Theory of Bipolar Outflows from High-Mass Young Stellar Objects

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ABSTRACT

There is a growing number of observational indicators for the presence of bipolar outflows in massive, young stellar objects that are still accreting mass as part of their formation process. In particular, there is evidence that the outflows from these objects can attain higher velocities and kinetic luminosities than their lower-mass counterparts. Furthermore, the higher-mass objects appear to smoothly continue the correlation found in T Tauri stars between outflow and accretion signatures, and in several cases there are direct clues to the existence of a circumstellar disk from optical and infrared imaging and spectroscopy as well as from millimeter-wavelength interferometry. These results suggest that the disk–outflow connection found in low-mass pre–main-sequence stars extends to more massive objects, and that a similar physical mechanism may drive the outflows in both cases. I examine the observational basis for this hypothesis and consider how the commonly invoked centrifugally driven wind models of bipolar outflows in low-mass stars would be affected by the various physical processes (such as photoionization, photoevaporation, radiation pressure, and stellar wind ram pressure) that operate in higher-mass stars. I then list some of the interesting questions that one could hope to address as this young field of research continues to develop.

Subject headings: accretion, accretion disks — stars: circumstellar matter — stars: formation — stars: magnetic fields — stars: mass loss — stars: pre–main-sequence

1. Introduction

The subject of accretion-driven outflows from luminous, high-mass stars is still a fairly new area of research. In order to define the framework within which the significance of the various observational findings could be assessed and meaningful theoretical models formulated, it is useful to first review what is already known, and what the remaining open questions are, in the more mature field of research concerning accretion-driven outflows from low-luminosity stars.
There are now over 150 catalogued optical outflow sources associated with low-luminosity ($L_{\text{bol}} < 10^3 L_\odot$) young stellar objects (YSOs). They appear as high-velocity (radial speeds $\sim 200 - 400 \text{ km s}^{-1}$) ionized and neutral gas jets and as bipolar (molecular) flows, which evidently represent ambient gas entrained and driven by the jets (see Edwards et al. 1993a and Bachiller 1996 for reviews). There is a strong apparent correlation between the presence of outflow signatures (such as P Cyg line profiles, forbidden line emission, and thermal radio radiation) and accretion disk diagnostics (such as ultraviolet, infrared, and millimeter excess emission) in these sources (e.g., Hartigan et al. 1995). Most notably, the so-called classical T Tauri stars (cTT’s) consistently exhibit both types of properties, whereas the weak-lined T Tauri stars (wTT’s), which in most other respects closely resemble cTT’s, lack both outflow and accretion characteristics. Direct evidence for the presence of disks in YSOs has been obtained from millimeter and submillimeter interferometric mappings, which have resolved the structure and velocity fields of disks down to scales of a few tens of AU (e.g., Sargent 1996; Guilloteau et al. 1997; Kitamura et al. 1997; Wilner and Lay 1999). High-resolution images of disks in low-luminosity YSOs have also been obtained in the near infrared (NIR) using adaptive optics and in the optical using the Hubble Space Telescope (e.g., Stapelfeldt et al. 1997; McCaughrean et al. 1999).

Another important observational finding in low-mass ($M \lesssim 2 M_\odot$) YSOs (where, from here on, “low-M” is used interchangeably with “low-$L_{\text{bol}}$”) is that many of them have been inferred to possess a strong ($\lesssim 10^3 \text{ G}$) stellar magnetic field that truncates the disk at a distance of a few stellar radii from the YSO and channels the flow toward high-latitude accretion shocks on the stellar surface. The evidence for this comes from the detection of periodic surface “hot spots” (e.g., Herbst et al. 1994) as well as from spectral line profiles, particularly of the upper Balmer lines and Na D (e.g., Edwards et al. 1994), Br$\gamma$ (e.g., Najita et al. 1996a), He I and He II (e.g., Guenther and Hessman 1993; Hamann and Persson 1992; Lamzin 1995), and the Ca II infrared triplet (e.g., Muzerolle et al. 1998). Direct measurements of stellar magnetic field strengths are difficult, but several kilogauss-strength detections have already been reported (e.g., Basri et al. 1992; Guenther et al. 1999; Johns-Krull et al. 1999). The magnetic interaction between the star and the disk could in principle account for the typically low rotation rates of cTT’s (e.g., Königl 1991) as well as for the systematically shorter rotation periods measured in wTT’s (Bouvier et al. 1993; Edwards et al. 1993b).

Finally, it is worth mentioning that accretion onto low-mass YSOs is evidently nonsteady. In particular, these objects exhibit episodic accretion events that have been inferred to last $\sim 10^3 \text{ yr}$ and to repeat on a time scale of $\sim 10^3 \text{ yr}$ during the initial $\sim 10^5 \text{ yr}$ of the YSO lifetime (e.g., Hartmann and Kenyon 1996). The mass accretion rate during these episodes is quite high, and it has been estimated that most of the mass that ends up in the central star could be accreted in this fashion. It has also been determined that these so-called FU Orionis outbursts give rise to high-velocity gas outflows that originate at the surfaces of the circumstellar accretion disk (Calvet et al. 1993).

The current “paradigm” of bipolar outflows in low-$M$ YSOs, which attempts to interpret the
above observational results, can be summarized as follows. The outflows are powered by accretion, and probably represent centrifugally driven winds from the disk surfaces (see Königl and Ruden 1993 and Königl and Pudritz 1999 for reviews). The accretion and outflow are mediated by a magnetic field that corresponds either to interstellar field lines that had been advected by the inflowing matter (e.g., Wardle and Königl 1993) or to a stellar, dynamo-generated magnetic field (e.g., Shu et al. 1994). The origin of the field (and, correspondingly, the origin of the outflow in relation to the YSO), as well as the precise manner by which a sufficiently strong open field configuration is maintained along the disk, or, alternatively, the manner by which a stellar field can both channel an inflow and drive an outflow, are among the key issues of the theory that are not yet fully resolved. The currently favored interpretation of FU Orionis outbursts is that they represent a dwarf nova-like thermal instability in the innermost, weakly ionized (in quiescence) region of the disk. The effect of a magnetic field on the evolution of this instability and its possible role in driving the associated outflows are other important open questions in the theory.

Having outlined the relevant observations of low-luminosity YSOs, I now turn to examine the data on high-luminosity outflow sources. I focus attention on pre–main-sequence (PMS) stars and examine, first, whether the observations of higher-mass YSOs can be interpreted within the same framework as their lower-mass counterparts, and, second, whether the new information on high-luminosity outflow sources can shed light on any of the outstanding questions in the theory of low-\(L_{bol}\) YSOs.

### 2. Observations of Outflows from High-Luminosity Stars

Energetic outflows from luminous young stars have been detected by similar means to those used in identifying bipolar outflows in low-luminosity YSOs, namely, through molecular line emission from the swept-up ambient gas, and through optical and radio emission from the ionized gas component in stellar jets. Since high-mass YSOs are often found in regions of low-mass star formation, confusion with low-luminosity objects may complicate the determination of the flow structure as well as the identification of the driving source (which, for example, may be based on the presence of an isolated IRAS source or of an ultracompact HII region on or near the flow axis). For example, in the case of NGC 2024, Chernin (1996) has argued (on the basis of 4′′-resolution maps) that several outflows are, in fact, present in the region and that they do not appear to be driven by the known far-infrared sources. He suggested that the outflows might be driven, instead, by as yet unidentified low-mass stars.\(^1\) In a similar vein, radio continuum sources interpreted as ultracompact HII regions could instead trace the sites of shock excitation by the outflow: such a

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\(^1\)In this connection it is worth noting that NIR speckle interferometry of HAeBe stars has revealed that a significant (31 ± 10%) fraction of them possess a close IR companion with a projected separation in the range 50 – 1300 AU (Leinert et al. 1997).
misidentification has, for example, been claimed to have occurred in the case of the outflow from the high-luminosity YSO Cep A (see Corcoran et al. 1993 and Hughes and Wouterloot 1984). Nevertheless, the number of bipolar flows studied with adequate resolution by means of molecular line interferometry has been gradually increasing, and there is accumulating evidence that, as in the case of low-mass objects, they are a common property also of newly formed high-mass stars (see Richer et al. 1999 for a review). It appears that the higher-luminosity objects typically produce less well-collimated molecular flows than their lower-$L_{bol}$ counterparts, although this could possibly be due to the fact that these outflows tend to emerge from their surrounding molecular cloud cores at a relatively early stage. The basic spatial and kinematic structures of the flows do not, however, seem to depend on the underlying source luminosity, and the momentum deposition rate in the outflow evidently increases as a simple power law of the luminosity for $L_{bol}$ ranging all the way from $\sim 1$ to $\sim 10^6 L_{\odot}$.

Optical observations of jets from high-luminosity sources are subject to several detection biases (Mundt and Ray 1994), including short evolutionary timescales, typical association with comparatively distant star-formation regions, and confusion by bright, extended reflection nebulae as well as by background HII emission. Another bias can be traced to the effect of the ionizing flux from the central object (see Fig. 1 below). Despite these complicating factors, a significant number of sources with outflow signatures have already been detected. Mundt and Ray (1994) list 24 examples of optical jets associated with Herbig Ae/Be stars (HAeBe’s) and other high-luminosity YSOs, whereas Corcoran and Ray (1997) report that 28 out of 56 HAeBe’s that they studied had detectable [OI]$\lambda 6300$ forbidden line emission. As discussed in the above references, the jet outflow speeds in high-luminosity ($L_{bol} > 10^3 L_{\odot}$) sources lie in the range $\sim 600 – 900$ km s$^{-1}$, which are a factor $\sim 2 – 3$ higher than the corresponding speeds in the low-$L_{bol}$ sources, and have inferred mass outflow rates that are a factor $\sim 10 – 100$ times higher than in the low-luminosity YSOs. There is also an indication that a larger fraction of the jets in luminous sources are poorly collimated.

3. The Accretion Disk Connection

There is now growing evidence that the correlation found in low-mass YSOs between the signatures of energetic outflows and accretion disks extends also to the more massive HAeBe stars. Corcoran and Ray (1997) discovered that, in most cases, the centroid velocity of the low-velocity component of the [OI]$\lambda 6300$ emission line is blueshifted with respect to the stellar rest velocity. The same behavior is found in cTT’s and has been convincingly interpreted as evidence for the presence of extended, optically thick disks that block the redshifted line-emission region from our view. The forbidden emission lines in cTT’s often exhibit both a low-velocity component (LVC), which has been attributed to a disk-driven outflow, and a high-velocity component (HVC), whose interpretation is still controversial but which evidently originates in the vicinity of the YSO. The
HVC is also observed in the [OI] line emission from some HAeBe’s, but it is found less frequently than in cTT’s (see also Böhm and Catala 1994). The latter finding was attributed by Corcoran and Ray (1997) to an evolutionary effect (wherein the HVC disappears before the LVC as the outflow activity gradually diminishes), although it is conceivable that at least in some luminous sources the absence of a high-velocity neutral oxygen component may be the result of photoionization near the outflow axis (S. Martin 1994, personal communication). In view of the fact that the ionization potential of neutral oxygen is nearly identical to that of hydrogen, one would not expect to detect [OI] emission within the Strömgren surface bounding the HII region around the star.

If the disk is a source of a centrifugally driven outflow, the density distribution around the star will be highly stratified (e.g., Safier 1993) and the Strömgren surface will have a roughly conical shape centered on the symmetry axis (see Fig. 1). Under these circumstances, the HVC [OI] emission, produced near the stellar surface, will be absent, but the LVC, presumably generated above the disk surface further out in a region that is shielded from the ionizing radiation, will be detectable. This interpretation is supported by observations of a source like LkHα 234, in which a well collimated, high-velocity jet is detected (Ray et al. 1990) even though only a low-velocity [OI] component is seen in the vicinity of the central star.

Another robust correlation, identified by Corcoran and Ray (1998), relates the [OI] 6300 line luminosity (a signature of an outflow) and the infrared excess luminosity (a possible signature of a disk). It appears that the relationship between these two quantities, originally found in cTT’s (e.g., Cabrit et al. 1990), extends smoothly to YSOs with masses of up to \( \sim 10 M_\odot \) and spans 5 orders of magnitude in infrared luminosity. Corcoran and Ray (1998) analyzed additional correlations between the forbidden-line and NIR emission properties of HAeBe’s and pointed out that they all follow the same trends as in cTT’s. They also found that all the HAeBe stars in their sample that exhibit both forbidden line emission and IR excesses have NIR colors that are consistent with the presence of an optically thick disk or a disk surrounded by a dusty envelope. Previous infrared studies of HAeBe’s (e.g., Hillenbrand et al. 1992) have revealed that many of these objects show infrared excesses with a spectral shape \( \lambda F_\lambda \propto \lambda^{-4/3} \) (\( \lambda \gtrsim 2.2 \mu m \)). Such spectra are characteristic of optically thick disks that are either “active” viscous accretion disks or “passive” reprocessing flat disks. The apparent spectral decline below \( \sim 2.2 \mu m \) has been interpreted as indicating the presence of effective “holes” in the optically thick disks on scales \( \sim 3 – 25 \) times the stellar radius (see also Lada and Adams 1992). It was originally suggested that the holes could represent regions where the disk is either truncated by a stellar magnetic field or else is optically thin. For reasonable accretion rates, a stellar magnetic field is unlikely to truncate a disk beyond a few stellar radii (e.g., Königl 1991). However, the innermost regions might be optically thin because of a low local mass accretion rate (Bell 1994; see §5). The mass accretion rate required to reproduce the \( \sim 3 \mu m \) peak in the NIR spectral energy distribution is too large (\( \gtrsim 10^{-6} M_\odot yr^{-1} \)) for the innermost disk regions to remain optically thin, but Hartmann et al.

\[ ^2 \text{It is has been suggested, however, that the jet in this source is driven by a cold mid-infrared companion rather than by LkH\alpha234 itself (Cabrit et al. 1997).} \]
Fig. 1.— Strömgren surfaces in a disk-driven wind near a high-luminosity YSO, calculated using the direct stellar ionizing flux but neglecting the diffuse radiation field. The dashed and solid lines represent the shape of the surfaces for mass outflow rates (in the cylindrical radius range $\varpi = 0.1 - 1$ AU) of $10^{-6} M_\odot\,\text{yr}^{-1}$ and $10^{-7} M_\odot\,\text{yr}^{-1}$, respectively, assuming wind model B of Safier (1993) and the parameters of the HAeBe star HD 37490 ($L_{\text{bol}} = 2 \times 10^4 L_\odot$, $T_{\text{eff}} = 20,400$ K, $R_\star = 11.4 R_\odot$). The shaded region represents an accretion disk of height $h(\varpi) = 0.1\varpi$. (Courtesy of S. Martin.)
(1993) argued that the observed peak could, instead, be due to the transient heating of grains in a dusty envelope by ultraviolet photons from the central star (see also Natta et al. 1992, 1993).

The interpretation of the infrared and sub-mm spectra of HAeBe’s in terms of disks has not been universally accepted: several authors have, in fact, claimed that the spectra can be explained entirely in terms of dusty spherical envelopes (e.g., Miroshnichenko et al. 1997; Pezzuto et al. 1997). It was similarly suggested that much of the millimeter emission in these systems arises in extended envelopes, and, furthermore, that the contribution from ionized gas may have led to an overestimate of the dust emission in many sources (e.g., Di Francesco et al. 1997). Furthermore, in some cases there are indications that the measured far-infrared emission may not even arise in the immediate vicinity of the HAeBe’s (Di Francesco et al. 1998). However, several strong disk candidates have by now been identified by mm-wavelength interferometry (e.g., Mannings and Sargent 1997). Among the sources observed by Mannings and Sargent, two appear as elongated molecular line-emission regions and exhibit ordered velocity gradients along their major axes, which is strongly suggestive of the presence of rotating disks. The disk radii and masses determined by these authors are similar to those found in cTT’s, although, in view of the short clearing time of optically thick disks inferred for HAeBe’s (∼0.3 Myr, as compared with ∼0.3 Myr for cTT’s; Hillenbrand et al. 1992), this may reflect the comparatively large age of the objects in their sample (∼5 – 10 Myr, compared to ∼1 Myr for typical cTT’s). Further support for the presence of disks around HAeBe’s has come from adaptive-optics IR imaging polarimetry and HST optical images of the object at the origin of the R Mon outflow, which were interpreted in terms of a ∼10^2 AU optically thick accretion disk surrounding a ∼10 M⊙ HAeBe star (Close et al. 1997).

Another suggestive piece of evidence is the detection in several HAeBe’s of CO overtone bandhead emission that exhibits broadening by a peristellar velocity distribution that scales with radius as v(r) ∝ r^{-1/2} (e.g., Chandler et al. 1995; Najita et al. 1996b). This velocity field is consistent with Keplerian rotation and the emission has therefore been attributed to a circumstellar disk. An alternative interpretation (which, like the disk model, also applies to low-luminosity YSOs in which CO bandhead emission has been detected) is that the emission originates in a magnetic accretion funnel that channels the inflowing matter from an accretion disk, with the observed broadening produced as the gas free-falls along the stellar magnetic field lines toward the stellar surface (Martin 1997). There are, in fact, other tantalizing observational clues that point to the presence of magnetospheric accretion in certain HAeBe’s. These include, in particular, the detection of inverse P Cygni (IPC) Hβ line profiles in a number of such stars (see Fig. 2). In one survey of HAeBe stars (Ghandour et al. 1994), 4 out of 29 objects were found to show clear evidence for such profiles, with the redshifted absorption feature occurring between ∼100 and ∼700 km s^{-1} relative to the rest velocity (L. Hillenbrand 1996, personal communication). Sorelli et al. (1996) proposed a similar interpretation of the redshifted Na D

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For comparison with this ∼14% apparent frequency, 40% (6/15) of the cTT’s surveyed by Edwards et al. (1994)
absorption components observed in several HAeBe’s. As the latter authors have noted, the Na D lines are likely to originate in a region containing neutral hydrogen, which could give rise to detectable Lyα absorption features. These may, however, prove difficult to identify in the presence of broad emission features originating in an associated outflow. It is, however, important to bear in mind that alternative interpretations of the IPC profiles have been proposed. For example, they have been attributed to the evaporation of comet-like bodies that reach the vicinity of the star (e.g., Grinin et al. 1994) as well as to ongoing quasi-spherical infall onto the YSO (Bertout et al. 1996). A detailed comparison between the data and the specific predictions of each model would therefore be necessary before one could accept the presence of IPC profiles in these stars as unequivocal evidence for magnetospheric accretion (see Sorelli et al. 1996). Firm evidence might be provided, for example, by the discovery of periodic surface “hot spots” of the type previously found in some cTT’s, although the low expected contrast between the effective temperatures of the accretion shock and of the surrounding stellar photosphere in a hot star would make such detections difficult.

Disk signatures (including NIR excess, optical veiling, and CO bandhead emission) have been reported also in higher-mass (∼ 5 – 20 \( M_\odot \)) stars (Hanson et al. 1997). These findings are of particular interest, since, for a representative mass inflow rate \( \dot{M}_{\text{in}} = 10^{-5} M_\odot \text{ yr}^{-1} \), stars with masses \( M > 8 M_\odot \) are predicted to reach the main sequence before disk accretion has ceased (Palla and Stahler 1993). Such disks may therefore be expected to show the effects of the interaction with the strong radiation field and stellar wind that are produced by a high-mass main-sequence star. The direct imaging of disk candidates in high-\( M \) stars and a comparison between their properties and those of disks in low-\( M \) YSOs are thus an important challenge for future observations. Since the structure of a circumstellar disk likely depends on how the central star is formed, these studies could also help to test the suggestion (Stahler et al. 1999) that stars with masses \( M \geq 10 M_\odot \) are assembled through the coalescence of lower-mass objects at the centers of young stellar clusters. One piece of evidence that has been cited in support of this interpretation is the apparent stellar clustering around HAeBe stars: Testi et al. 1997; see also Hillenbrand 1995) found that such clustering becomes significant for stars of spectral type B7 or earlier and argued that this is consistent with intermediate-mass YSOs representing a transition between the low-mass and high-mass modes of star formation. If so, then the study of disks in HAeBe’s could also be useful for testing the coalescence picture.

It is noteworthy that several independent studies have established correlations of the type \( \dot{M} \propto L_{\text{bol}}^{0.6} \) for the mass accretion rate (from IR continuum measurements; Hillenbrand et al. 1993) exhibited IPC profiles in Hβ. The detection frequency for the above sample of HAeBe’s would, however, increase to ∼ 25% if one also included objects with a more tentative IPC classification; see Ghandour et al. 1994.

Blondel et al. (1993) detected Lyα emission lines in several HAeBe stars and attributed them to radiation from magnetic accretion funnels; however, one can argue that a wind origin is more likely in this case (L. Hartmann 1996, personal communication).
Fig. 2.— Residual H\textsc{$\beta$} spectra of HAeBe stars with IPC profiles, obtained by subtracting in each case a standard photospheric spectrum for a star of the same spectral type. The displayed spectra are vertically offset from each other for the sake of clarity and have normalized intensities. These are the best examples of IPC profiles among a sample of 29 HAeBe's observed in 1992 at the KPNO 2.1m telescope. (Courtesy of L. Hillenbrand.)
1992), the ionized mass outflow rate in the jets (from radio continuum observations; Skinner et al. 1993), and the bipolar molecular outflow rate (from CO line measurements; Levreault 1988) in both low-luminosity and high-luminosity YSOs. Taken together, these relationships suggest that a strong link between accretion and outflow exists in both low-mass and high-mass stars.

4. Modeling Issues

The detection of similar accretion and outflow signatures in low-$L_{\text{bol}}$ and high-$L_{\text{bol}}$ YSOs and the evidence for a strong correlation between them that continues smoothly from low- to high-luminosity objects provide strong arguments in favor of a similar underlying physical mechanism operating in all newly formed stars. In particular, the disk-driven hydromagnetic wind scenario, which is currently the leading model for the origin of bipolar outflows in low-$L_{\text{bol}}$ stars (see §1), may also apply to HAeBe’s and even higher-mass stars. It is important to note, however, that the basic model worked out for the low-luminosity objects would need to be extended and modified by the inclusion of several new effects that are specific to high-luminosity objects. Some of these effects have already been considered before in a different context, but incorporating them all together into a self-consistent accretion/outflow model is one of the main theoretical challenges in this new field of research. Among the anticipated new elements of the theory, one can list the following:

- Enhanced field–matter coupling near the disk surface due to both the direct and the diffuse ionizing radiation from the central star, leading to higher mass accretion and outflow rates (e.g., Pudritz 1985).

- Disk photoevaporation (e.g., Hollenbach et al. 1994; Yorke and Welz 1996), creating a low-velocity ($v$ of order the sound speed $c_s \approx 10 \text{ km s}^{-1}$) disk outflow beyond the “gravitational radius” $r_g = GM/c_s^2 \approx 10^{15}(M/10M_\odot) \text{ cm}$ (or even further in the presence of a strong stellar wind). Photoevaporation may facilitate the injection of mass into a centrifugally driven disk outflow, but a hydromagnetic wind from the inner disk could reduce the mass evaporation rate further out by intercepting some of the ionizing radiation from the central star.

- A strong, radiatively driven stellar wind, which may be transformed into a highly collimated jet through a dynamical interaction with a disk-driven wind (e.g., Frank and Mellema 1996) or a disk magnetic field (e.g., Kwan and Tademaru 1995). A strong, radiatively driven outflow may also be induced in the disk by the intercepted stellar radiation: this outflow is predicted to originate within a few stellar radii from the YSO’s surface, to be predominantly equatorial, and to have significantly lower speeds than those of the stellar wind (Drew et al. 1998).
• Radiation pressure effects on dust. Because of the large dust scattering cross section at UV and optical wavelengths, the effective Eddington luminosity for a dusty gas is much lower than the electron-scattering critical luminosity, and is given by $L_{\text{crit, dust}} \approx 4 \times 10^2 (M/10M_\odot) L_\odot$ (e.g., Wolfire and Cassinelli 1987). Radiation pressure effects could thus be important beyond the dust sublimation radius $r_{\text{sub}} \approx 1 (L_{\text{bol}}/10^2 L_\odot)^{1/2}$ AU and might contribute to the flow acceleration and also lead to the “opening up” of the streamlines (see Königl and Kartje 1994). The latter effect could be at least partially responsible for the apparently lower degree of collimation of jets from high-$L_{\text{bol}}$ sources (Mundt and Ray 1994; see §2).

• Photoionization heating and radiative excitation. The strong stellar radiation field is expected to be the main heating mechanism of the gas in the stellar vicinity. In particular, it may dominate the ambipolar diffusion heating that is important for weakly ionized outflows in low-luminosity YSOs (Safier 1993) and could, in fact, cut it off altogether within the Strömgren surface. Radiative excitation may give rise to unique emission signatures, including Ly$\alpha$ lines (e.g., Blondel et al. 1993) and enhanced overtone emission from the higher CO bandheads (Martin 1997).

The incorporation of low-luminosity and high-luminosity YSOs into the same theoretical framework may help resolve some of the outstanding issues in the modeling of bipolar outflows from low-mass stars. For example, the origin of the LVC and HVC forbidden line emission is not yet fully understood. Magnetically driven outflows have been leading candidates for their interpretation, but both stellar field-based (e.g., Shang et al. 1998) and disk field-based (e.g., Cabrit et al. 1999) models have been proposed. As noted in §3, the apparent decrease in the detection frequency of the [OI] HVC (relative to the [OI] LVC) in higher-luminosity YSOs might be related to the locations of the HVC and LVC emission regions with respect to the star. If so, this could prove useful in the attempt to discriminate between the competing models.

5. Further Questions

5.1. The Role of a Stellar Magnetic Field in Channeling Accretion and Driving an Outflow

In one of the proposed models for the origin of bipolar outflows and jets from low-mass stars, the stellar magnetic field plays a pivotal role in the generation of the underlying centrifugally driven wind (e.g., Shu et al. 1999). If all YSO outflow sources can indeed be described by the same general model (see §4), then this interpretation requires that HAeBe’s (as well as higher-mass
As was pointed out in §3, there is, in fact, persuasive evidence in at least some HAeBe's for the existence of a magnetic field that is strong enough to channel accreting gas onto the stellar surface. There is also evidence for a strong, ordered magnetic field in nonaccreting HAeBe stars. In particular, VLBI radio measurements have revealed the presence of extended ($\sim 3 - 10 R_\star$), organized magnetic field configurations that are similar to those observed in certain wTT's, and which also resemble the field structures of magnetic Ap and Bp stars, in at least two such objects (André et al. 1992).

The evidence for strong magnetic fields in at least some HAeBe's is puzzling, since such stars are not expected to have a deep convective layer, and therefore, according to the conventional picture, could not generate a strong field through dynamo action. In fact, according to the calculations of Palla and Stahler (1993), stars that accrete at a constant rate of $10^{-5} M_\odot \, yr^{-1}$ during the PMS phase should be fully convective for $M < 2.4 M_\odot$, have a subsurface convection layer due to deuterium burning for $2.4 M_\odot < M < 3.9 M_\odot$, and be fully radiative for $M > 3.9 M_\odot$. One possible resolution of this apparent difficulty is that the observed structures represent a fossil magnetic field and that HAeBe's possessing such strong fields are, in fact, the precursors of the main-sequence Ap/Bp stars (André et al. 1992). The association with Ap/Bp stars could in principle be tested by comparing the rotation rates of HAeBe's that are strong nonthermal radio sources (accepting André et al.'s argument that such emission is a reliable tracer of a large-scale, organized stellar field) with the rotation rates of other HAeBe's. As a class, HAeBe's are intermediate rotators (rotating at $\sim 0.3$ of breakup with mean projected speeds of $\sim 100$ km s$^{-1}$; e.g., Böhm and Catala 1995), but those objects that have extended magnetospheres may be expected to rotate more slowly, in accordance with the observed trend in Ap/Bp stars. It remains to be explained, however, how a closed magnetic field configuration would arise from the unipolar field that is likely to be incorporated into the star during the PMS accretion phase (e.g., Li and Shu 1996).

An alternative interpretation of the field is that it originates in a stellar dynamo that taps directly into the large rotational energy reservoir of the star without requiring convection to also be present. Tout and Pringle (1995) and Lignières et al. (1996) have explored specific models along these lines. A dynamo mechanism is a promising candidate for the enhanced surface activity exhibited by HAeBe stars of the P Cygni subclass (e.g., Böhm and Catala 1995), and it may also account for the X-ray emission detected toward a fair number of HAeBe's (Zinnecker and Preibisch 1984).

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5 As discussed by Catala et al. (1986), at least $\sim 20\%$ of HAeBe's (those belonging to the P Cygni subclass; see Finkenzeller and Mundt 1984) give rise to powerful winds with mass loss rates in the range $\sim 10^{-8} - 10^{-6} M_\odot \, yr^{-1}$. The existence of a stellar magnetic field is also required in models that attribute the acceleration of these winds to hydromagnetic waves (e.g., Strafella et al. 1998).

6 HAeBe stars are commonly taken to be YSOs in the mass range $2 M_\odot \lesssim M \lesssim 8 M_\odot$. 
Tout and Pringle's (1995) model requires the mean poloidal field to be rather weak and thus cannot account for either the large-scale organized field or the magnetically channeled accretion inferred in several of these objects. It is also unclear how any model that relates the dynamo action to the stellar rotation can explain the apparent lack of a correlation between the various activity tracers and the projected rotation speed (Zinnecker and Preibisch 1994; Böhm and Catala 1995), which contrasts with the observed trend in T Tauri stars (e.g., Neuhäuser 1997).

It is interesting to note in this connection that even the youngest low-mass YSOs, which likely are not yet fully convective objects, already show evidence for strong outflows. In fact, the momentum discharges inferred in these so-called Class 0 sources are a factor of $\sim 10$ higher than the values implied by the tight correlation between the momentum discharge and the source bolometric luminosity that is found in older (Class I) low-mass YSO's (Bontemps et al. 1996). If the Class 0 outflows are driven by a stellar magnetic field, then the mechanisms invoked for producing strong fields in non-convective YSOs could be relevant not only to HAeBe's but also to very young low-mass objects. In order to properly address the above questions, it would be necessary to carry out a self-consistent calculation of the stellar and magnetic field evolution that would take into account the the spatial distribution of radiative and convective regions within the star as well as the effects of field-mediated accretion onto the YSO, magnetic braking of the stellar rotation, etc.

5.2. Does the FU Orionis Phenomenon Have an Analog in Higher-Mass Stars?

Bell (1994) suggested that the large apparent “holes” that have been inferred from the infrared spectral modeling of HAeBe’s (see §3) may be associated with the “low” phase of a thermal ionization instability that operates in the inner disk region. As was mentioned in §1, the “high” phase of this instability has been proposed as the origin of the FU Ori outburst phenomenon in low-mass YSOs (e.g., Bell and Lin 1994). Given that several other arguments also point to a comparatively low ($\lesssim 10^{-7} M_{\odot}$ yr$^{-1}$; e.g., Hartmann et al. 1993) current mass accretion rate onto the central object in a number of HAeBe’s, it is conceivable that a similar mode of nonsteady accretion is present in higher-mass stars. One possible check on this idea might

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7Zinnecker and Preibisch (1994) discuss stellar wind shocks as the most likely source of the X-rays. However, Skinner and Yamauchi (1996), analyzing ASCA data for a bright Herbig Ae star, have concluded that the X-rays in that case originate from the immediate stellar vicinity, although possibly from a late-type companion. In fact, confusion with nearby low-mass YSOs is a potentially serious problem for measurements with existing X-ray telescopes, whose angular resolution typically does not exceed $\sim 5''$.

8Note, however, that if some of the observed activity in HAeBe’s is powered by magnetically channeled accretion, then the absence of a clear correlation with the stellar rotation might be due to the interaction between the stellar magnetic field and a circumstellar disk, which would tend to reduce the rotation rate (see §1). As a test of the latter effect, it would be useful to search for a correlation (similar to the one found in T Tauri stars) between the rotation speeds of HAeBe’s and the strength of their accretion signatures.
be a search for multiple bow shocks along the associated jets: such shocks have been detected in several low-$L_{\text{bol}}$ objects, and it has been argued that they are likely associated with the strong disk-outflow episodes that characterize FU Ori outbursts (e.g., Reipurth 1989). In the case of the higher-luminosity YSOs it would, however, be necessary to examine the effect of the strong stellar radiation field on the evolution of the instability. In particular, one would need to check to what extent the inner disk could be maintained in a state of low temperature and ionization during the “low” phase of the instability (see van Paradijs 1996 and King et al. 1996).

5.3. Disk Evolution around Massive Stars

Accretion disks around high-mass stars are probably the predecessors of the Vega-type systems first discovered by IRAS; in particular, $\beta$ Pictoris has likely evolved from an HAeBe star. The evolution of such disks could in principle be traced by comparing the high-$M$ analogs of cTT’s with the corresponding analogs of wTT’s as well as with Vega-type systems (e.g., Strom et al. 1991). The analogs of cTT’s and wTT’s can be identified through their accretion signatures (in particular, their infrared spectra; Lada and Adams 1992, Hillenbrand et al. 1992) as well as through their outflow signatures (in particular, their forbidden line emission and the H$\alpha$ equivalent width; Corcoran and Ray 1998). A systematic search for the high-mass analogs of wTT’s may potentially be carried out by means of an X-ray survey (cf. Casanova et al. 1995), although this approach is subject to the caveats that the X-ray emission from HAeBe’s might be associated with outflows rather than being intrinsic to the YSOs (Zinnecker and Preibisch 1994) or that it originates in close, low-mass companions (e.g., Skinner and Yamauchi 1996). It is, however, also conceivable that a sufficiently large data base might be obtained as part of a more general mapping project, such as the Sloan Digital Sky Survey.

Hillenbrand et al. (1992) concluded from an analysis of a sample of 47 HAeBe’s that the shorter evolutionary timescales of more massive stars are reflected in the clearing timescales of their respective disks, with optically thick disks around such stars surviving for less than 0.3 Myr (as compared with $\sim$ 3 Myr for a typical T Tauri star). It has, in fact, been surmised that the disk clearing time may in some cases be even shorter than the stellar evolution time, resulting in a possibly significant shortening of the evolutionary phase over which these YSOs would be classified as HAeBe stars (de Winter et al. 1997). The faster disk evolution in the more luminous YSOs may reflect the effects of photoevaporation and strong stellar winds in such objects (see §4), although it is also possible that the time-averaged mass accretion rate through these disks is higher (perhaps as a result of a stronger ionizing flux from the central star; see §4). The disk clearing mechanism in YSOs is still an open question, and its resolution could benefit from continued comparative studies of low-mass and high-mass objects. Such studies, coupled with searches for low-luminosity companions, could also shed light on the issue of planet formation in protostellar disks (e.g., by constraining the timescale of planetesimal growth; see Strom et al. 1991).
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