RevMexAA (Serie de Conferencias), **1**, 275-283 (1995)

DISK-DRIVEN HYDROMAGNETIC WINDS IN YOUNG STELLAR OBJECTS

Arieh Königl
Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA

RESUMEN

Después de revisar brevemente la evidencia de vientos de disco en objetos estelares jóvenes, me concentro en un mecanismo que explica de una forma natural la conexión entre los discos de acrecimiento y los flujos energéticos en estrellas jóvenes. Más concretamente, considero la posibilidad de que el momento angular que se libera por el acrecimiento de materia sea transportado lejos a través de un viento generado centrífugamente, encauzado a lo largo de las líneas abiertas del campo magnético que enhebran el disco. Discuto el origen del campo magnético en el disco y su acoplamiento con el material fundamentalmente neutro, en diferentes condiciones de densidad. Después, describo las características generales dinámicas y cinemáticas de tales flujos, así como su estructura térmica, resaltando algunas de las implicaciones observacionales de estas propiedades.

ABSTRACT

After briefly reviewing the evidence for disk-driven winds in young stellar objects, I concentrate on one attractive mechanism that offers a natural explanation for the inferred link between accretion disks and energetic outflows in young stars. Specifically, I consider the possibility that the angular momentum liberated by the accreting matter is transported away by means of a centrifugally driven wind that is channeled along open magnetic field lines that thread the disk. I discuss the origin of the magnetic field in the disk and its coupling to the mostly neutral matter in different density regimes. I then describe the general dynamical and kinematic characteristics of such outflows as well as their expected thermal structure, and point out some of the observational implications of these properties.

Key words: **ACCRETION, ACCRETION DISKS — ISM: JETS AND OUTFLOWS — MHD — STARS: MASS LOSS — STARS: PRE–MAIN-SEQUENCE**

1. INTRODUCTION

Many of the presentations in this meeting have provided compelling evidence for the presence of accretion disks and energetic, bipolar outflows in young stellar objects (YSOs). It is now recognized that there is an intimate link between accretion and outflow signatures in pre–main-sequence stars (e.g., Edwards et al. 1993). For example, among T Tauri stars, forbidden line emission (arising in the outflow) and optical veiling (produced in the course of accretion onto the YSO) are found only in objects that exhibit a near-infrared color excess (a signpost to distributed circumstellar mass, most likely a disk). This immediately suggests that the outflows are powered by accretion. The measured high velocities indicate an origin in the region near the stellar surface, where the liberated gravitational potential energy is high, but it is as yet unclear whether the outflows originate right at the stellar surface or nearby in the accretion disk. The detection of high-velocity emission from *neutral* species (such as Na and CO) argues, particularly in the case of high-surface-temperature source, against the possibility that the gas started out on the stellar surface itself.

Another piece of evidence for the existence of disk-driven outflows has come from recent high-resolution, ground-based long-slit spectroscopy (e.g., Solf & Böhm 1993; Hirth et al. 1994; Böhm & Solf 1994) and from

HST imaging (e.g., Kepner et al. 1993) of low-luminosity YSOs. These observations have probed the spatial distribution of the forbidden optical line emission ([O I], [S II], [N II]), which is one of the main diagnostics of outflows in these stars. This emission is detected on scales of $\sim 10 - 100$ AU, and one of the chief puzzles associated with its interpretation has been the nature of the heating mechanism that keeps the emitting gas at a temperature of $\sim 10^4$ K so far away from the central object. The observations have revealed the existence of two distinct components: a high-velocity ($\gtrsim 100 \mathrm{~km~s^{-1}}$) component (HVC) that is relatively broad ($\Delta V_{\mathrm{FWHM}} \approx 50 - 100 \mathrm{~km~s^{-1}}$), although it appears that the width decreases with distance from the origin (possibly signifying collimation), and a low-velocity ($\sim 5 - 40 \mathrm{~km~s^{-1}}$) component (LVC) that is relatively narrow ($\Delta V_{\mathrm{FWHM}} \approx 20 - 40 \mathrm{~km~s^{-1}}$), although one can occasionally identify a red wing that extends to $\gtrsim 10^2$ km $\mathrm{s^{-1}}$. The HVC emission extends to $\gtrsim 10^{16}$ cm and appears to continue smoothly into the large-scale optical jet. Furthermore, like the emission in the outer jet, it is characterized by high excitation, which is likely shock-induced. By contrast, the LVC emission region is an order of magnitude smaller, and this component is characterized by high density and relatively low excitation. The [O I] LVC emission peaks at $\sim 15 - 20$ AU from the YSO and extends to ~ 50 AU, whereas the [S II] LVC emission usually peaks further out, and one finds evidence for acceleration between the [O I] and [S II] emission regions. These properties are consistent with the LVC being associated with a disk-driven wind that originates at some distance from the YSO. The HVC could in principle also originate in the disk: in fact, there is evidence indicating that the high-velocity gas expelled during FU Orionis outbursts comes out of the disk surface rather than the star (Calvet et al. 1993). However, the absence of detectable HVC [O I] $\lambda 5577$ emission (Edwards et al. 1989; Hamann 1994) suggests that the HVC may not yet be excited near the base of the outflow where the electron densities are $\gtrsim 10^6 - 10^8$ $\mathrm{cm^{-3}}$: this situation could arise if, for example, the shocks that give rise to this emission only develop further out along the jet (see next paragraph for one possible scenario).

Another key property of YSO outflows that has been emphasized in this meeting is their apparent variability. A nonsteady outflow is likely to lead to shock formation along the jet, which may be manifested as emission knots and bow structures. Various groups have studied the evolution of such flow disturbances both analytically and numerically (e.g., Raga & Kofman 1992; Hartigan & Raymond 1993; Gouveia Dal Pino & Benz 1994). Schematically, if the jet velocity V_{j} varies by an amount ΔV_{j} on a time scale t_{var}, then a pair of shocks (an internal "working surface") will first form at a distance X from the origin after a time t_{on}, with X and t_{on} related by $X \approx V_{\mathrm{j}} t_{\mathrm{on}}$. Subsequent shocks will have a separation $\Delta X \approx V_{\mathrm{j}} t_{\mathrm{var}}$, with $\Delta X / X \approx \Delta V_{\mathrm{j}} / V_{\mathrm{j}}$. Based on this picture, Hirth et al. (1994) have inferred $t_{\mathrm{on}} \lesssim 10$ yr for CW Tau, which is consistent with the direct measurement of velocity variability in this source, whereas Reipurth et al. (1992) have deduced a time scale of decades for t_{var} in HH 111. In the case of HH 46/47, Raga et al. (1990) inferred a time scale between major outbursts (leading to the formation of bow shocks along the jet) of $\gtrsim 10^3$ yr, which is compatible with the estimated typical time between FU Ori outbursts in YSOs (Bell & Lin 1994). These values are consistent with the suggestion (Herbig 1989) that there may be a progression of variability time scales, with t_{var} increasing with source luminosity on going from flash variables to EX Ori-type stars to FU Ori stars. In fact, it is also conceivable that individual star/disk systems may experience a variety of nonsteady outflow episodes, characterized by different time scales and kinetic luminosities, with the dominant mode of eruption possibly depending on the evolutionary stage of the star.

The most promising models for YSO outflows involve magnetohydrodynamically driven winds, which, unlike radiatively or thermally driven outflows, can readily account for the large momentum and energy discharges inferred from the observations. In §2 I summarize the salient features of MHD winds, in §3 I consider them in the context of magnetized disk models, and in §4 I discuss some of their unique observational signatures.

2. CENTRIFUGALLY DRIVEN OUTFLOWS

The most widely accepted models for magnetically driven outflows in YSOs assume that they originate as centrifugally driven winds from circumstellar disks (see Königl & Ruden 1993 for a review). In this picture, the disks are threaded by open magnetic field lines and material is expelled centrifugally from their surfaces like beads on inclined, rotating wires. The outflows are powered by the liberated gravitational potential energy of the accreted gas and could in principle transport most of the angular momentum of the inflowing matter, which is removed by magnetic torques in the disk. This scenario could account in a natural way for the intimate connection between disks and jets: the outflows are the means by which the gas in the rotating disk disposes of its angular momentum and potential energy in order to reach the stellar surface.

Blandford & Payne (1982) were the first to consider centrifugally driven winds in a disk threaded by a large-scale, ordered magnetic field. As they pointed out, the basic outflow mechanism can be understood with the help of a mechanical analogy to a bead on a rotating, rigid wire: for a Keplerian rotation law, the bead (representing the matter) will be flung out if the wire (representing the magnetic field line in the ideal-MHD limit) is inclined at an angle > 30° to the disk normal. Using a self-similar (in the spherical radial coordinate), cold wind model, they constructed explicit solutions of flows that are magnetically dominated above the disk surface and become super-Alfvénic and magnetically collimated further out.[1] Furthermore, they showed that such winds are an efficient means of extracting angular momentum from the disk because any given field line (rotating with the angular velocity of the material at the radius ϖ_0 where it leaves the disk) enforces corotation out to the (cylindrical) Alfvén radius $\varpi_{\rm A}$, thereby increasing the lever arm of the torque that acts back on the disk. Since $\varpi_{\rm A}$ could be $\gg \varpi_0$, the mass outflow rate that is required for the removal of all the liberated angular momentum might be only a small fraction of the mass accretion rate: $\dot{M}_{\rm wind}/\dot{M}_{\rm acc} \approx (\varpi_0/\varpi_{\rm A})^2$. The wind could also tap a significant fraction of the gravitational potential energy given up by the accreted matter and carry it out in the form of a Poynting flux. Given the comparatively low mass outflow rate, the terminal (poloidal) speed of the wind would be correspondingly large, $V_{\rm p\infty} \approx (\varpi_{\rm A}/\varpi_0)V_{\rm K0}$ (where $V_{\rm K0}$ is the Keplerian speed at ϖ_0). The kinetic power carried by the outflow from a narrow slice of the disk that is centered at ϖ_0 is thus $\sim 0.5\,\dot{M}_{\rm acc}V_{\rm K0}^2$, i.e., the wind is also expected to transport a large fraction of the gravitational potential energy liberated in the disk.

In the self-similar model of Blandford & Payne (1982), the scaling of the speed V, magnetic field amplitude B, and gas density ρ with the spherical radial coordinate R is determined from the relations $B/\sqrt{\rho} \propto V \propto V_{\rm K} \propto R^{-1/2}$ and from the assumption that the mass outflow rate from any given decade of radius, $\dot{M}_{\rm wind}(\varpi_0) \propto \rho_0 V_0 \varpi_0^2$, is constant, which imply $\rho_0 \propto \varpi_0^{-3/2}$ and $B_0 \propto \varpi_0^{-5/4}$. Contopoulos & Lovelace (1994) generalized this class of self-similar solutions by considering winds with a density scaling $\rho \propto R^{-\beta}$, for which $B \propto R^{-(\beta+1)/2}$ and $\dot{M}_{\rm wind}(\varpi_0) \propto \varpi_0^{(3/2-\beta)}$ (with $\beta = 3/2$ corresponding to the Blandford & Payne solution). A favored "minimum energy" solution, corresponding to a constant axial current $I = 2\pi c r B_\phi$ across the jet, is given by $\beta = 1$. These self-similar solutions are characterized by constant values of the (normalized) specific angular momentum (including kinetic and magnetic contributions) and mass-to-flux ratio throughout the flow, and all the flow lines cross the disk at the same angle to its surface.

Pelletier & Pudritz (1992) further generalized the centrifugally driven wind solutions to a class of non-self-similar outflows. In particular, they considered outflows in which the quantity $\frac{V_{\rm K0}^2\varpi_{\rm A}^2}{V_{\rm A}^2\varpi_0^2}|\nabla\varpi_{\rm A}|_{\rm A}^2$ (where the subscript A denotes the Alfvén point) is everywhere a constant, and derived solutions in which the poloidal magnetic field component at the disk surface scales as ϖ_0^{-x} (with x expected to lie between 1 and 2). The asymptotic outflow velocity along a flow line that intersects the disk at ϖ_0 scales as $V_{\rm p\infty}(\varpi_0) \propto \varpi_0^{2(1-x)}$, whereas $\dot{M}_{\rm wind}(\varpi_0) \propto \varpi_0^{(4x-5)}$. The Blandford & Payne solution is recovered by setting $x = 5/4$: for $x < 5/4$, the angle between the flow lines and the disk surface increases with ϖ_0, whereas for $x > 5/4$ the flow lines converge toward the axis and the wind has a finite lateral extent. The $I = const.$ solution is given in this case by $x = 3/2$, which corresponds to $V_{\rm p\infty} \propto \varpi_0^{-1}$ and $\dot{M}_{\rm wind}(\varpi_0) \propto \varpi_0$. Note that this differs from the self-similar $I = const.$ solution discussed above, which is characterized by $V_{\rm p\infty} \propto \varpi_0^{-1/2}$ and $\dot{M}_{\rm wind}(\varpi_0) \propto \varpi_0^{1/2}$. Although the simple Blandford & Payne model captures the essential features of the more general wind solutions, the latter are important for investigating the properties of real sources and more work is needed on their development (see also Sauty & Tsinganos 1994).

The origin of the magnetic field that threads the disk is still an open question. One likely possibility is that it corresponds to interstellar field lines that are frozen into the parent molecular cloud and that have been advected inward either during the collapse of the molecular cloud core (cf. Fiedler & Mouschovias 1993; Galli & Shu 1993) or subsequently by accretion through the disk (e.g., Lubow et al. 1994). This possibility is supported by the close alignment between the ambient field and the outflow direction that has been inferred in many sources. Another possibility is that the magnetic field in the disk has been amplified by a local dynamo process (e.g., Stepinski et al. 1993 and these proceedings). Alternatively, the outflow may be driven by stellar magnetic field lines (e.g., Shu et al. 1994; Fendt et al. 1995; see also the contributions of Najita (1995) and of Ostriker & Shu, poster session, in these proceedings). It is worth noting that, even in the latter class of models, the mass driven out in the wind is most often postulated to come from the disk rather than from the star.

---

[1] In the centrifugally driven wind scenario, the toroidal magnetic field component is not important in driving the outflow near the disk surface, although it plays a central role in collimating the wind by hoop stresses beyond the Alfvén point. It is in principle possible for magnetized outflows to be driven from the start by the gradient in B_ϕ (e.g., Lovelace et al. 1991), but such winds might be hard to maintain in a steady state (e.g., Cao & Spruit 1994).

3. MAGNETIZED DISK MODELS

A fundamental question related to the disk-driven MHD wind models is: how exactly does the magnetic field mediate the accretion and outflow processes? More specifically, how is the angular momentum transferred from the disk to the wind and how does part of the inflow turn into an outflow? Wardle & Königl (1993) addressed these issues in the context of weakly ionized disks and constructed steady-state disk/wind models in which the radial advection and azimuthal shearing of the field lines are counteracted by ambipolar diffusion (Fig. 1). Their models are directly applicable to the low-density regime of circumstellar disks around solar-mass YSOs (midplane densities $n_{\rm m} \approx 10^{10}$ cm^{-3} on scales $\varpi_0 \approx 100$ AU), where the electric current is mediated by metal ions and electrons, and where the accretion proceeds throughout the entire vertical cross section of the disk. Analogous models can be constructed for the high-density regime ($n_{\rm m} \approx 10^{14}$ cm^{-3}, $\varpi_0 \approx 1$ AU), where the current is mediated by small charged grains or by ions and electrons that recombine without grains, and where the field is sufficiently well coupled to the mostly neutral matter only for densities $\lesssim 10^{13}$ cm^{-3}, so that accretion only proceeds through the surface layers of the disk (see Königl 1995a).

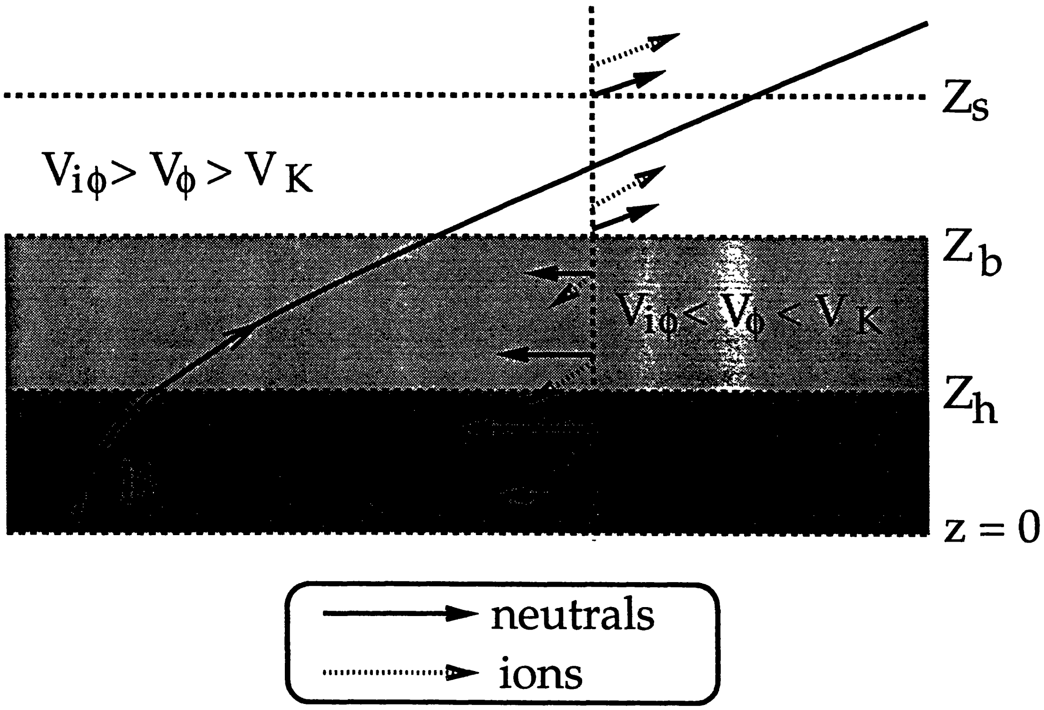

Fig. 1.— Schematic diagram of the vertical structure of an ambipolar diffusion-dominated disk, showing a representative field line and the poloidal velocities of the neutral (*solid arrowheads*) and the ionized (*open arrowheads*) fluid components. The relationship between the azimuthal velocities is also indicated. The disk possesses three distinct zones: a quasi-hydrostatic, matter-dominated region below a density scale height $Z_{\rm h}$, a field-dominated transition zone where the inflow gradually diminishes with height, and an outflow region that corresponds to the base of a centrifugally driven wind. The first two regions are characterized by a radial inflow and sub-Keplerian rotation, while the gas in the wind region flows out with $V_\phi > V_{\rm K}$. Note that the poloidal velocity of the ions vanishes at the midplane ($z = 0$) and is small for both fluids at the base of the wind ($z = Z_{\rm b}$). The outflow passes through a sonic point at $Z_{\rm s}$.

At radii smaller than a few tenths of an AU, the degree of ionization (and hence the field–matter coupling) decreases to such a level that only a fraction of the incoming mass can continue to flow in at a steady rate. The charge density in this region could, however, increase as a result of collisional ionization induced by the compressional heating of the inflowing gas. In particular, the disk might be subject to the thermal ionization instability originally discussed in the context of dwarf novae and more recently invoked as a possible explanation of FU Ori outbursts (e.g., Bell & Lin 1994 and these proceedings). In this picture, accretion in the innermost disk proceeds in a nonsteady fashion, with a "gate" at $\lesssim 0.25$ AU opening every $\sim 10^3$ yr or so after the accumulated column density has become large enough to trigger the instability. During the "high" phase of the instability (which is identified with an outburst) the gas is hot ($T \gtrsim 10^4$ K) and almost completely ionized, and mass rains in at a rate $\gtrsim 10^{-5}\, M_\odot\, {\rm yr}^{-1}$, whereas during the "low" phase the temperature and degree of ionization decline sharply, and the accretion rate drops to $\lesssim 10^{-7}\, M_\odot\, {\rm yr}^{-1}$. In the context of the magnetized disk model, one can attribute the increase in the accretion rate as the gas becomes highly ionized to the reestablishment of good coupling between the field and the matter, which allows the field to extract the angular momentum of the accreting gas. This could account both for the marked increase in $\dot{M}_{\rm acc}$ and for the strong disk outflow that evidently accompanies it (e.g., Calvet et al. 1993). [2]

During the high-ionization phase of the instability there would be no significant magnetic field diffusion (a necessary ingredient of quasi-steady disk models) unless some anomalous resistivity were present. One plausible mechanism, which is consistent with the likely occurrence of hydrodynamic and/or hydromagnetic turbulence in the disk, is turbulent Ohmic diffusivity. This can be conveniently expressed in the mixing-length approximation as

$$\eta_{\rm Ohm} = \tilde{\eta} C_{\rm s} h_{\rm T} \, ,$$

where $C_{\rm s}$ and $h_{\rm T}$ are the thermal sound speed and scale height, respectively, and where $\tilde{\eta}$ is a parameter $\lesssim 1$. Using this parametrization, one can construct quasi-steady disk/wind solutions for this case in complete analogy with the Wardle & Königl (1993) formulation (Königl 1994, 1995a; see also Ferreira & Pelletier 1995 for a related work). In particular, in the low-resistivity limit $\tilde{\eta}/2a^2 \ll 1$ (where $a \equiv B_{\rm m}/(4\pi\rho_{\rm m})^{1/2}C_{\rm s}$ is the ratio of the midplane Alfvén speed to the isothermal sound speed), the solutions exhibit the same behavior as in the ambipolar diffusion-dominated case, with the radial field component dominating the azimuthal field within the disk. For a constant $\tilde{\eta}$, one can show that the following inequalities must be satisfied by a viable solution,

$$(\tilde{\eta}/2)^{1/2} \lesssim a \lesssim 2 \lesssim a^2\epsilon/\tilde{\eta} \lesssim 0.4 V_{\rm K0}/C_{\rm s} \, ,$$

where $\epsilon \equiv -V_{r{\rm m}}/C_{\rm s}$ is the normalized midplane inflow speed. The first inequality corresponds to the requirement that the disk remain sub-Keplerian, the second to the wind launching condition (the field should make an angle $> 30°$ to the normal at the disk surface; see §2), and the third to the requirement that the base of the wind lie well above a density scale height in the disk. The last inequality expresses the constraint that the Ohmic dissipation rate at the midplane should not exceed the rate of gravitational potential energy release.

One can relate the magnetized disk model to the "α-viscosity" model employed in the analysis of Bell & Lin (1994) by making the identification $\alpha = \epsilon\varpi_0/h_{\rm T}$ $(= \epsilon[V_{\rm K0}/C_{\rm s}])$. Writing $C_{\rm s}/V_{\rm K0} = 0.1\, s_{-1}$ and $\alpha = 10^{-3}\alpha_{-3}$, the 3rd and 4th inequalities above become

$$2.5 \times 10^{-5}\alpha_{-3}s_{-1}^2 \lesssim \tilde{\eta}/a^2 \lesssim 5 \times 10^{-5}\alpha_{-3}s_{-1} \, .$$

It is thus seen that, for the characteristic values of the viscosity parameter inferred by Bell & Lin for FU Ori systems in outburst ($\alpha \approx 10^{-3}$) and for typical values of s in circumstellar disks, the magnetized accretion disk model could be consistent with the formulation of the thermal ionization instability (which, in turn, effectively fixes the value of the parameter combination $\tilde{\eta}/a^2$). Of course, a full solution of the disk/wind equations and an explicit thermal stability calculation within the framework of the magnetized disk model are required to substantiate this tentative conclusion.

---

[2] In his presentation in this meeting, L. Hartmann noted that the inferred outflow kinetic luminosities in FU Ori objects are significantly lower than the measured radiative luminosities, whereas they are expected to be comparable if the wind carries most of the angular momentum liberated in the disk (see §2). Even if these inferences continue to hold, they need not invalidate the magnetized disk interpretation. In particular, the outflow may still be modeled as a centrifugally driven wind, and even the increase in the angular momentum transport in the disk may be attributed to the presence of a well-coupled magnetic field by invoking a mechanism for the production of an effective magnetic viscosity (e.g., Hawley et al. 1995).

4. MAGNETIZED WIND SIGNATURES

Centrifugally driven winds from circumstellar disks have several unique characteristics that may have important implications to the observational properties of YSOs.[3] In particular, such outflows are distinguished by a highly stratified density and velocity structure, a high momentum discharge that results in the efficient uplifting of dust from the associated disks, and, particularly in the case of low-luminosity YSOs, a robust ambipolar diffusion-heating mechanism that raises the temperature in the inner regions of the wind (on scales $\gtrsim 10^2$ AU) to $\gtrsim 10^4$ K. The strong ρ and V stratification is a consequence of the rapid acceleration of the wind near the disk surface (Fig. 2). The uplifted dust would be evaporated by the YSO radiation field (of luminosity L_*) within the sublimation radius $\varpi_{\rm sub} \approx 0.1\,(L_*/L_\odot)^{1/2}$ AU, but at larger distances the dust would survive and would exhibit the same density distribution as the gas in which it is embedded.

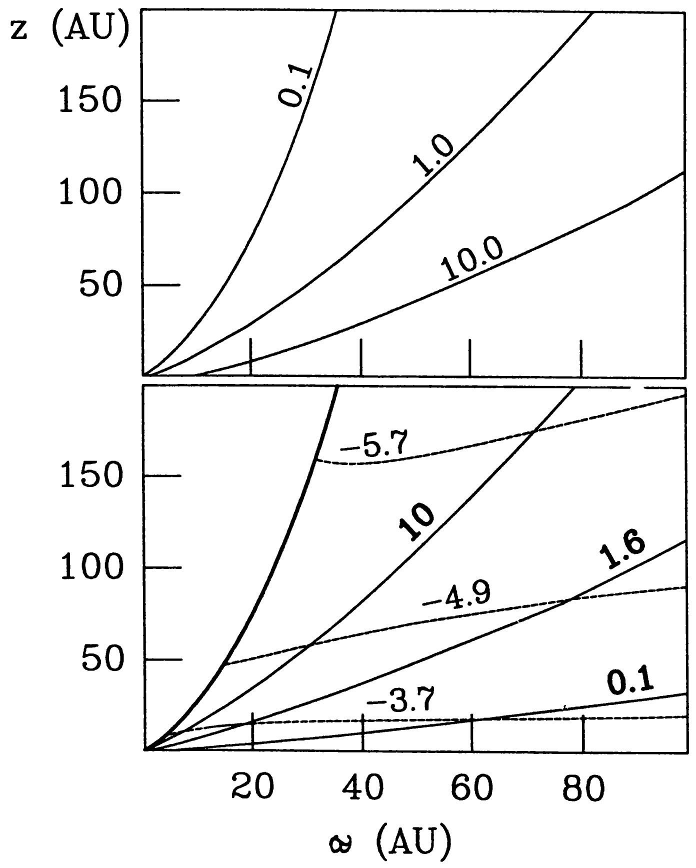

Fig. 2.— Structure of a self-similar ($\beta = 3/2$), centrifugally driven wind from a Keplerian accretion disk (from Safier 1993a). In this solution, the central mass is $0.5\,M_\odot$ and the mass outflow rate between 0.1 and 10 AU is $\sim 1 \times 10^{-7}\,M_\odot\,{\rm yr}^{-1}$. (*top*) Meridional projections of the flow lines (labeled by the value, in AU, of the radius where they intersect the disk). (*bottom*) Contours of constant $V_{\rm p\infty}/V_{\rm K1}$ (*solid* lines), where $V_{\rm p\infty}$ is the asymptotic poloidal speed and $V_{\rm K1}$ is the Keplerian speed at 1 AU, and *log*(ρ/ρ_1) (*dashed* lines), where ρ_1 is the density at the base of the wind at 1 AU. The heavy line on the left indicates the flow line that originates at 0.1 AU.

The stratified dust distribution predicted in disk-driven wind models would lead to angle-dependent obscuration that could strongly influence the statistics of optically visible YSOs (see Königl & Kartje [1994] for a discussion of the analogous effect that such winds might have on the classification of active galactic

---

[3] A more detailed review of the topics discussed in this section is given in Königl (1995b).

nuclei). Such a dust distribution is also expected to account naturally for the centrosymmetric + parallel equatorial polarization pattern that characterizes many YSOs (cf. Whitney & Hartmann 1993). Furthermore, the scattering and reprocessing of the YSO continuum radiation by the dust in the wind and the disk could give rise to the observed infrared spectra. In particular, one can readily show (e.g., Natta 1993) that a wind in which the density scales with the $\beta = 1$ density power-law index of the "minimum energy" self-similar wind solution (see §2) would give rise to a flat λF_λ near- and mid-infrared spectrum akin to that exhibited by several actively accreting YSOs.

The magnetic field that accelerates the mostly neutral gas in centrifugally driven winds from weakly ionized disks is coupled to the bulk of the matter through ion-neutral collisions. As was discussed in detail by Safier (1993a), the accompanying collisional dissipation could be the dominant heating mechanism in winds from solar-mass YSOs, and, for flow lines that originate within $\lesssim$ 3 AU from the star, it could lead to $\sim 10^4$ K temperatures (and correspondingly high ionization fractions $f_p \equiv n_{H+}/n_H$) that would be maintained over three decades in distance irrespective of the initial radius (Fig. 3).

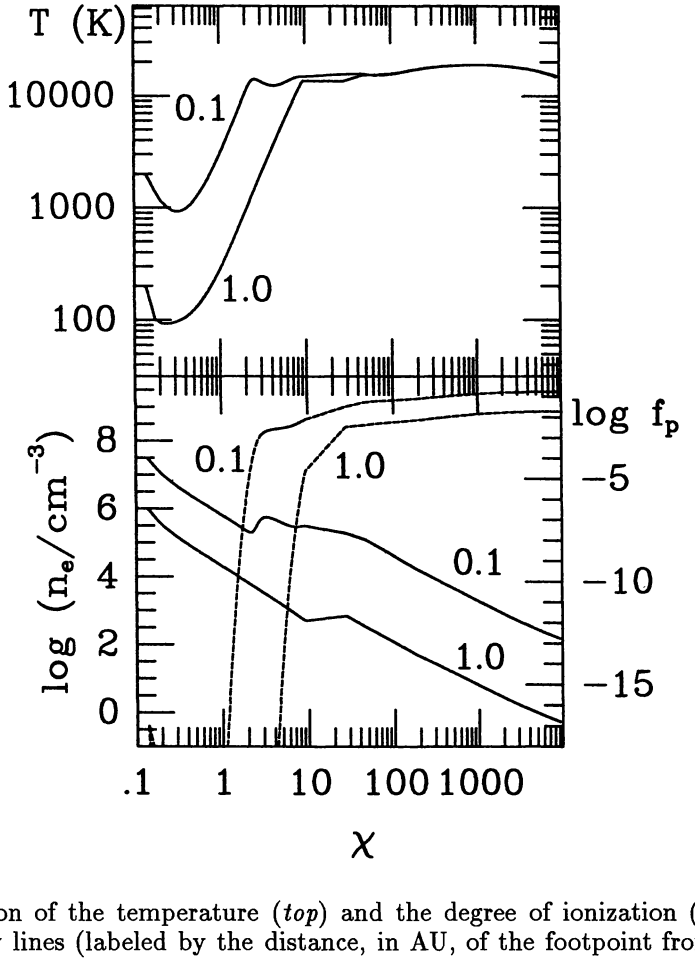

Fig. 3.— The distribution of the temperature (*top*) and the degree of ionization (*bottom*) as a function of $\chi \equiv z/\varpi_0$ along two flow lines (labeled by the distance, in AU, of the footpoint from the central source) for the wind model of Fig. 2 (from Safier 1993a). The ***solid*** lines in the bottom panel correspond to the electron density n_e, whereas the ***dashed*** lines describe the ionization fraction f_p.

The predicted temperatures and electron densities in winds that are subject to this "ambipolar diffusion" heating are consistent with the values inferred from the forbidden line emission in T Tauri stars on scales of a few tens of AU. In fact, this model can account quantitatively for the observed line luminosities as well as for the correlation between these luminosities and the measured infrared excesses (which, in this picture, are produced by reprocessing of the stellar radiation in the dusty outer regions of the wind). Disk-driven winds could thus contribute to the observed forbidden line emission, especially to the low-velocity component (see Safier 1993b). However, the simple self-similar models considered so far have difficulty reproducing the observed line profiles, particularly the single, low-V peak of the LVC (see §1). This mechanism may also play an important role in producing several other emission signatures of YSOs, including the thermal radio radiation (Martin 1995) and the CO infrared bandhead emission (Safier et al. 1995).

I am grateful to Steve Martin, Pedro Safier, and Mark Wardle for valuable discussions and for assistance with the preparation of the figures. I also thank the organizers of this conference for encouraging and facilitating my participation. This work has been supported in part by NASA grants NAGW-2379 and NAG 5-2766.

REFERENCES

Bell, K. R., & Lin, D. N. C. 1994, ApJ, 427, 987
Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883
Böhm, K.-H., & Solf, J. 1994, ApJ, 430, 277
Cao, X., & Spruit, H. C. 1994, A&A, 287, 80
Calvet, N., Hartmann, L., & Kenyon, S. J. 1993, ApJ, 402, 623
Contopoulos, J., & Lovelace, R. V. E. 1994, ApJ, 429, 139
Edwards, S., Cabrit, S., Ghandour, L. O., & Strom, S. E. 1989, in Low Mass Star Formation and Pre-Main Sequence Objects, ed. B. Reipurth (Garching bei München: ESO), 385
Edwards, S., Ray, T., & Mundt, R. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson: Univ. of Arizona Press), 567
Fendt, C., Camenzind, M., & Appl, S. 1995, A&A, in press
Ferreira, J., & Pelletier, G. 1995, A&A, in press
Fiedler, R. A., & Mouschovias, T. Ch. 1993, ApJ, 415, 680
Galli, D., & Shu, F. H. 1993, ApJ, 417, 243
Gouveia Dal Pino, E. M., & Benz, W. 1994, ApJ, 435, 261
Hamann, F. 1994, ApJS, 93, 485
Hartigan, P., & Raymond, J. 1993, ApJ, 409, 705
Hawley, J. F., Gammie, C. F., & Balbus, S. A. 1995, ApJ, in press
Herbig, G. H. 1989, in Low Mass Star Formation and Pre-Main Sequence Objects, ed. B. Reipurth (Garching bei München: ESO), 233
Hirth, G. A., Mundt, R., & Solf, J. 1994, A&A, 285, 929
Kepner, J., Hartigan, P., Yang, C., & Strom, S. 1993, ApJ, 415, L119
Königl, A. 1994, in Theory of Accretion Disks – 2, ed. W. J. Duschl, J. Frank, F. Meyer, E. Meyer-Hofmeister, & W. M. Tscharnuter (Dordrecht: Kluwer), 53
———. 1995a, in Research Trends in Plasma Astrophysics, ed. R. Kulsrud (New York: AIP Press), in press
———. 1995b, in Disks and Outflows around Young Stars, ed. H. J. Staude (Heidelberg: Springer-Verlag), in press
Königl, A., & Kartje, J. F. 1994, ApJ, 434, 446
Königl, A., & Ruden, S. P. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson: University of Arizona Press), 641
Lovelace, R. V. E., Berk, H. L., & Contopoulos, J. 1991, ApJ, 379, 696
Lubow, S. H., Papaloizou, J. C. B., & Pringle, J. 1994, MNRAS, 267, 235
Martin, S. C. 1995, in preparation
Najita, J. 1995, in Disks, Outflows and Star Formation, ed. S. Lizano & J. M. Torrelles, RevMexAASC, 1, 293
Natta, A. 1993, ApJ, 412, 761
Pelletier, G., & Pudritz, R. E. 1992, ApJ, 394, 117
Raga, A. C., Cantó, J., Binette, L., & Calvet, N. 1990, ApJ, 364, 601
Raga, A. C., & Kofman, L. 1992, ApJ, 386, 222
Reipurth, B., Raga, A. C., & Heathcote, S. 1992, ApJ, 392, 145
Safier, P. N. 1993a, ApJ, 408, 115
———. 1993b, ApJ, 408, 148
Safier, P. N., Martin, S. C., & Königl, A. 1995, in preparation
Sauty, C., & Tsinganos, K. 1994, A&A, 287, 893

Shu, F. H., Najita, J., Ostriker, E., Wilkin, F., Ruden, S., & Lizano, S. 1994, ApJ, 429, 781
Solf, J., & Böhm, K.-H. 1993, ApJ, 410, L31
Stepinski, T. F., Reyes-Ruiz, M., & Vanhala H. A. T. 1993, Icarus, 106, 77
Wardle, M., & Königl, A. 1993, ApJ, 410, 218
Whitney, B. A., & Hartmann, L. 1993, ApJ, 402, 605