which could result in similar observable outflow signatures as shown in Figure 1. For both early B and O stars, the flows begin collimated and become less-collimated as the star reaches the ZAMS and generates significantly more Lyman continuum photons. This evolutionary sequence appears to qualitatively fit the observations however it must be tested against both theory and observations.

6.1. *Impact of Luminosity on Outflows*

Once a massive OB star reaches the main sequence, the increased radiation from the central star generates significant Lyman continuum photons and will likely ionize the outflowing gas even at large radii. The result may be an increase in the plasma pressure at the base of the flow which could overwhelm any collimating effects of a magnetic field (see, e.g., Shepherd 2003, Königl 1999). It may also affect the inherent collimation of the ionized wind from the *stellar* surface as suggested in the simulations by Yorke &

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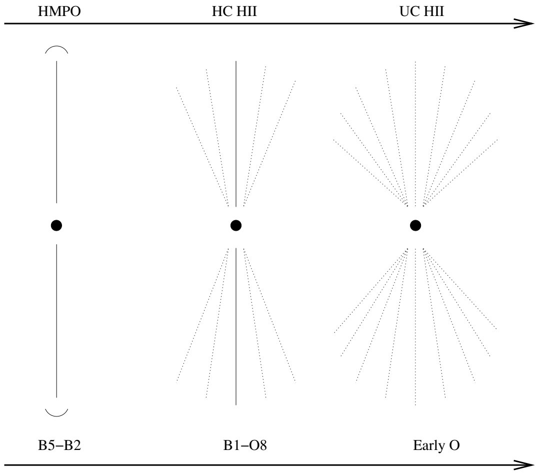

Figure 1. Sketch of the proposed evolutionary outflow scenario (Beuther & Shepherd 2005). The three outflow morphologies can be caused by two evolutionary sequences: (top) the evolution of a typical B1-type star from a high-mass protostellar object (HMPO) via a hyper-compact Hii (HC HII) region to an ultra-compact Hii (UC HII) region, and (bottom) the evolution of an O5-type star which goes through B1- and O8-type stages (only approximate labels) before reaching its final mass and stellar luminosity.

Sonnhalter (2002). Recollimation of the outflowing gas from the disk is expected under ideal magneto-hydrodynamic (MHD) conditions where the recombination timescale is much greater than the dynamical timescale of the outflow. Thus, the ionized plasma becomes 'frozen-in' to the magnetic field lines. 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). It is interesting to note that several early B protostars with strong jet components in the outflows have $\sim 30°$ opening angle jets that do not appear to re-collimate. Perhaps this is due to a break-down in ideal MHD conditions along the outflow cone?

6.2. *Impact of Mass-Loading on Outflows*

Two conditions expected for luminous YSOs are increased disk surface heating (due to increased stellar radiation and shocks) and a higher level of disk turbulence when $M_D/M_\star > 0.3$ where M_D is the disk mass and $M_\star$ is the (proto)stellar mass. Increased disk surface heating causes increased mass loading (e.g. Ferriera 2002) and since winds carry angular momentum away, this means that a warmer, denser wind causes the disk to rotate slower. Pudritz (these proceedings) has evaluated the impact of mass loading on magnetized disk-winds under conditions appropriate for massive protostars that have not yet reached the ZAMS (e.g. no significant heating from the central protostar). Solutions show that a strong wide-angle wind develops as the mass-loading increases. Thus, the outflow dynamics and geometry appears to change as the outflow rate increases.

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6.3. *Impact of Disk Turbulence on Outflows*

Disks around early-B YSOs are significantly more massive than those around A-type and T Tauri YSOs. Further, $M_D/M_\star$ 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). There are a growing number of early-B (proto)stars that are actively powering molecular outflows and have circumstellar disks or molecular tori with masses ranging from $0.1\,M_\odot$ to tens of solar masses. The increased $M_D/M_\star$ suggests that the detailed dynamics of infall and outflow in early-B YSOs may differ from their lower mass counterparts. Recently, Lodato & Rice (2005) have made simulations of circumstellar disks in which $M_{disk} = 0.1$, 0.5, and $1.0\,M_\star$ to evaluate the behavior of spiral density waves. They find that the mass of the disk dramatically changes the characteristics of the spiral density waves that can transport angular momentum efficiently. As the disk mass increases, the waves become stronger and in some cases episodic. The associated accretion onto the central star increases during periods when spiral density waves are strong and carry away significant angular momentum. It is not clear how or even if such behavior will cause significant changes in the outflow characteristics but one might expect it would since accretion and outflow are so inherently linked. The simulations of Lodato & Rice are in a regime in which fragmentation of the disk is not allowed, further, only disk heating and cooling are considered (no stellar heating or heating due to the outflow or shocks above the disk plane). Additional improvements to the simulations are planned which will incorporate more realistic heating and cooling functions and disk heating from the star and outflow. Indeed, simulations of disks around low-mass stars which include realistic heating from the central star and outflow suggest that irradiation can quench fragmentation due to local gravitational instabilities because the disk temperature is raised above the parent cloud temperature (Matzner & Levin 2005).

The simulations of Lodato & Rice (2005) suggest an increase in $\dot{M}_{acc}$ if spiral density waves transport angular momentum to the outer parts of the disk - one would not expect a corresponding increase in the disk wind mass loss rate, $\dot{M}_w$, since there is not excess angular momentum in the inner disk where the wind is generated. Thus, significant angular momentum transport associated with spiral density waves in the disk may contribute to a decrease in $\dot{M}_w/\dot{M}_{acc}$ as well. Is there observational evidence for a decrease in $\dot{M}_w/\dot{M}_{acc}$? Richer *et al.* (2000) demonstrate that one can measure the Outflow force/Accretion Force vs L_{bol} and that this quantity can be related to $\dot{M}_w/\dot{M}_{acc}$. Shepherd (2003) shows that there is marginal evidence for such a decrease but the errors in the data are large and any trend is at best, marginal. Further observations are necessary to determine if such a trend actually exists.

7. Summary

Mid- to early-B protostars and late O protostars have accretion disks and outflows that can be well-collimated. Ionized jets in very young sources (age $\lesssim 10^4$ years) can have opening angles $\sim 30°$ with no recollimation detected or they can re-collimate similar to jets from low-luminosity protostars. Once an HII region forms, the associated ionized outflows have strong wide-angle winds and a collimated jet is often not detected. The non-detection of a jet in older sources is unlike low-mass outflows were there is evidence for a two-component wind (jet+wide-angle) even in older sources e.g. Arce & Goodman 2002). Mid to early O stars have poorly collimated outflows and explosive events suggest that protostellar or protostar/disk interactions are common. Current observations suggests that outflows from early OB protostars begin collimated and then become less collimated

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with time once the star reaches the main sequence. This evolution in outflow dynamics and morphology could be due to, e.g.: increased ionizing radiation from the star as it begins to burn hydrogen; mass-loading onto the disk wind; and/or disk instabilities which can be an efficient angular momentum transport mechanism in massive disks.

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